Scaphoid Variation and an Anatomical Basis for Variable Carpal Mechanics

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Abstract

The morphology and function of the wrist is poorly understood. Improved understanding of carpal anatomy may facilitate improved understanding of carpal mechanics and may enhance the clinical management of wrist dysfunction. Many detailed investigations of wrist structure have been reported, many of which have focussed on the scaphoid and its ligamentous supports. The results of these studies are not readily collated to provide an accurate description of the scaphoid and its supports.

This study attempted to provide a detailed description of the anatomy of the scaphoid and its supporting structures. A detailed nomenclature was proposed to facilitate accurate description of the scaphoid and related structures. Gross observation enabled separation of the sample population of scaphoids into two groups. Morphometric analyses were used to determine any significant differences between the groups (type one and type two). The histological sections were then used to facilitate accurate gross identification of ligaments and computed tomographs were used to investigate the *in situ* variation of scaphoid orientation.

The investigations suggest that two distinct populations of scaphoid existed within the sample population. The scaphoids varied in bone morphology, arrangement and degree of ligamentous support and position relative to the capitate. Articular facet shape and size differed between scaphoid types. The orientation and number of ligaments supporting the scaphoid were suggestive of variable scaphoid motion. The variation in ligamentous patterns was supported by histological investigation. Computed tomographs through the

longitudinal axis of the scaphoid suggested a variable position of the scaphoid relative to the capitate.

The variation of these structures was discussed in relation to the kinematic findings of others. A theoretical model of variable scaphoid function was proposed based on the anatomical findings. The data presented and the reviewed kinematic data may be extrapolated to suggest two models of scaphoid motion. The scaphoids may be divided into rotating/translating scaphoids and flexing/extending scaphoids. This must be confirmed by a combined anatomical and mechanical study. The clinical implications of different scaphoid structure and function may be profound. The ability to identify such differences *in situ* may facilitate varied clinical management for the various types of wrist suggested.

Declaration

This work contains no material that has been accepted for the award of any other degree or diploma in any university or tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and for photocopying.

Quentin A Fogg 12/ 03/ 04

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Publications Resulting from this Thesis

Fogg QA, Bain GI, and Tedman RA (2003) Functional carpal anatomy and its clinical implications. *Clinical Anatomy* **16 (6)**: 555 (Abstract).

Fogg QA, Bain GI, and Tedman RA (2004) Functional scaphoid anatomy and its clinical implications. *Clinical Anatomy* (in review).

Preface

Thesis Intent and Structure

The wrist is poorly understood. Detailed analyses of structure and function have been performed but a consensus on either is yet to be reached. This thesis is a collection of studies conducted with the general aim of clarifying the structure of the scaphoid, discussing the structural detail in a functional context, and determining whether the structural understanding can be applied in a clinical environment. These aims are addressed in four chapters.

The first chapter aims to improve understanding of scaphoid structure and variation. To facilitate this a detailed nomenclature for the scaphoid and related structures is proposed. Morphometric variations in the scaphoid were used to separate the sample population into two groups or types. Differences between the groups were discussed and the functional significance of the variations was hypothesised.

The second chapter addresses a common issue in joint research. Can ligament and joint capsule be accurately differentiated? A histological investigation was conducted in an attempt to answer this question. Various tissues were identified and the bone to which each tissue was attached was measured. This gave an indication of the degree of force transmitted through each tissue to the bone, and hence acted as a quantitative test of the differentiating power.

The third chapter utilised the observations of chapter two in conjunction with a gross investigation of ligamentous support of the scaphoid. The combination of histological and gross data was used to improve the accuracy and limit the subjectivity of the investigation. Patterns of ligaments were used to separate the wrists into groups and the differences between the groups were discussed. The functional significance of the differences was hypothesised.

The fourth chapter aims to identify scaphoid variation applicable to the clinical environment. Computed tomographs were used to assess scaphoid morphology and orientation in situ. The differences in morphology and orientation are discussed, and their functional significance hypothesised.

The fifth chapter summarises all of the investigations and collates the results into an overall theory of scaphoid function. It is hoped that with improved understanding of scaphoid structure and its supporting structures that understanding of scaphoid function may be improved. The results within this thesis may provide a new perspective on the investigation of wrist structure and function. It is anticipated that the functional hypotheses within this thesis will be tested in future investigations.

Chapter 1

Scaphoid Morphology and Carpal Nomenclature

1.1 Introduction

The wrist is a common region of dysfunction, yet its structure is poorly understood. The clinical importance of the wrist may attest to the large number of articles published annually that reflect investigation into wrist function and dysfunction. The wealth of information therefore available is vast, but close scrutiny suggests that many contradictory results are presented. Inconsistent and imprecise descriptions make inter-study comparisons difficult and limit the effective application of the results. Therefore this part of the study aims initially to address such contradictions by generating a consistent and detailed description of the scaphoid and to investigate the degree of structural variation. The influence of any variations on the function and the surrounding anatomy will be discussed.

The orientation of the carpal bones is such that their irregular morphologies can be utilised to some mechanical advantage (Kauer, 1986). Their design is a compromise between motion and stability, allowing a unique combination of precise positioning and stability over a large range of motion (Berger, 1996; Bogumill, 1988; Kauer and de Lange, 1987; Lewis *et al*, 1970). It is therefore important to understand these morphological characteristics before attempting to understand the mechanics of wrist function, or to attempt surgical repair of wrist dysfunctions (Merida-Velasco *et al*, 1996; Viegas, 2001a; Viegas, 2001b). Analysis of other structures within the wrist also requires understanding of the skeletal morphologies, and particularly how variations of these morphologies relate to variations in soft tissue orientation (Viegas, 2001b). Ultimately, understanding such variations will facilitate clearer understanding of the function and dysfunction of the wrist.

Carpal motion is poorly understood. Numerous theories abound concerning the biomechanical relationships between carpal bones. The most common theories support either a two-row or a three-column model of carpal motion (Craigen and Stanley, 1995). The evidence upon which these conclusions are made is often unclear. Theories of carpal motion are commonly devised from analyses of carpal bone morphology or patterns of ligamentous support for the carpus, most notably from analyses of the structure and supporting tissues of the scaphoid (Craigen and Stanley, 1995; Garcia-Elias *et al*, 1995; Kauer, 1986; Linscheid, 1986; Moojen *et al*, 2003; Wolfe *et al*, 2000). The literature, however, lacks a consistent* and detailed nomenclature for description of these structures (Kumar *et al*, 2004). Imprecise descriptions allow too much reader subjectivity, reducing the impact of the results and limiting their application.

The anatomy of the scaphoid and its articulation with neighbouring bones is central to developing a comprehensive understanding of carpal mechanics. Theoretical motion of the scaphoid is integral to the formation of carpal motion theories and is dictated by scaphoid anatomy (Compson *et al*, 1994; Moojen *et al*, 2003; Nuttal *et al*, 1998; Wolfe *et al*, 2000). Numerous studies have suggested morphological differences between individual scaphoids (Boabighi *et al*, 1993; Cantor, 1999b; Compson *et al*, 1994; Moojen *et al*, 2002a; Wolfe and Crisco III, 1994) and alluded to potential functional significance of the variations. Understanding the degree of variation in the morphology of the scaphoid is an important step in understanding carpal kinematics (Berger, 2001b; Compson *et al*, 1994). Significant variation may suggest variable movement, and may preclude certain

* in order to main consistency in this document, a single set of descriptive terms will be used, often necessitating the replacement of analagous terms used in the cited literature.

movements. The results of an investigation into scaphoid anatomy may then suggest what movements are anatomically feasible for the scaphoid.

The reviewed literature provides a great deal of support for morphological analyses of the carpus (Berger, 2001b; Compson *et al*, 1994; Middleton *et al*, 2003; Takechi and Kono, 1983; Yalden, 1970), but these investigations have not been united into a detailed description of the carpus in relation to carpal motion. This study attempts to provide a nomenclature for accurate description of fine detail of the scaphoid and related structures. This nomenclature will be used in an attempt to describe scaphoid morphological variation, its functional importance, and its clinical significance. It is hoped that this study will provide a detailed understanding of the scaphoid, and its potential function in global function of the wrist. This study may then act as a template for investigation of the remaining carpal bones, and other complex regions of the body.

1.1.1 Structure of the Carpal Bones

The skeletal structure of the *Homo sapiens* wrist is composed of eight bones collectively known as the carpal bones (Berger, 1996; Bogumill, 1988) (figure 1.1). The carpal bones are the skeletal link between the forearm and the hand. Their morphologies and intricate interactions enable the hand to be positioned with great precision, and to perform the numerous tasks that help us define ourselves as human (Berger, 1996; Berger *et al*, 1982; Bogumill, 1988). The ability to manipulate the environment to specific and increasingly complex needs has been the hallmark of modern *Homo sapiens* development. This development would have been less extensive had the wrist not evolved to enable such

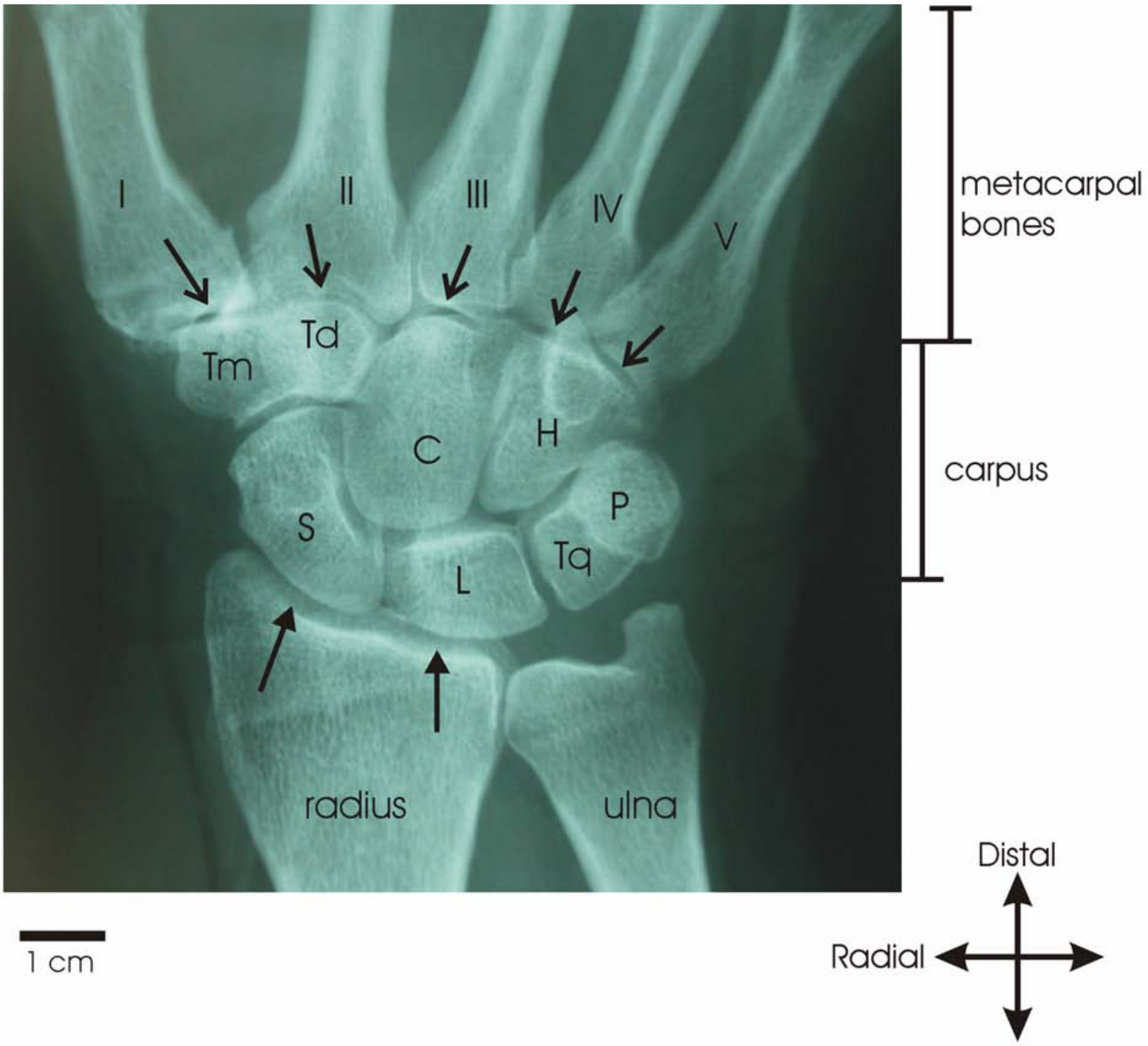

Figure 1.1 The Wrist. The wrist is composed of the carpal bones (carpus) and the structures with which they are articulated. Proximal to the carpus is the radius and ulna. The radius is articulated with the scaphoid and lunate to form the radiocarpal joint (closed arrows). The distal articulations of the carpus are with the metacarpals (numbered I - V, starting with the thumb) at the carpometacarpal joints (open arrows). These may vary anatomically (Nakamura *et al*, 2001); S - scaphoid, L - lunate, Tq - triquetrum, Tm - trapezium, Td - Trapezoid, C - capitate, H - hamate, P - pisiform.

precise placement and stability of the hand (Buckwalter *et al*, 1991; Fahrer, 1983; Garcia-Elias, 2001).

Discussion of the anatomy, function, and dysfunction of the wrist commonly involves replacing the standard anatomical terminology with more wrist/hand-specific descriptive terms (figure 1.2). This is largely due to the ability of the forearm to be pronated and supinated. Whilst referring to anatomical position is satisfactory for the rest of the body (and, indeed, is perfectly applicable to the wrist), discussions of the wrist and hand can become tedious and confusing when constantly visualising the anatomical position. For example, explaining the position of the thumb in both pronation and supination can get confusing; the once lateral thumb becomes medial, and all medial structures become lateral. The terminology of the wrist and hand revolves about the orientation of the skeletal structures immediately proximal to the wrist, the radius and ulna. Throughout pronation and supination, the radius and ulna maintain their spatial relationships with the distal structures. Consequently, lateral and medial can be replaced with radial and ulnar, the latter two terms referring to the sides occupied by the radius and ulna. In this fashion, the thumb is always considered radial, whereas it was lateral while supine and medial while prone. Conversely, the fifth phalanx (or little finger) is always considered ulnar. Similar confusion with anterior and posterior is alleviated with the substitution for palmar and dorsal. Legitimately, palmar and volar can both be used to indicate the anterior surface of the hand in anatomical position, but the former has been selected as the standard for this report in order to conform to the ruling of the Federative Committee on Anatomical Terminology (1999). Proximal and distal are retained, as the motion of the upper limb does not interfere with such orientations.

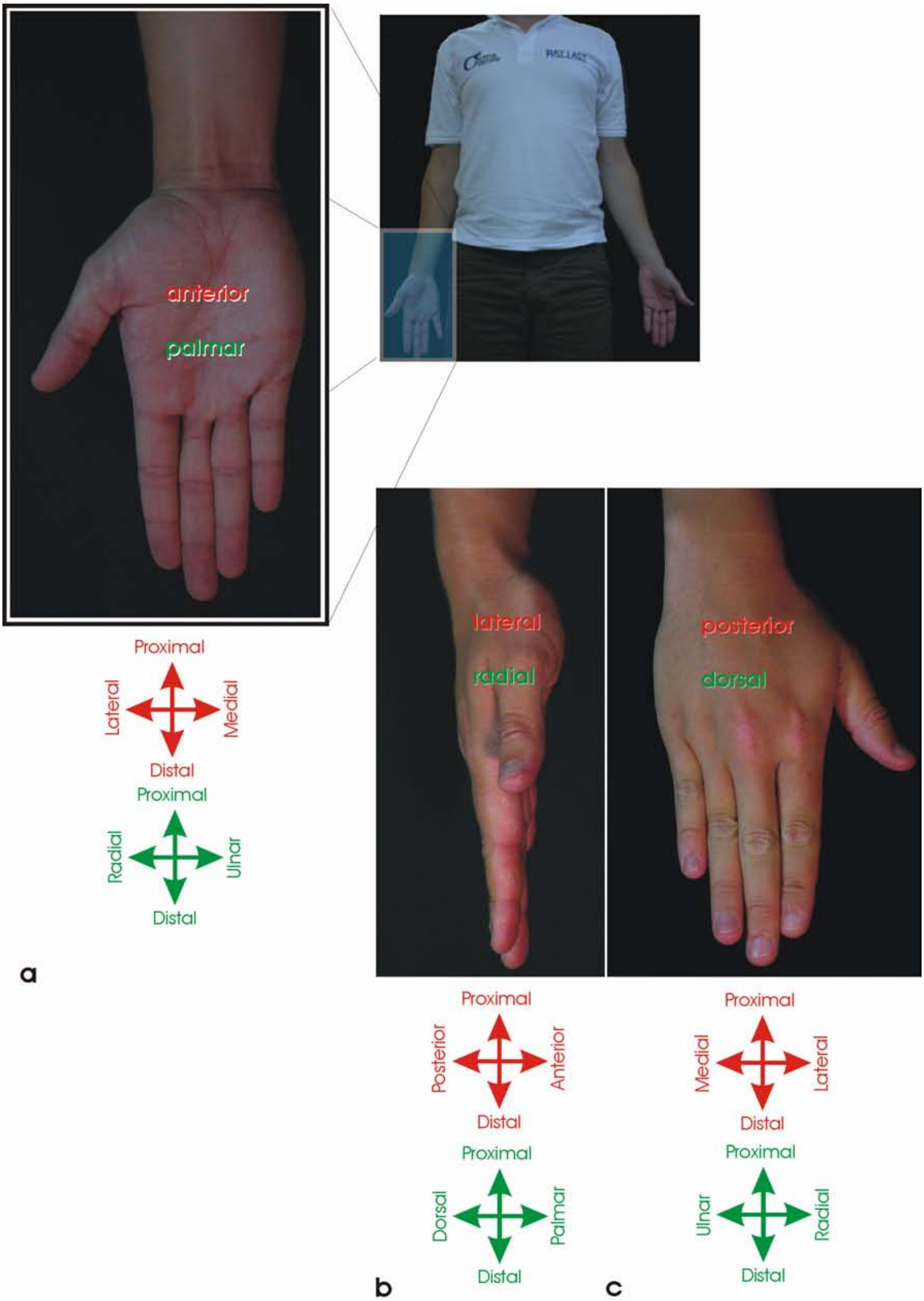

Figure 1.2 Anatomical terminology versus wrist terminology. a - anatomical position with enlarged inset of the hand in anatomical position (forearm supinated); b - the neutral rotatory position of the forearm with the thumb now anterior but still described as either lateral or radial; c - pronated forearm now has the posterior/dorsal aspect of the hand anterior. As the wrist terminology is distinct from traditional anatomical terminology the wrist and hand can be consistently described regardless of the rotation of the forearm; red terms - anatomical terminology, green terms - wrist-specific terminology.

The carpal bones are divided into anatomical groups based on their orientation (figure 1.3). The most common descriptive model is the division of the carpal bones into proximal and distal rows (Berger *et al*, 1982; Craigen and Stanley, 1995; Garcia-Elias, 2001). The proximal row includes the scaphoid, lunate, triquetrum and pisiform. The distal row includes the trapezium, trapezoid, capitate and hamate. Alternatively, the carpal bones can be divided into columns (Craigen and Stanley, 1995; Kauer and de Lange, 1987). The radial (or lateral) column contains the scaphoid, trapezium and trapezoid. The median column contains the lunate and capitate, whilst the ulnar (medial) column contains the triquetrum, hamate and pisiform. Both means of description relate to theories on the mechanics of the wrist, and are further modified to suit different theories, which will be discussed later. Others place the scaphoid alone in a radial column and the triquetrum alone in an ulnar column, thus creating a central column containing all of the remaining carpal bones except the pisiform, which is not included in this mechanical model (Berger, 1996; Craigen and Stanley, 1995; Fisk, 1983; Green, 1990; Ryu, 2001). A notable combination of the two types of carpal models is the "screw-clamp" theory (Craigen and Stanley, 1995; MacConaill, 1941).

Motion at the wrist joint complex will be described in a uniform manner related to the stated orientation terminology (figure 1.4). Palmar- and dorsi- flexion will be termed flexion and extension to maintain the clarity of the discussion. Abduction and adduction are subject to the same issues as medial and lateral, so they are replaced with radial and ulnar deviation respectively. Collaborative motion patterns, such as circumduction, which involve the combination of several simple movements, will be only briefly discussed, as their importance in wrist function is not as profound as the singular movements. This is

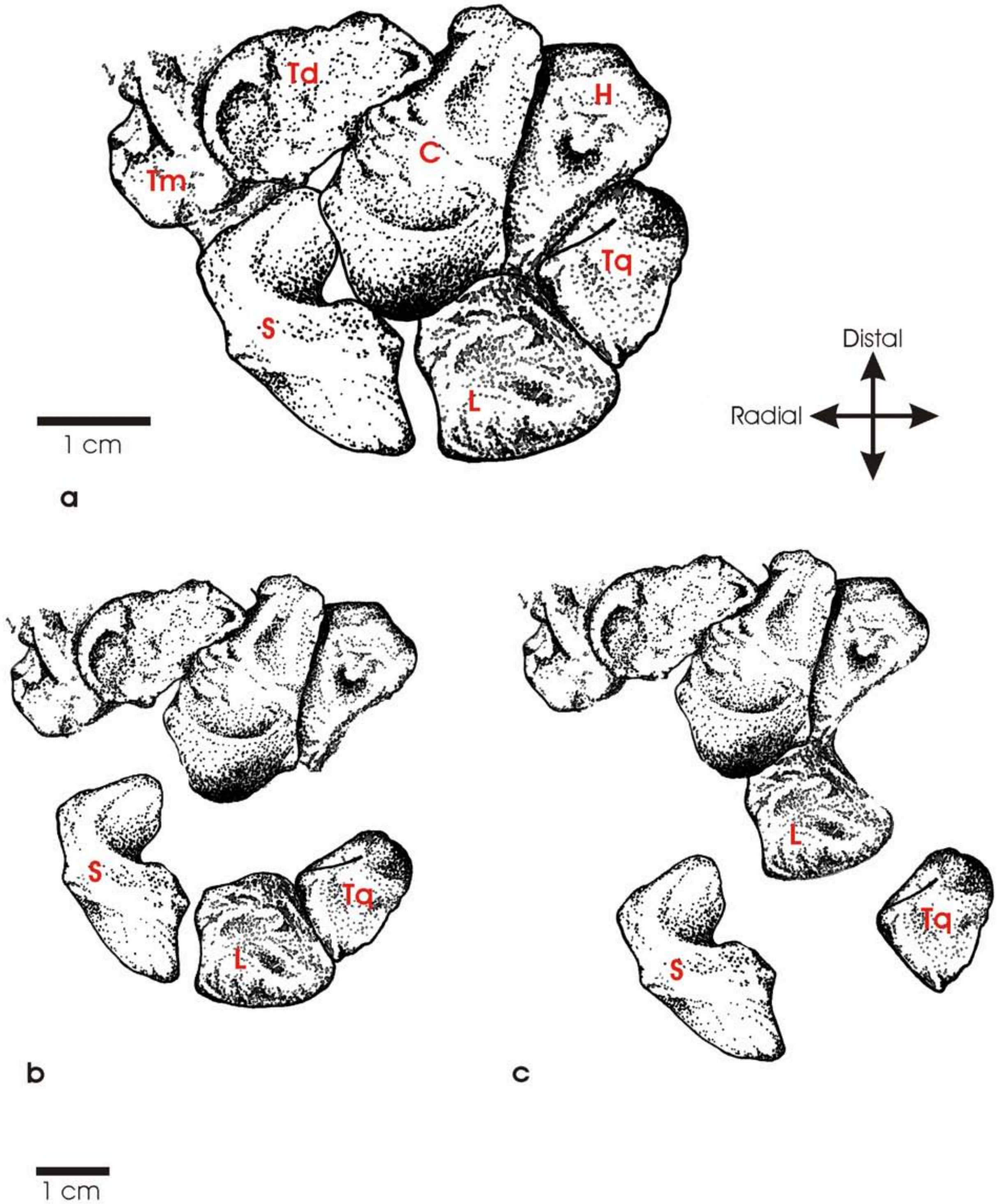

Figure 1.3 Divisions of Carpal Bones. a - schematic dorsal view of the carpus; b - standard anatomical description of the carpus as a proximal and distal row of bones; c - the current division according to the "Column Theory" of carpal mechanics, where the scaphoid and triquetrum reside in their own mobile columns (radial and ulnar respectively), whilst the remaining carpal bones form a t-shaped median column with a mobile component (the lunate); S - scaphoid, L - lunate, Tq - triquetrum, Tm - trapezium, Td - trapezoid, C - capitate, H - hamate; pisiform not visible from dorsal aspect but anatomically grouped proximal row.

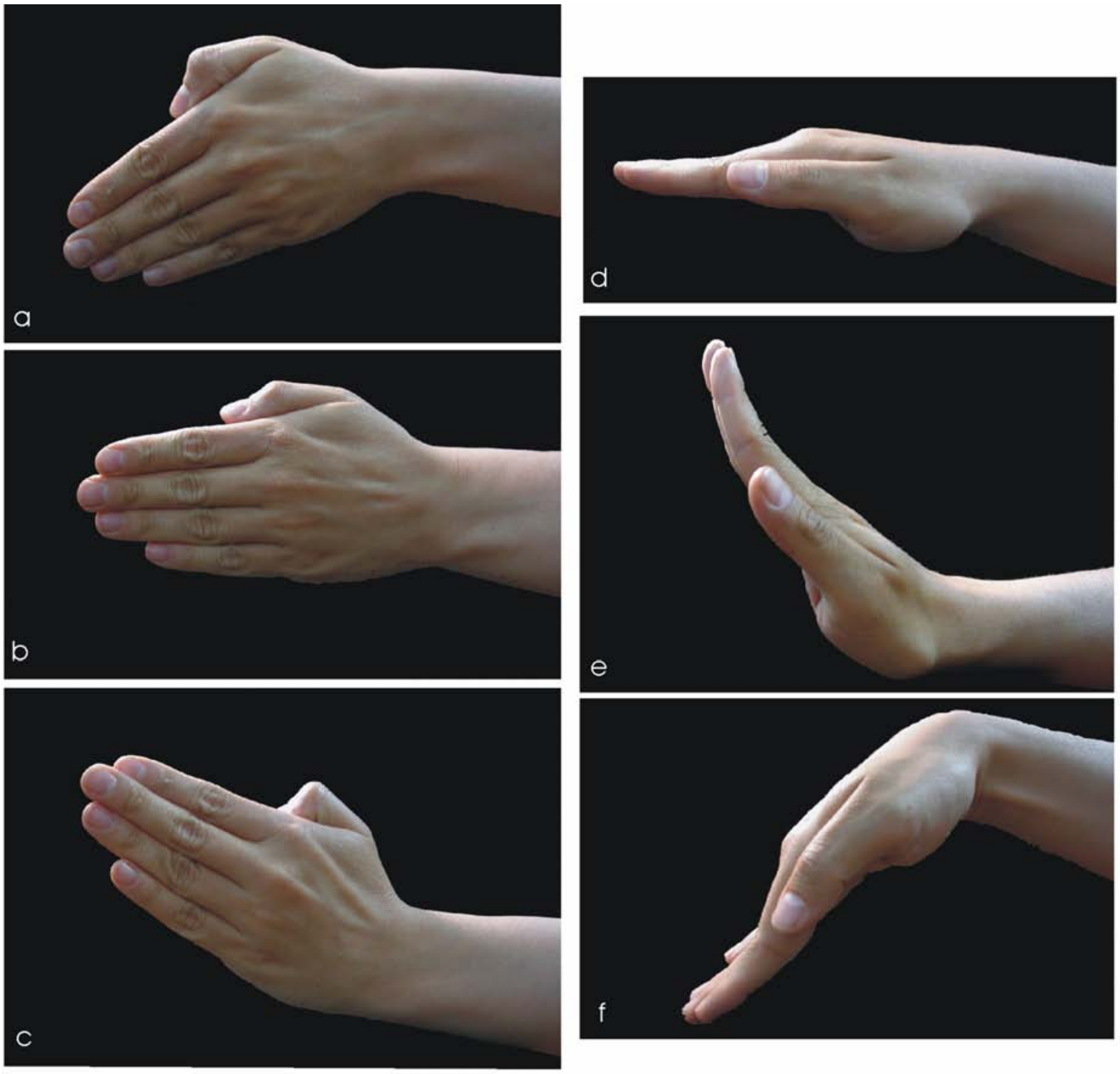

Figure 1.4 Global wrist motion. a - radial deviation (abduction); b - neutral; c - ulnar deviation (adduction); d - neutral; e - extension (dorsi-flexion); f - flexion (palmar-flexion). Circumduction of the wrist is a combination of these movements.

due to circumduction of the wrist being a combination of flexion, deviation and extension (Berger, 1996; Fisk, 1983; Flatt, 1990), thus making any discussion of these individual movements relevant to the ability to circumduct the wrist. This may be contrasted with the first carpometacarpal joint, which is not only circumducted, but rotated as part of opposition of the thumb. This motion is distinctly different from the combination of movements that produce circumduction (Bayat *et al*, 2002; Berger, 1996). When the wrist as a whole is concerned, motion will be described as 'global motion' (Moritomo *et al*, 2000b). The movements of individual components of the wrist will be described using similar terminology, as well as some additional terms. For example, the scaphoid may be flexed or extended, referring to movement in the same directions as global flexion and extension (figure 1.5a), or movement about the transverse axis of the scaphoid. The scaphoid may also be rotated, a movement distinct from flexion or extension, where the rotation is about the longitudinal axis of the individual bone, not the entire carpus (figure 1.5b).

The orientation of the carpal bones is such that their irregular morphologies can be utilised to some mechanical advantage (Kauer and de Lange, 1987; Ryu, 2001). Their design is a compromise between motion and stability, providing bony support to the extremes of the wrist's range of motion, and allowing fine muscular adjustments to influence the position of the wrist throughout this range (figure 1.6).

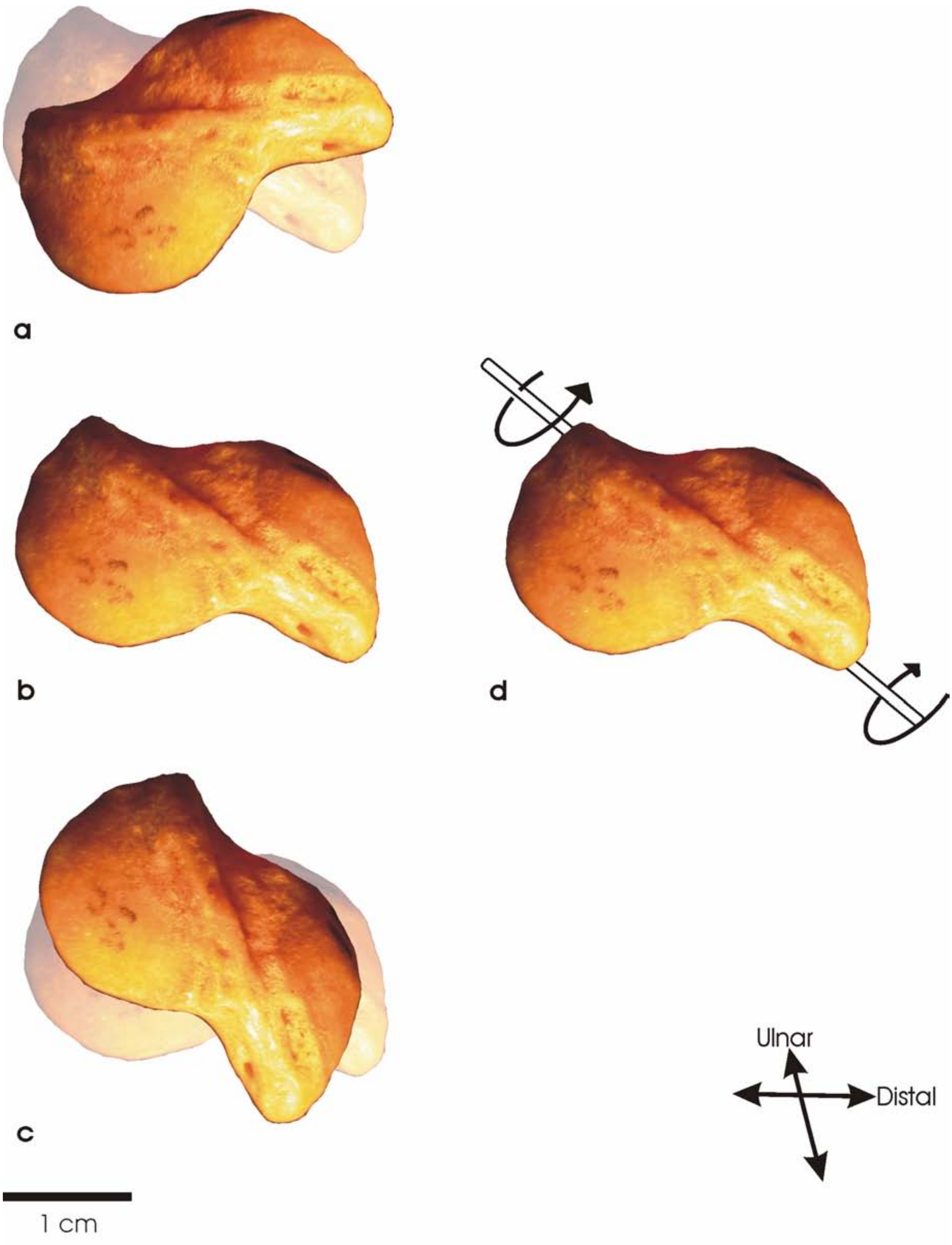

Figure 1.5 Scaphoid motion. a - extension about the transverse axis of the carpus; b - neutral is slightly flexed; c - flexion; d - rotation about the longitudinal axis of the scaphoid.

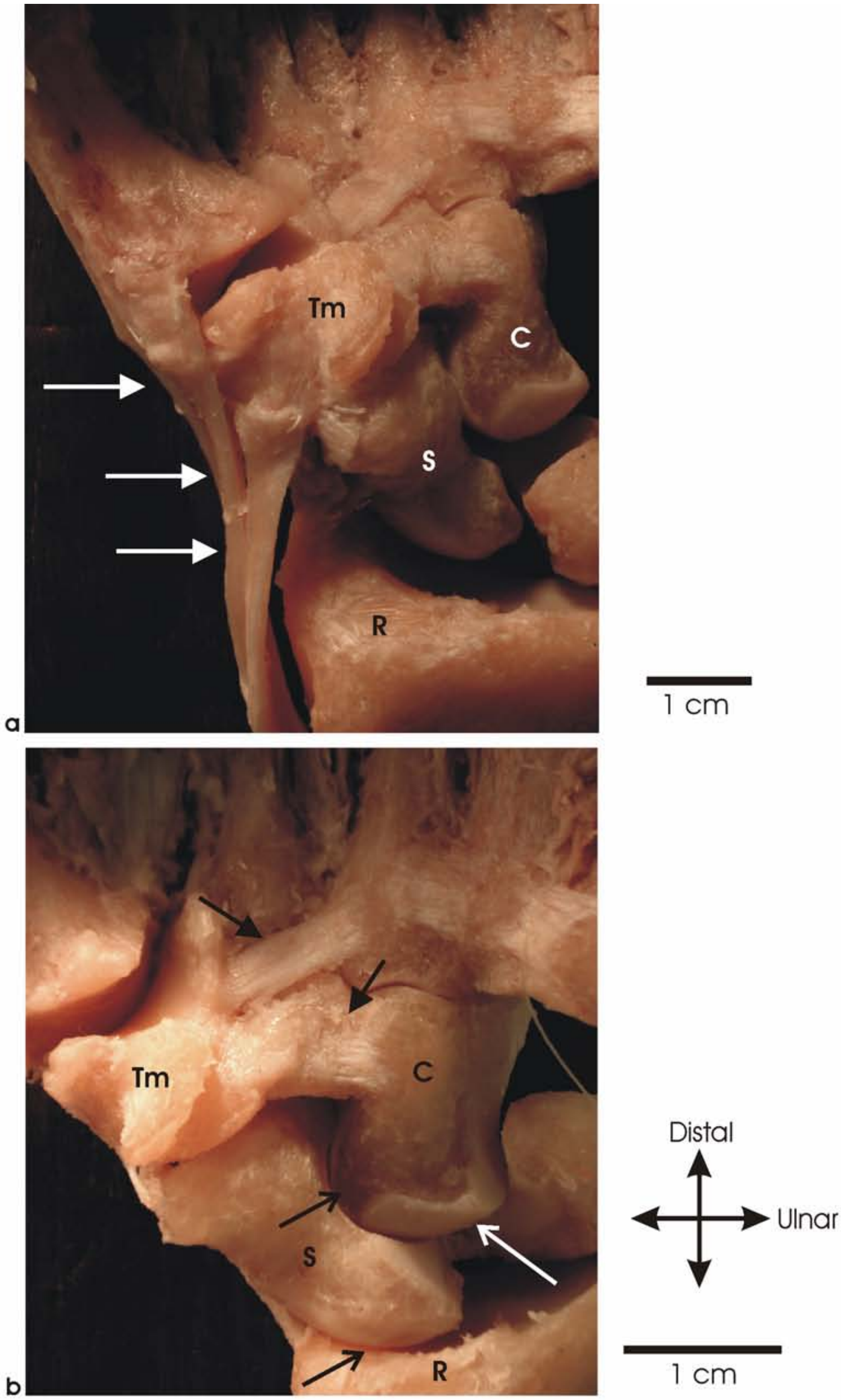

Figure 1.6 Forces through the carpus. a - tendons (closed arrows) are attached to, or distal to, the carpal bones allowing muscles in the forearm to generate movement of the carpal bones. For this to work force must be passed through the carpus efficiently; b - forces are transmitted through the carpus via the numerous congruent articular surfaces (open arrows) and by the many ligaments (closed arrows) that limit the movements of the bones relative to each other; S - scaphoid, C - capitate, R - radius, Tm - trapezium.

1.1.2 Scaphoid

The scaphoid is the most prominent bone in discussions involving the wrist, due in no small part to its unusual appearance (Cantor, 1999a). The bean-shaped scaphoid gained its name (TA* - Os scaphoideum) from its obscure semblance to a boat (*Gr*. scaphon), and is also referred to as the navicular (as in the tarsal bones) (Bogumill, 1988). Four articular facets dominate the morphology of the scaphoid (figure 1.7). The proximal articulation with the radius occupies much of the radial and proximal margins of the scaphoid; hence the scaphoid has an oblique orientation within the carpus that corresponds with the oblique distal articular surface of the radius (Belsole *et al*, 1986; Cantor, 1999b; Compson *et al*, 1994) (figure 1.7). The proximal surface of the scaphoid is bi-convex, fitting the concave scaphoid facet of the distal articular surface of the radius (Bogumill, 1988). The most distal point of articulation with the radius is also the most radial; hence the scaphoid lies disto-radial to proximo-ulnar in the neutral wrist (Craigen and Stanley, 1995; Kobayashi *et al*, 1997). The most ulnar of the articulations is with the lunate, which also occupies the proximal row of the carpus. The lunate is articulated with the scaphoid via a semi-lunar facet on the proximal third of the ulnar aspect of the scaphoid (Bogumill, 1988). Whilst the proximal facet of the ulnar aspect of the scaphoid is devoted to the scapho-lunate articulation, the distal facet of the ulnar aspect is devoted to the scapho-capitate articulation. The articular surface for the capitate is deeply concave, allowing the scaphoid to "cradle" the capitate head (Garcia-Elias, 2001). The distal pole of the scaphoid contributes to a multi-facet joint, articulated with the trapezium and trapezoid. The non-articular regions of the scaphoid are the waist and the tubercle (Berger, 2001b; Compson *et al*, 1994; Garcia-Elias, 2001). The poles (proximal and distal) are defined as those areas of

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* TA, Terminologia Anatomica, Federative Committee on Anatomical Terminology, 1999

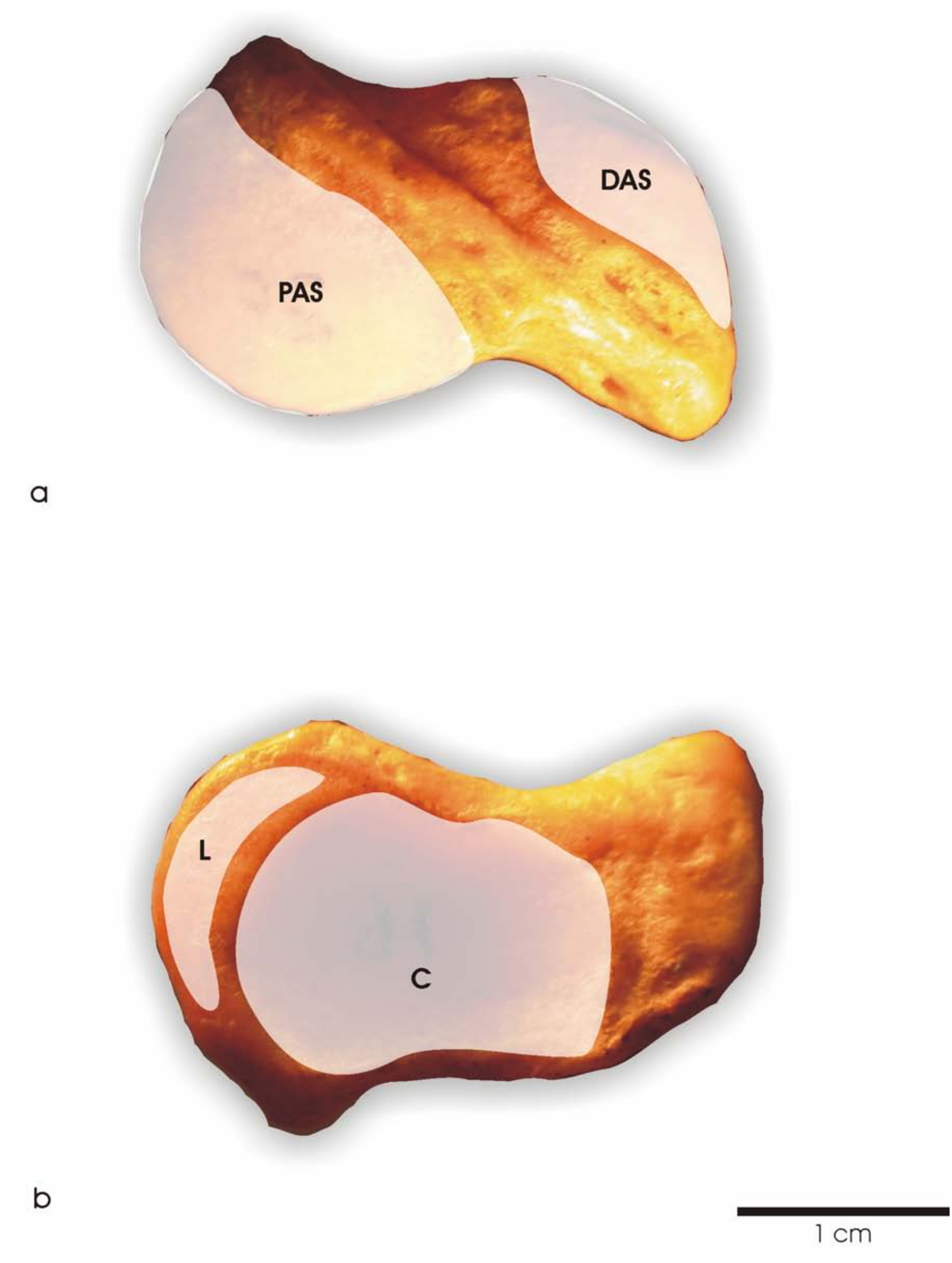

Figure 1.7 Scaphoid articular surfaces. a - radial aspect of the scaphoid with proximal articular surface (PAS) for the radius and distal articular surface (DAS) for the trapezium and trapezoid; b - ulnar aspect of the scaphoid with lunate articular facet (L) and capitate articular facet (C).

the scaphoid proximal or distal to the anatomical waist (Compson *et al*, 1994). With the wrist in a neutral position the scaphoid is flexed and radially deviated in relation to the capitate (Belsole *et al*, 1986).

1.1.2.1 Proximal Pole

The proximal pole of the scaphoid is solely articular. The radial aspect of the proximal pole contributes to the radio-scaphoid articulation, while the ulnar aspect of the pole contributes to the scapho-lunate articulation (Berger, 2001b; Compson *et al*, 1994). The scapho-lunate articulation is formed by the convex proximo-ulnar margin of the scaphoid being aligned with the reciprocally concave radial margin of the lunate (Compson *et al*, 1994; Kaplan, 1965). Berger (1996) suggested that this articular surface is not convex, but flat. The radial aspect of the scapho-lunate articulation is characterised by a sometimes crescent-shaped (Garcia-Elias, 2001), sometimes ovoid facet (Kauer and Landsmeer, 1983). Compson *et al* (1994) proposed a relationship between the morphology of the articular surface for the capitate and the width of the articular surface for the lunate.

Proximal to the articular surface for the lunate is a roughened border for the attachment of the scapholunate interosseous ligament (Garcia-Elias, 2001). The palmar border of this articular surface contains a shallow fossa into which the radioscapholunate ligament is attached (Taleisnik, 1985).

1.1.2.2 Distal Pole

The distal pole of the scaphoid is largely articular; the remainder constituting a bony prominence often regarded separately, the scaphoid tubercle (TA – Tuberculum ossis scaphoidei). The distal pole of the scaphoid articulates with the trapezium radially and the trapezoid ulnarly (Davies, 1967). These form a multi-facet joint, the scaphotrapeziotrapezoidal (STT) joint (Berger, 1997). Moritomo *et al* (2000) identified three characteristic shapes for the distal articular surface of the scaphoid:

Type A – dorsoulnar margin wide, radiopalmar margin tapered

Type B – dorsoulnar margin wide, radiopalmar margin rounded

Type C – dorsoulnar margin narrow, radiopalmar margin rounded

The incidence of each type amongst their sample size of 165 embalmed specimens was 52%, 38% and 10% respectively. Although unclear from the report of Moritomo *et al* (2000), others (Berger, 1996; Drewniany *et al*, 1985) have reported that the distal articular surface of the scaphoid is convex, complementary to the concavity of the proximal articular surfaces of the trapezium and trapezoid. The distal half of this joint is reportedly variable (Moritomo *et al*, 2000b), and will be discussed later.

The distal articular surface of the scaphoid may also have a ridge traversing the articular surface in an oblique direction. The ridge corresponds with the trapezio-trapezoidal articulation. The presence of such a ridge has previously been accepted (Compson *et al*, 1994; Kauer, 1986; Moritomo *et al*, 2000b; Taleisnik, 1985) and refuted (Berger, 1997; Nuttal *et al*, 1998). Bogumill (1988) describes the distal pole of the scaphoid as “smooth and convex”, and makes no mention of an articular ridge. Moritomo *et al* (2000) went beyond simply acknowledging the presence of the articular ridge and observed three grades of variation:

1 – ridge not visible or palpable

2 – ridge not visible, but palpable

3 – ridge clearly visible and palpable

The proportion of each grade in their sample was 19%, 25%, and 56% respectively. Thus, in 81% of specimens a ridge was recorded. Moritomo *et al* (2000) suggest that the ridge restricts the motion of the scaphoid against the trapezium and trapezoid, such that the scaphoid is moved in a similar manner independent of the global motion of the wrist. This implies that the ridge is capable of resisting mechanical strain, particularly rotation of the scaphoid. Evidence to the contrary (Fogg, 1999) suggests that the ridge is merely cartilaginous, and therefore cannot resist such forces. These (yet to published) data suggest that the ridge is a result of wrist motion, not a factor influencing motion. Therefore, when the scaphoid maintains a simple flexion/extension pattern through global motion of the wrist, a ridge is formed by the constant lack of pressure from the intermission in the trapezium-trapezoid articulation. When rotation is added to the motion of the scaphoid, the lack of pressure from the trapezium-trapezoid articulation is not constant; hence a ridge does not develop. These data therefore suggest that the ridge may be a marker of motion patterns in the wrist.

1.1.2.3 Ulnar Aspect

The ulnar aspect of the scaphoid is predominantly devoted to the articulation with the capitate (Bogumill, 1988). The proximal region of the ulnar aspect forms the radial part of the scapholunate joint, which has been discussed previously. The articular surface for the capitate is a larger concavity facing ulnar and slightly distal (Compson *et al*, 1994). The concavity is more pronounced in close proximity to the dorsal margin of the articular surface. Compson *et al* (1994) describe the occasional appearance of a notch on the dorsal margin of the capitate articular surface. The authors also discuss a ridge similarly placed on the dorsal margin for the attachment of the scapho-capitate interosseous ligament. It is unclear whether the two landmarks are the same, common variants, or otherwise.

Compson *et al* (1994) describe how the articulation with the capitate affects the morphology of the scaphoid. The authors report a relationship between the position of the scaphoid relative to the capitate, and the size of the scaphoid articular surface for the lunate. A large lunate facet is coupled with a small, distal capitate facet, whilst a small lunate facet is coupled with a large, proximal capitate facet. It is unclear whether scapho-capitate orientation is different for the two types of scaphoid, and the difference in facet shape is not given. None of the differences are reported from quantitative results. It is unclear whether or not this variability predisposes individuals with smaller lunate facets to greater incidence of carpal instability, particularly scapholunate advanced collapse (SLAC) wrist, as a reduction in articular surface area may suggest (Hamrick, 1996).

1.1.2.4 Groove / Ridge

The waist of the scaphoid, the region between its two articular surfaces (proximal and distal), occupies the radial two thirds of the scaphoid proximal to the STT joint articulation, and is not articulated with anything (Boabighi *et al*, 1993; Compson *et al*, 1994; Davies, 1967) (figure 1.8). The waist, instead, serves as an anchoring point for several ligamentous attachments (Berger, 1997; Mayfield *et al*, 1976; Taleisnik, 1976) and numerous foramina can be identified for the passage of nutrient vessels into the scaphoid (Bogumill, 1988) (figure 1.8). The waist connects the other non-articular region of the scaphoid, the dorsal complex of crests and sulci (Compson *et al*, 1994). The crest may provide attachment sites for ligaments (Berger, 2001b; Mayfield *et al*, 1976; Taleisnik, 1976) and joint capsule (Berger, 2001b) (figure 1.8). The crest terminates at either end in bony prominences termed apices (Compson *et al*, 1994) (figure 1.8). The dorsal apex forms the ulnar and proximal terminus of the crest and the radial apex forms the radial and distal terminus. It is unclear how the radial apex is related the scaphoid tubercle. The dorsal sulcus lies distal to the crest (Compson *et al*, 1994) and contains nutrient foramina (Bogumill, 1988). The sulcus may be divided into two sulci (Compson *et al*, 1994), but the details of such a division are unclear (figure 1.8).

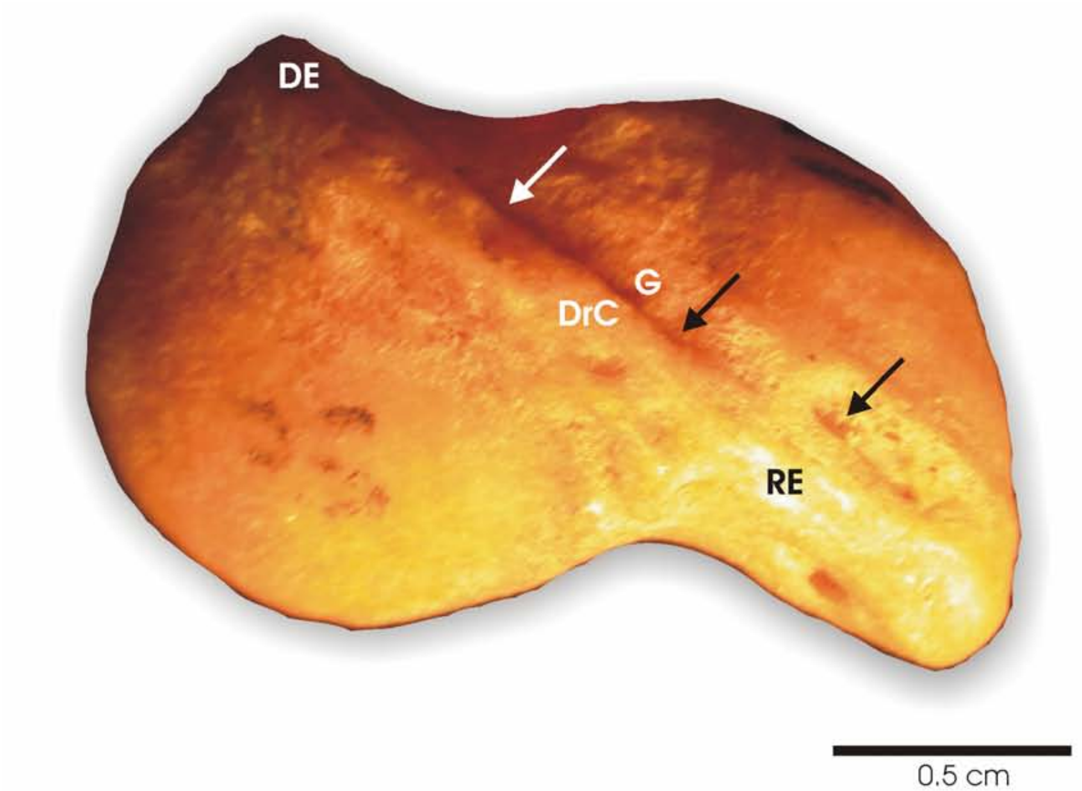

Figure 1.8 Dorsal landmarks of the scaphoid (seen from radio-dorsal perspective). The dorsal crest (DrC) traverses the dorsal aspect of the scaphoid from the dorsal eminence (DE) until the radial eminence (RE). Distal to the ridge lies the dorsal groove, in which nutrient foramina (arrows) allow blood vessels into the scaphoid.

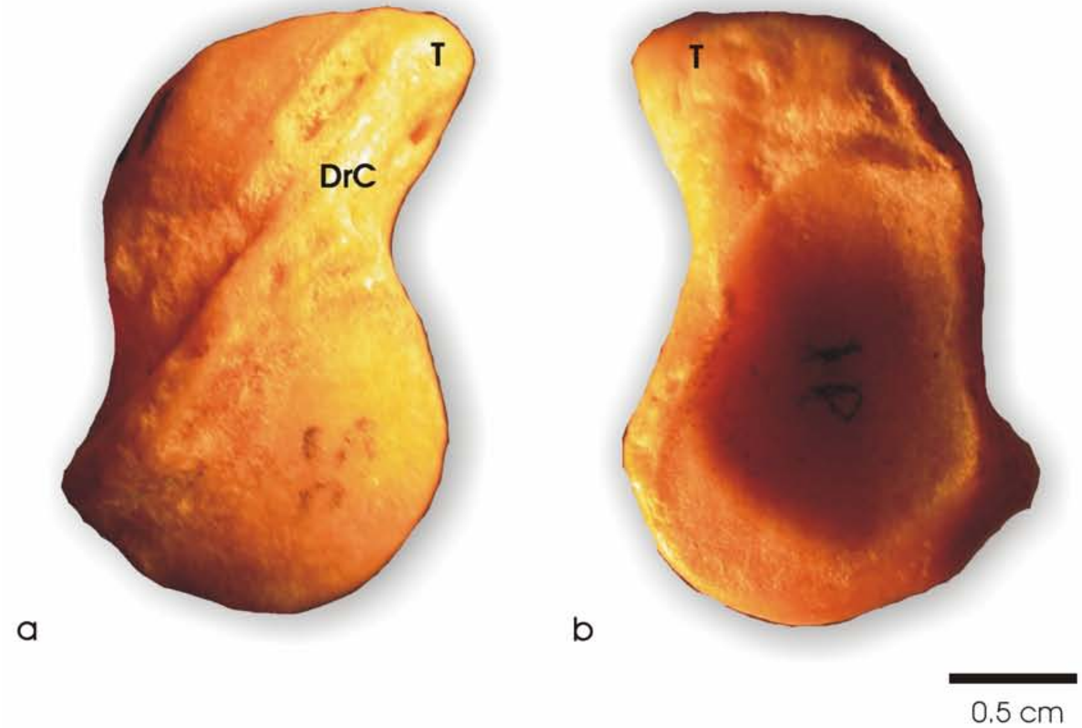

Figure 1.9 Scaphoid tubercle. The scaphoid tubercle (T) is a continuation of the dorsal crest (DrC) but the margins of the tubercle are difficult to identify; a - radio-dorsal view of the scaphoid; b - ulnar aspect of the scaphoid.

1.1.2.5 Tubercle

The tubercle is a rounded projection of the distal margin of the palmar aspect of the scaphoid (Bogumill, 1988). It is a continuation of the dorsal crest and has many reported variations of undetermined significance (Berger, 2001b; Compson *et al*, 1994). The boundaries of the tubercle are difficult to determine (Compson *et al*, 1994) (figure 1.9). It is described as pyramidal in shape, and may be considered separate to the rest of the scaphoid (the body) (Compson *et al*, 1994). Bogumill (1998) only mentions the attachment of the flexor retinaculum to the tubercle, and does not suggest any ligamentous attachments. Whilst others report attachments by the transverse carpal ligament (flexor retinaculum) (Berger, 1997; Bogumill, 1988; Cobb *et al*, 1993; Taleisnik, 1976), the floor of the flexor carpi radialis tendon sheath (Feipel and Rooze, 1999; Mayfield *et al*, 1976), and scaphotrapezotrapezoidal ligaments (Boabighi *et al*, 1993; Drewniany *et al*, 1985).

1.1.3 Trapezium

The trapezium, named so for its resemblance to a table, has also been termed the greater multangular (Williams, 1989). The latter term suggests the complexity of its morphology, and bears reference to its close relationship with the lesser multangular, but has been superseded by the former term, trapezium. The trapezium is the most radial of the distal row of carpal bones and is of great clinical significance due to its articulations with the scaphoid and the first metacarpal (Eaton, 1979; Swanson, 1972), and the high incidence of degenerative arthritis at these joints (Najima *et al*, 1997; Rogers and Watson, 1990; Watson and Ballet, 1984). The proximal aspect is small and slightly concave for articulation with the scaphoid (figure 1.10a). The ulnar aspect is flattened for articulation

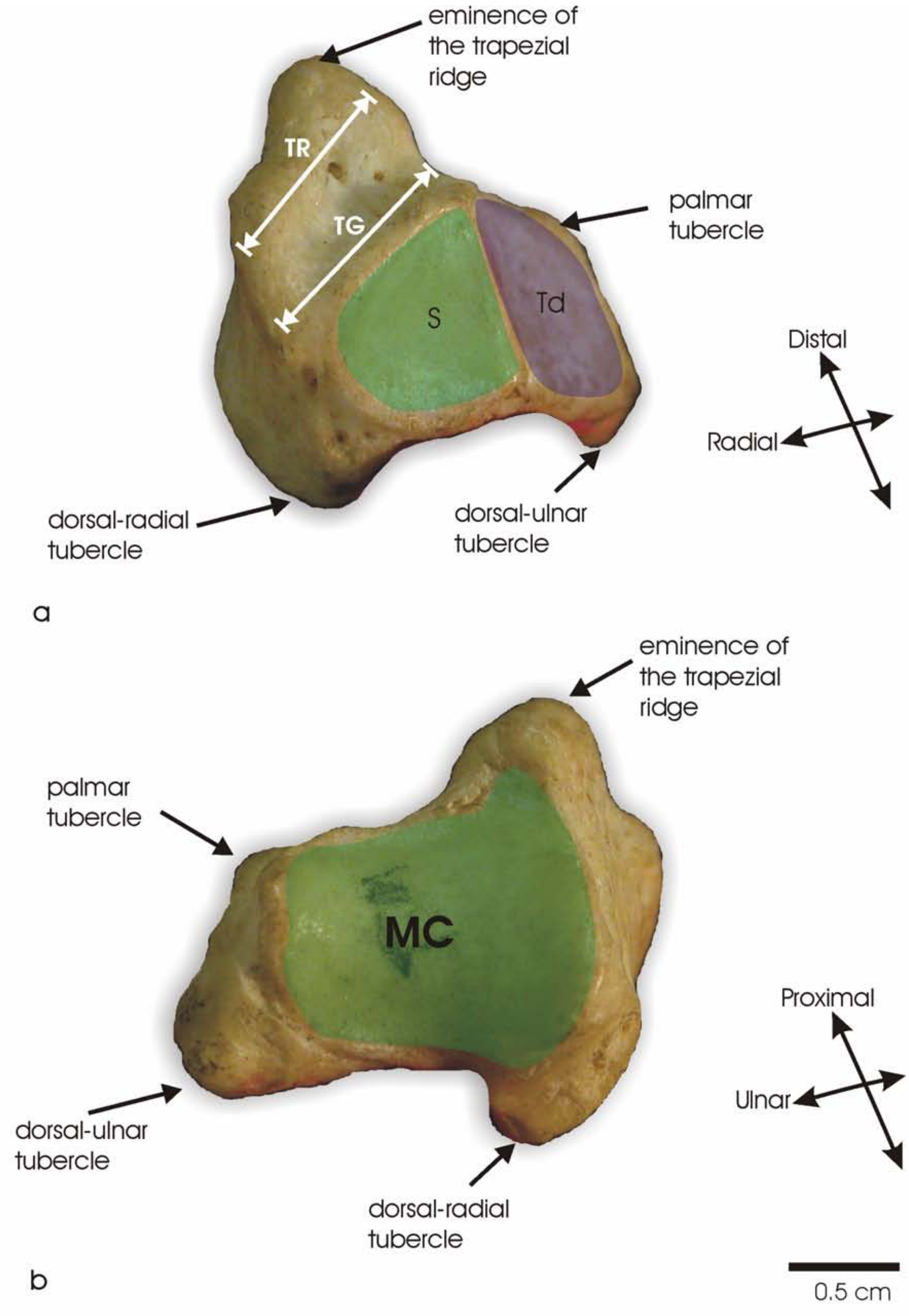

Figure 1.10 Trapezium Nomenclature of Humes *et al* (2004). a - Proximal-radial perspective. The trapezial groove (TG, for the flexor carpi radialis tendon) lies between the trapezial ridge (TR) and the palmar margin of the scaphoid-trapezoid facets. The radial and ulnar margins of the trapezium are accentuated dorsally by the dorsal-radial and dorsal-ulnar tubercles, between which lie the scaphoid (S) and trapezoid (Td) articular facets. b - distal aspect from which the marginal tubercles can be observed around the first metacarpal articular surface (MC).

with the trapezoid (Berger, 1996), and can be divided into two distinct articular facets; the large proximal facet for the trapezoid, and a small distal facet for the second metacarpal (Bogumill, 1988). The volar aspect of the trapezium contains a prominent tuberosity that provides distoradial support for the passage of the tendon for the flexor carpi radialis muscle. It also provides a radial attachment site for the flexor retinaculum (Bogumill, 1988). Ulnar to the tuberosity is a deep sulcus that forms the bony floor of the tunnel for the same tendon (Bogumill, 1988). The distal aspect of the trapezium is much greater in area than the proximal aspect, and forms a saddle joint with the base of the first metacarpal (Bogumill, 1988) (figure 1.10b). The trapezial aspect of this articulation is slightly concave to support the convex base of the first metacarpal. The dorsal aspect and parts of the volar aspect are roughened for ligamentous attachments (Bogumill, 1988).

1.1.4 Trapezoid

The trapezoid, or lesser multangular, is articulated with the ulnar aspect of the trapezium and occupies the distal row of the carpus. The articular surface for the trapezium is flat, whilst the proximal aspect is only slightly concave for articulation with the scaphoid (Berger, 1996; Bogumill, 1988) (figure 1.11). The ulnar aspect is smooth, convex, and articulated with the capitate (Bogumill, 1988) (figure 1.11), with dorsal and volar trapezoid-capitate ligaments being attached to the respective joint margins (Berger, 2001a). The trapezoid has a notch marking the attachment of the deep band of the trapezoid-capitate ligament (Berger, 2001a). The distal aspect of the trapezoid is flattened and articulated with the second metacarpal, and may include an oblique articular facet for the third metacarpal (Moritomo *et al*, 2000b) (figure 1.11). The articular surface for the second

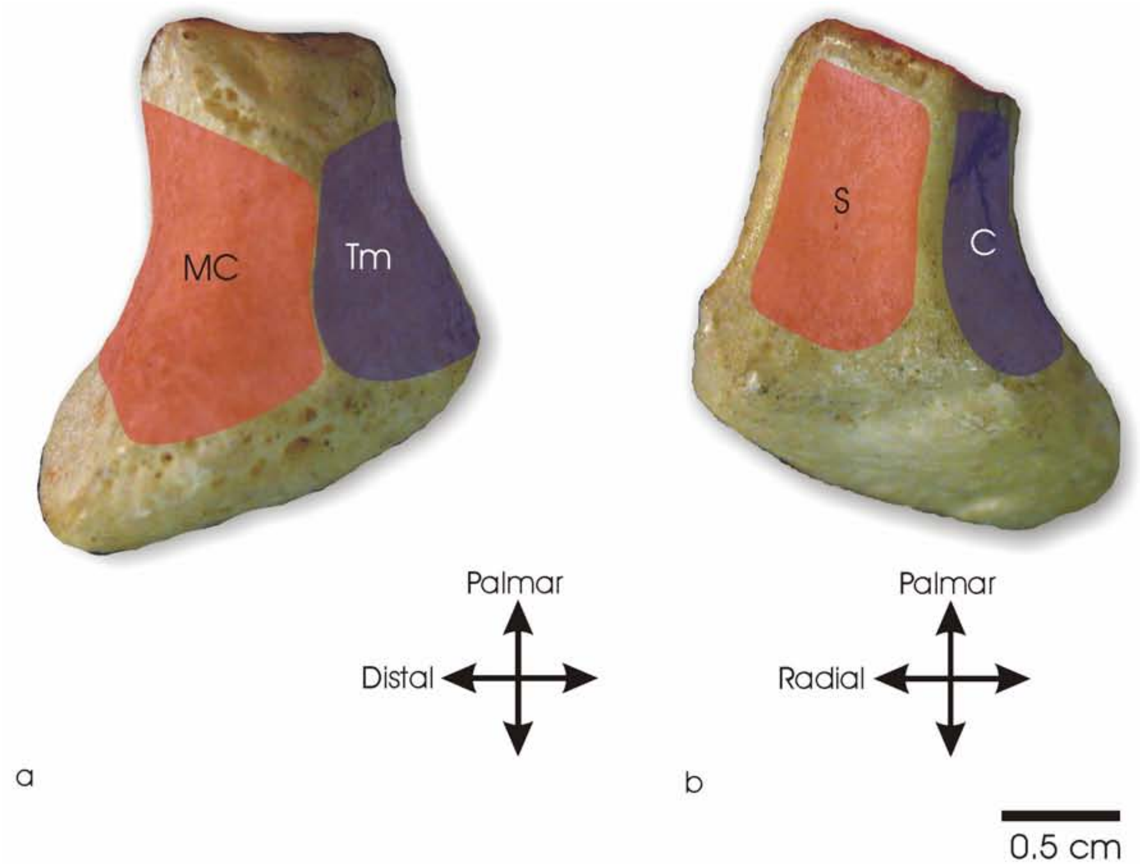

Figure 1.11 The Trapezoid. a - distal-radial perspective with articular facets for the trapezium (Tm) and the second metacarpal (MC); b - proximal aspect with articular facets for the scaphoid (S) and the capitate (C).

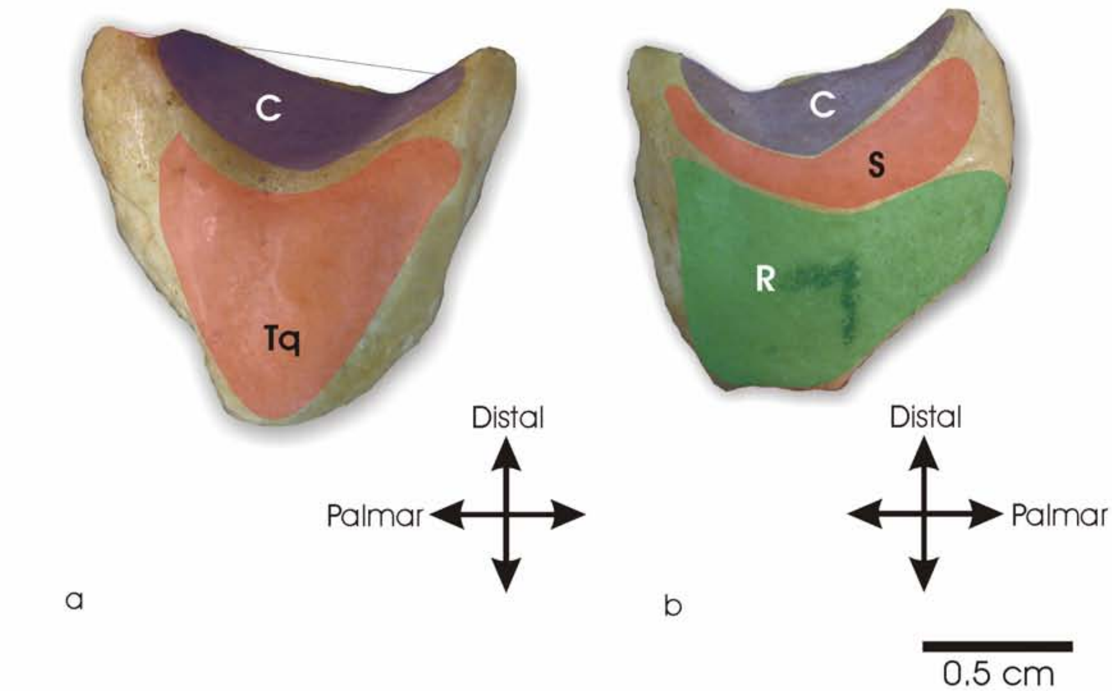

Figure 1.12 The lunate. a - ulnar aspect predominated by the articular facet for the triquetrum (Tq). This facet is connected to the articular facet for the capitate (C); b - radial aspect with connected radius (R), scaphoid (S) and capitate (C) articular facets.

metacarpal may also be divided into two facets by a longitudinal ridge (Bogumill, 1988). The dorsal and volar aspects are non-articular (Bogumill, 1988), but are roughened to receive attachments from the dorsal trapezium-trapezoid, volar trapezoid-capitate, dorsal trapezoid-capitate, dorsal trapezoid-metacarpal, and volar trapezoid-metacarpal ligaments (Berger, 1996).

1.1.5 Lunate

The lunate, as its name implies, is a crescent-shaped bone, reminiscent of a crescent moon (Davies, 1967) that lies in the proximal row of the carpus. It is divided into volar and dorsal poles (Berger, 1996), of which the dorsal pole is smaller, thus giving the lunate a wedge-like appearance (figure 1.12). Concave in coronal and sagittal planes, the distal aspect of the lunate is articulated with the capitate, and on occasion, the hamate (Berger, 1996; Viegas, 1990). Supporters of the column theory of carpal mechanics designate the lunate and capitate as the constituents of the central column of the carpus (Craigen and Stanley, 1995; Kauer, 1986). Much like the scaphoid, the proximal margin of the lunate is articulated with the concave distal articular surface of the radius (Boabighi *et al*, 1993; Bogumill, 1988) (figure 1.12). The radioscaphoid and radiolunate articulations form the majority of the radiocarpal joint complex. The radial and ulnar aspects of the lunate are flat and contain small articular surfaces for the scaphoid and triquetrum (Berger, 1996; Bogumill, 1988) (figure 1.12).

1.1.6 Capitate

The capitate is the largest of the carpal bones, and occupies much of the centre of the carpus. The capitate can divided into head, neck and body (Berger, 1996) (figure 1.13a). The head is the hemispherical proximal aspect of the capitate (Bogumill, 1988). The head is purely articular receiving no ligamentous attachments (Berger, 1996). It is articulated with the concave distal aspect of the lunate and the concave facet on the ulnar aspect of the scaphoid (Bogumill, 1988). Distal to the head is a narrow neck lined with periosteum. The remaining region of the capitate distal to the neck is termed the body. The dorsal and volar aspects of the body are predominately covered with ligamentous attachments (Berger, 1997; Bogumill, 1988; Feipel and Rooze, 1999; Taleisnik, 1976). The volar aspect may have part of the adductor pollicis muscle inserted into it (Bogumill, 1988). The hamate and trapezoid are articulated with the ulnar and radial aspects of the capitate respectively (figure 1.13b). The hamate is articulated with a flat but elongated facet on the ulnar aspect of the capitate (Bogumill, 1988). The articular surfaces of these two joints are interrupted by the attachment sites for the deep trapezoid-capitate and capitate-hamate ligaments (Berger, 1996). The capitate is notched where these ligaments are attached (Berger, 2001a). It is suggested that the distal articular surface of the capitate is divided into two angled facets, each for articulation with the third metacarpal (Viegas, 2001b). The ulno-dorsal margin of the ulnar facet is extended distally and dorsally, resembling “a pan handle” (Berger, 1996). Others, for example (Bogumill, 1988), suggest that the distal aspect of the capitate is divided into three facets by two articular ridges. The facets are then articulated with the second, third and fourth metacarpals respectively. The volar trapezoid-capitate, dorsal trapezoid-capitate, volar capitate-hamate, dorsal capitate-

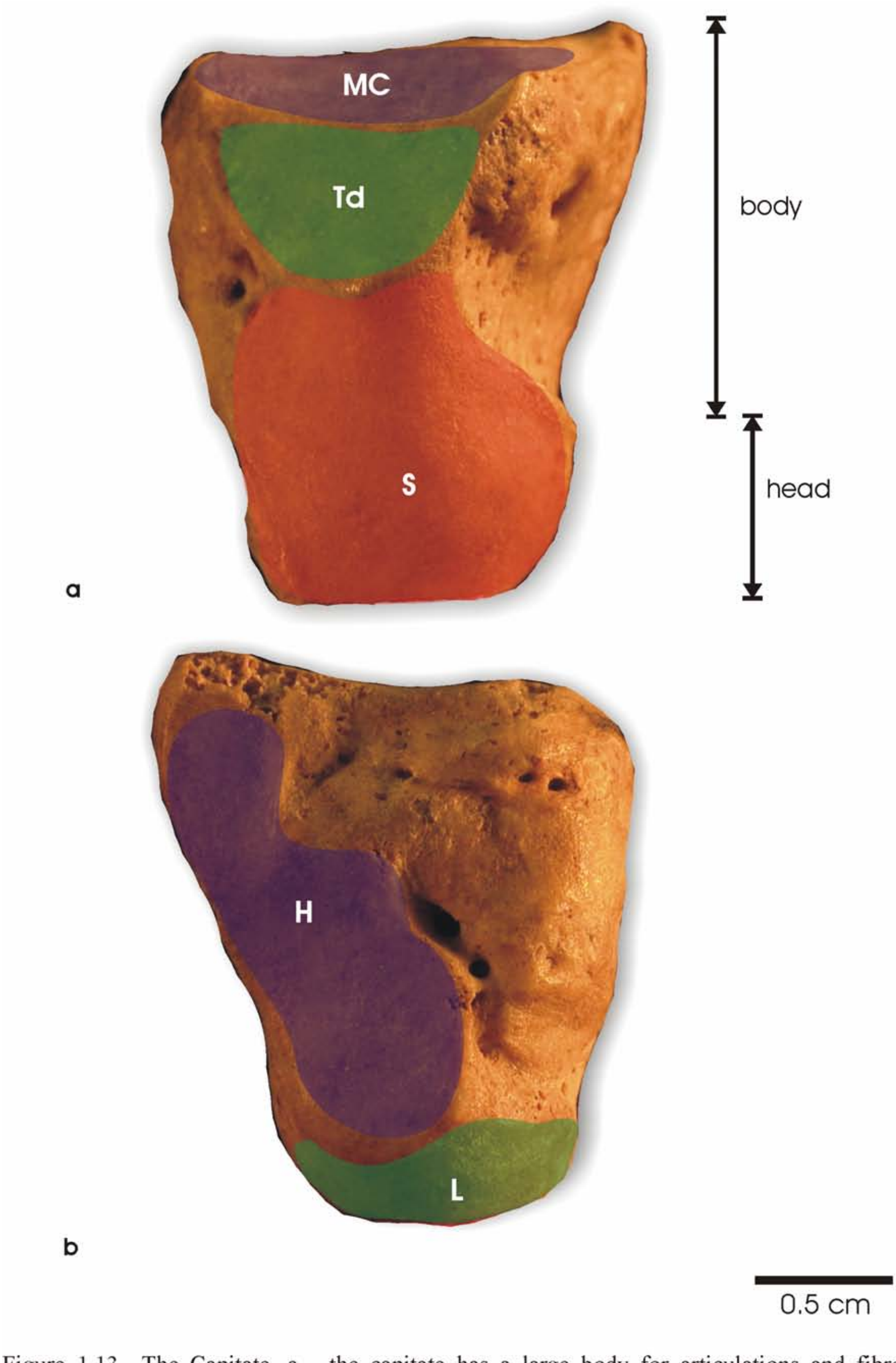

Figure 1.13 The Capitate. a - the capitate has a large body for articulations and fibrous attachments, and a proximal head for articulations only. The radial aspect with articular surfaces for the second metacarpal (MC), trapezoid (Td), and scaphoid (S); b - the ulnar aspect with articular surfaces for the hamate (H) and lunate (L). The palmar and dorsal aspects are non-articular with the exception of the capitate head.

hamate, radioscaphocapitate, scaphocapitate, triquetrum-capitate, ulnocapitate and the capitate-metacarpal ligaments are attached to the body of the capitate (Berger, 1996).

1.1.7 Carpal Motion

Global motion of the wrist is the result of co-ordinated movements of the carpal bones (Belsole *et al*, 1986). The global motion is influenced by both soft tissue support and the morphology of the carpal bones and surrounding skeletal structures. Osseous anatomy has been given little consideration in biomechanical studies of wrist global motion (Belsole *et al*, 1986). In both major theories of carpal mechanics (row and column), the scaphoid is considered an essential structure (Berger, 2001b; Craigen and Stanley, 1995). In row theories the scaphoid is deemed to function as a link between the two rows (Fisk, 1983). Column theories designate the scaphoid as the major structure in the mobile (lateral/ radial) column (Taleisnik, 1976). This involves the tendency of the scaphoid to assume a vertical position when the carpus is longitudinally compressed. Ligamentous support prevents intercarpal collapse. Separate ligament support for the distal pole of the scaphoid and the proximal pole has been cited (Belsole *et al*, 1986). This ligamentous support is also reported to synchronise the minute movements of the carpal bones (Belsole *et al*, 1986).

Motion at the wrist is independent from forearm rotation due to the minimal involvement of the ulna in carpal mechanics. Of the three ulno-carpal ligaments reported by Berger (2001), only one ligament (ulnocapitate) is attached directly to the ulna[*]. Ulnar

[*] Berger (2001) suggests that some proximal fibres of the ulnotriquetral ligament may be attached to the ulnar styloid process.

stability of the carpus is therefore maintained with little cost to mobility of the forearm and wrist. Despite this, the degree of carpal bone rotation through the normal range of global motion differs between when the forearm is pronated and when it is supinated (Berger *et al*, 1982). When the wrist is moved from neutral to an extended position, rotation of the carpal bones is increased, whilst rotation is decreased when the wrist is moved from neutral to a flexed position. It has been suggested that this is due to the increased tension of the dorsal radiocarpal ligament when the forearm is pronated (Berger *et al*, 1982).

The row theory of carpal mechanics suggests that the carpal bones move together as two separate rows (figure 1.14a). The movement of the two rows is observed as the global motion of the wrist (Craigen and Stanley, 1995; Nagelvoort *et al*, 2002). This involves the transmission of mechanical forces from one side of the carpus to the other through ligaments, thus co-ordinating movements between the carpal bones within the row.

The column theory suggests that the carpal bones interact as three separate columns (figure 1.14b). The median column (capitate and lunate) provides stability to the wrist, and has little influence over range of motion. The radial column, also called the mobile column, has the greatest influence over how far the wrist can be moved (Craigen and Stanley, 1995; Kauer, 1974; Kauer, 1986). The scaphoid is most important in this, as its motion allows the radial carpus to become closely packed in flexion and radial deviation, and loosely packed in extension and ulnar deviation (Berger *et al*, 1981; Craigen and Stanley, 1995; Kauer, 1974; Moojen *et al*, 2002b). The column theory has been refined to limit the radial column to the scaphoid, the ulnar column to the triquetrum, and the median column to the remaining carpal bones except the pisiform (Craigen and Stanley, 1995; Kauer, 1986). It has been demonstrated *in vivo* that the scaphoid is moved independently to

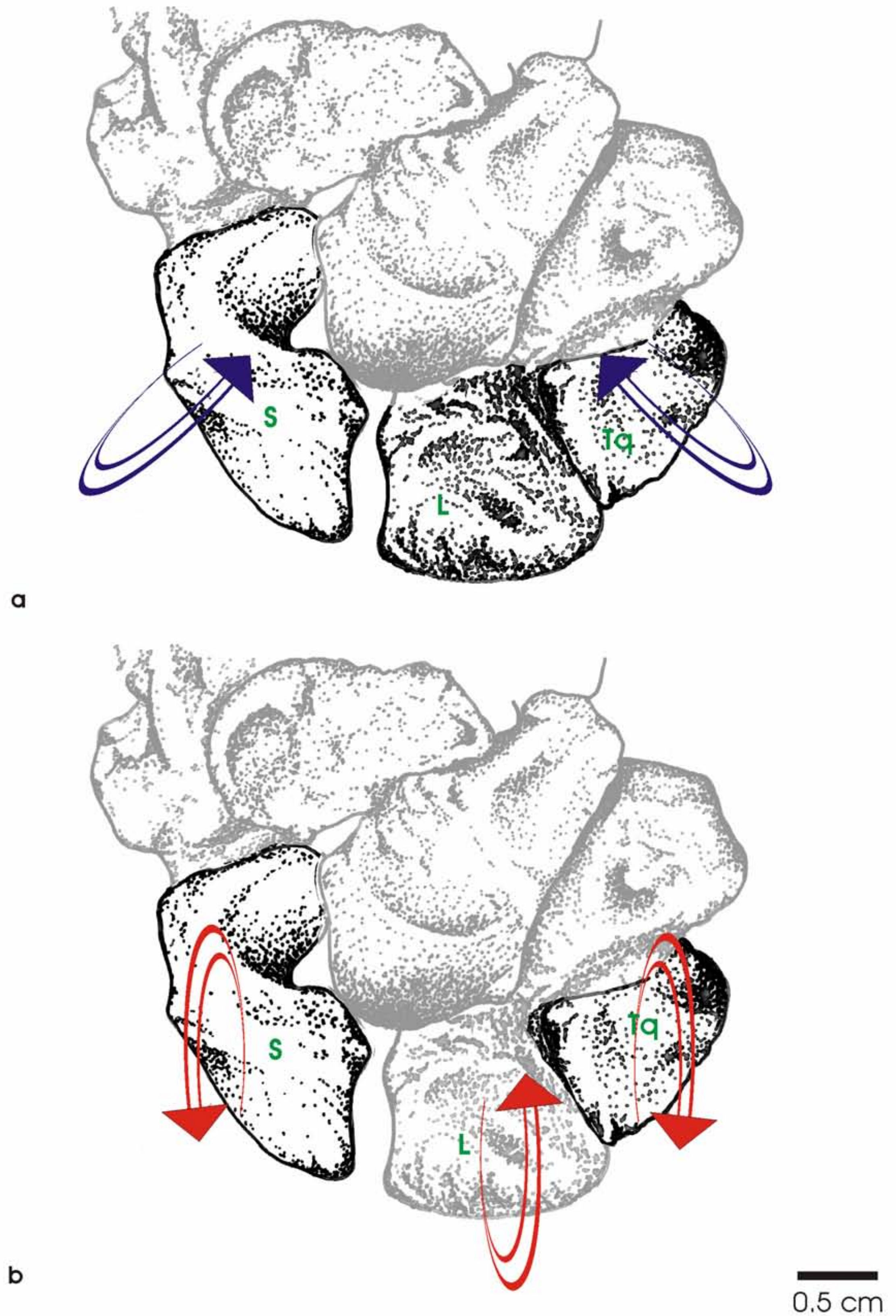

Figure 1.14 Theoretical Carpal Motion. a - row theory may involve rotation about the longitudinal axes of the mobile components of the proximal row, namely the scaphoid (S) and triquetrum (Tq). Mechanical forces may be passed from one side to the other via the lunate (L); b - column theory may involve flexion/extension of the mobile columns about the transverse axis of the carpus. The radial mobile column is the scaphoid (S), whilst the ulnar column is the triquetrum (Tq). The lunate (L) may be moved during global flexion/extension but may not contribute to global radial and ulnar deviation.

the combined complex of the trapezium, trapezoid and capitate (Berger *et al*, 1981; Moojen *et al*, 2002b; Moritomo *et al*, 2000a). Two distinct types of scaphoid motion have also been reported; flexion/extension about the transverse axis of the scaphoid, and rotation about the longitudinal axis of the scaphoid (Nuttal *et al*, 1998). Understanding the degree of variation in the morphology of the scaphoid is therefore an important step in understanding carpal kinematics, such as the suggestion by Moritomo *et al* (2000a) that a ridge across the distal articular surface of the scaphoid may indicate a clear pattern of motion relative to the trapezium-trapezoid joint.

Supination and extension are observed in proximal row carpal bones when the wrist is moved into ulnar deviation (Berger *et al*, 1982). The distal carpal row is not collectively extended as the wrist is moved into radial deviation (Berger *et al*, 1982). The trapezoid is rotated against the stable capitate when the wrist is moved through radial and ulnar deviation (Berger *et al*, 1982).

When the wrist is moved from a flexed position to neutral, the lunate and triquetrum are pronated relative to the scaphoid. When the wrist is moved from neutral to an extended position the scaphoid and triquetrum are flexed only slightly. The lunate is flexed as the wrist is extended (Berger *et al*, 1982). The reversal of lunate rotation supports MacConaill's 'screw-clamp' theory (MacConaill, 1941) of scapho-lunate motion (Berger *et al*, 1982), where the components of the proximal row move in opposition to each other. Other theories, such as the "four unit" theory suggested by Ryu (Ryu, 2001) and supported by numerous studies (Kobayashi *et al*, 1997; Linscheid, 1986; Moojen *et al*, 2003; Wolfe *et al*, 2000), suggest complex individual movements of the proximal row carpal bones against a stable complex of the distal row carpal bones.

1.1.8 Carpal Instability

A scapholunate angle greater than 70^0 is considered abnormal (Black *et al*, 1987). A pathologic scapholunate gap is present when the radiographic space between the scaphoid and the lunate is more than double the normal cartilaginous space between adjacent joints (Linscheid and Dobyns, 1985). Scapholunate gap is always associated with DISI and increased scapholunate angle (Black *et al*, 1987). Dorsal intercalated segment instability (DISI) is indicated when the capitate-lunate angle is greater than ten degrees (Black *et al*, 1987).

Scapholunate instability is characterised by the palmar dislocation of the lunate (Belsole *et al*, 1986). Following traumatic injury to the wrist, the scaphoid may also be abnormally orientated in various positions throughout the full range of wrist motion. Scaphoid instability patterns can be classed as static, dynamic or unclear (Watson and Ballet, 1984). Static instability is represented by fixed deformities that have reproducible radiographic scaphoid disorientation. Dynamic instability patterns only present during a particular phase of wrist motion or stress (Caputo *et al*, 2001; Cooney *et al*, 1990; Hand, 1999; Kleinman, 2001). For example, the scaphoid may only subluxate when the wrist is moved into full extension or ulnar deviation. Unclear instability patterns exhibit no abnormal scaphoid positioning through any motion or loading of the wrist (Gelberman *et al*, 2000; Mayfield, 2001; Ruch and Paterson Smith, 2001).

The direction of scaphoid collapse is determined by the osseous structure of the scaphoid and those bones to which it is articulated. A decrease or loss of soft tissue support results in such a collapse (Belsole *et al*, 1986). The degree of subluxation is determined by the amount of soft tissue support lost. Minute loss of support will result in a subluxation that is unlikely to be diagnosed, whilst complete loss of tissue support results in full subluxation or dislocation. Integrity of the scapho-lunate joint has been suggested to be essential for carpal stability (Belsole *et al*, 1986; Boabighi *et al*, 1993; Kauer, 1986; Kobayashi *et al*, 1997; Linscheid and Dobyns, 2002; Short *et al*, 2002). It is important to establish whether or not this variability predisposes individuals with the latter example to greater incidence of carpal instability.

Palpation of the anatomic 'snuffbox', the sulcus between the tendons of extensor pollicis longus and extensor pollicis brevis, commonly reveals a scaphoid fracture. The patient will report pain upon palpation of the centre of the snuffbox. If the discomfort is localised in the distal region of the snuffbox, scaphotrapeziotrapezoidal joint arthrosis is suggested. If the scaphoid gives under the pressure of the palpation, sometimes with an audible click, scapholunate ligament disruption is suggested (Beckenbaugh, 1984).

1.1.9 Aims

This study aims to generate a consistent and detailed nomenclature for the description of select carpal bones. The detailed nomenclature will provide a framework for description of related structures in later chapters. The anatomical variation of the scaphoid will then be assessed to determine how this may influence theories of carpal motion. It is hypothesised that there will be morphological differences between scaphoids that suggest variable scaphoid motion.

1.2 Materials

The dry bone collection of the Ray Last Anatomy Laboratory, Department of Anatomical Sciences, the University of Adelaide contained six complete disarticulated carpal sets, 20 articulated sets, and ten incomplete sets. Cadaveric specimens already used in other parts of this study, were also included, yielding a further 50 sets of carpal bones. The Department of Anatomy and Histology, Flinders University, kindly provided 14 articulated carpal sets for inclusion in the study. A total of 100 scaphoids were therefore available for the study, in addition to 85 trapezia and 80 capitates. No other carpal bones were measured as part of this study.

Permission for the use of specimens, as granted by the Head of the Department of Anatomical Sciences, was covered by the Anatomy Act of South Australia (1983). All specimens were previously embalmed through the normal procedures of the Ray Last Anatomy Laboratory (see Appendix I).

1.3 Methods

1.3.1 Nomenclature

The nomenclature of the radial carpal bones was assessed. The trapezoid, lunate, and capitate were excluded from the study. The excluded bones were either well researched and consistently described (lunate) or evidence was presented in the literature to suggest that the nomenclature currently in use was adequate for detailed descriptive purposes.

Rules for the description of structures in the wrist were devised in accordance with the Federative Committee on Anatomical Terminology (Terminology, 1999). Descriptive terms and landmarks already present in the literature were collated and new names were given as necessary. The complete list of structures and descriptive terms were then modified subject to the established rules.

1.3.2 Scaphoid Morphology

An initial sample of 20 scaphoids was subject to a series of manual measurements and photographed. The measurements were proximal articular surface-distal articular surface length, dorsal crest length, capitate facet length, and lunate facet length. The same measurements were performed digitally using the shareware program, Image J (Rasband, 2002). Each series of manual and digital measurements were repeated three times and the results compared. A Student's T Test of the sample means of each measurement suggested no significant difference between manual and digital measurements. The remaining sample population (n = 80) was digitally photographed (Nikon Coolpix 995, Nikon Corporation, Japan) in a precise series of positions (radial, ulnar, palmar and dorsal aspects, oblique facet view and oblique waist view) and measured digitally. The digital measuring software enabled perimeter and area measurements to be made of the capitate and lunate facets, and crest height, in addition to the length measurements of the manual series.

To ensure accuracy all measures were done in triplicate. Each sequence of measuring was done a significant time after the previous sequence, and the order of measuring individual specimens was always arbitrary. The triplicate measures were analysed statistically for significant differences and none were found. This suggests the measurements made were consistently accurate within the bounds of the equipment and the measured structures were consistently identifiable.

The pole length, tubercle length, dorsal crest height, capitate articular facet length, and lunate articular facet length was measured for each space. The area of the distal articular surface, capitate articular facet and lunate articular facet were measured. Each of these measures was divided by the pole length of each scaphoid to generate values for each measurement relative to the length of the scaphoid. The analysis of relative measures enabled comparisons between groups of specimens to be made regardless of specimen size.

All of the specimens were separated into two groups based on macroscopically evident differences. Measures of the variant structures were tested for statistically significant differences using the Student's T Test when only two characters were being tested and ANOVA when more than two characters were being tested. Pearson's correlation coefficient was calculated to identify statistically significant relationships between related dimensions within specimen groups.

1.4 Results

1.4.1 Nomenclature

Rules that provide a consistent and detailed means of describing the carpal bones were developed. The terminology used was derived from the recommendations of the Federative Committee on Anatomical Terminology (Terminology, 1999). Use of descriptive terms should follow a single pattern and eliminate the possibility of confusion by using terms both unique and defining of the characteristic. Abbreviated terms are to be avoided, as are generalised terms for specific structures. Hence proximo-ulnar becomes proximal-ulnar and trapezio-trapezoid becomes trapezium-trapezoid. Likewise the presence of a dorsal scaphoid crest implies the presence of a palmar scaphoid crest, whilst the presence of a single scaphoid crest that happens to be on the dorsal aspect of the scaphoid does not.

General terms, such as body, may be used but only in conjunction with more detailed descriptive terms. For example, “the ligament was attached to the body of the capitate” does not provide much useful information, whereas “the ligament was attached to the radial margin of the palmar aspect of the capitate body” provides much more specific information. Some of the more common terms are defined below:

Term	Definition
Crest	Elongated bony protuberance with definable direction of which length is greater than height; synonymous with ridge
Groove	Elongated invagination of bone with definable direction; sometimes incorrectly synonymous with fossa
Fossa	Large spherical or pyramidal concavity (cf. sulcus)
Facet	Articular surface divided anatomically or functionally into distinct areas
Eminence	Small bony protuberance with base and tip of similar area; replaces tubercle in most cases within the carpus.
Tubercle	Large bony protuberance with base of greater area than tip; synonymous with apex

The rules used attempt to minimise the need for mass change of terminology whilst providing a basis for the consistent description of structures in the wrist.

Each of the carpal bones can be visualised as simple shapes. Each of these shapes has four aspects and two poles. Bones such as the scaphoid and capitate have proximal and distal poles, whereas bones such the trapezium have palmar and dorsal poles. This arrangement must be established for each bone before any further description can take place. Four aspects were used to describe the major surfaces of the bone (figure 1.15). The aspects of each bone are bordered, or defined, by their margins. The use of margins enables more precise descriptions of structures on each aspect of a bone. Use of "surface" and "articular surface" together may create confusion, so "surface" is reserved for "articular surface" only (figure 1.16).

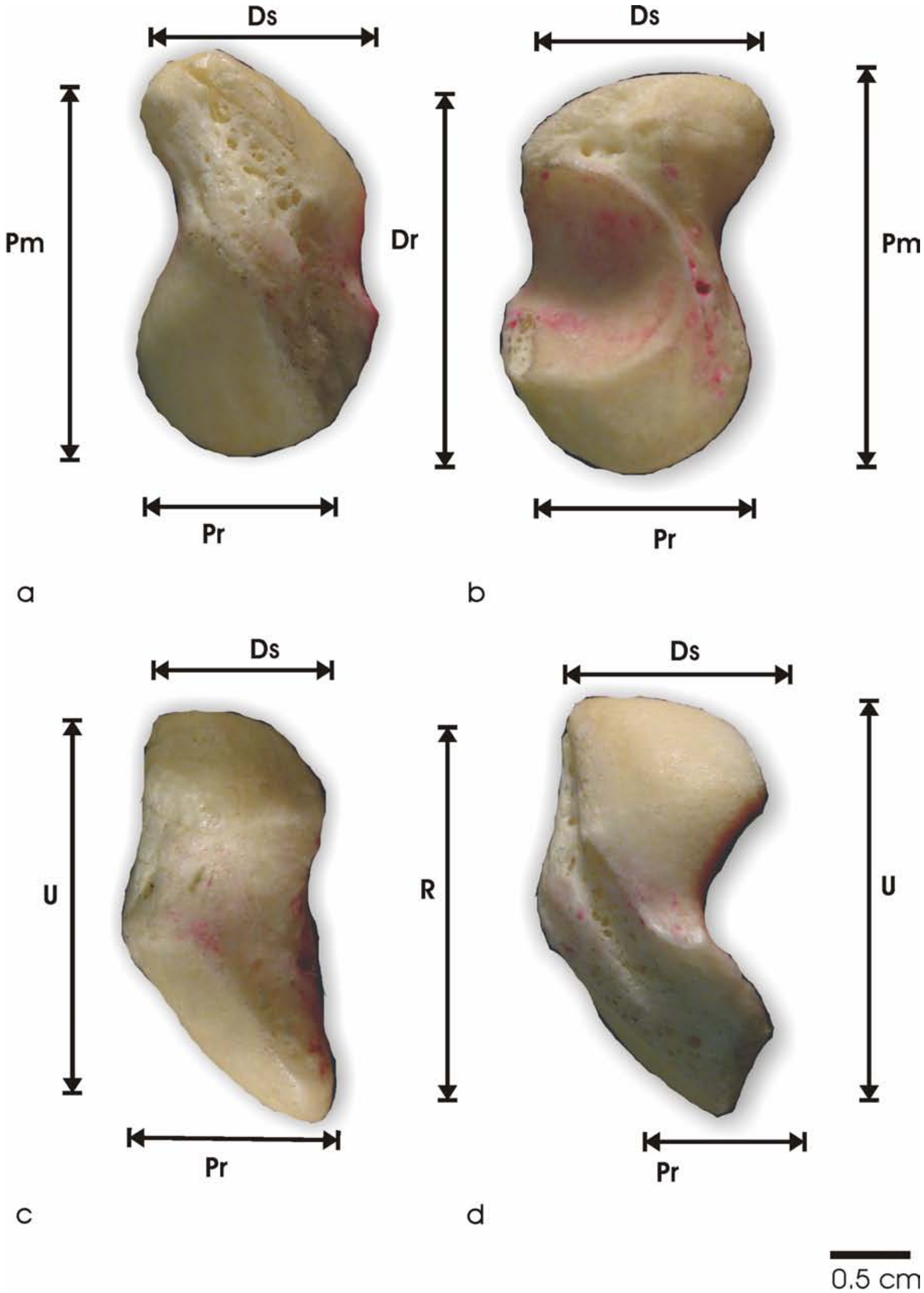

Figure 1.15 Aspects and margins of the scaphoid. a - radial aspect with proximal (Pr), distal (Ds), palmar (Pm), and dorsal (Dr) margins defining the borders of the aspect; b - ulnar aspect with proximal (Pr), distal (Ds), palmar (Pm), and dorsal (Dr) margins; c - palmar aspect with radial (R), ulnar (U), proximal (Pr) and distal (Ds) margins; d - dorsal aspect with radial (R), ulnar (U), proximal (Pr) and distal (Ds) margins. The same terminology can be applied to the margins of the proximal and distal poles.

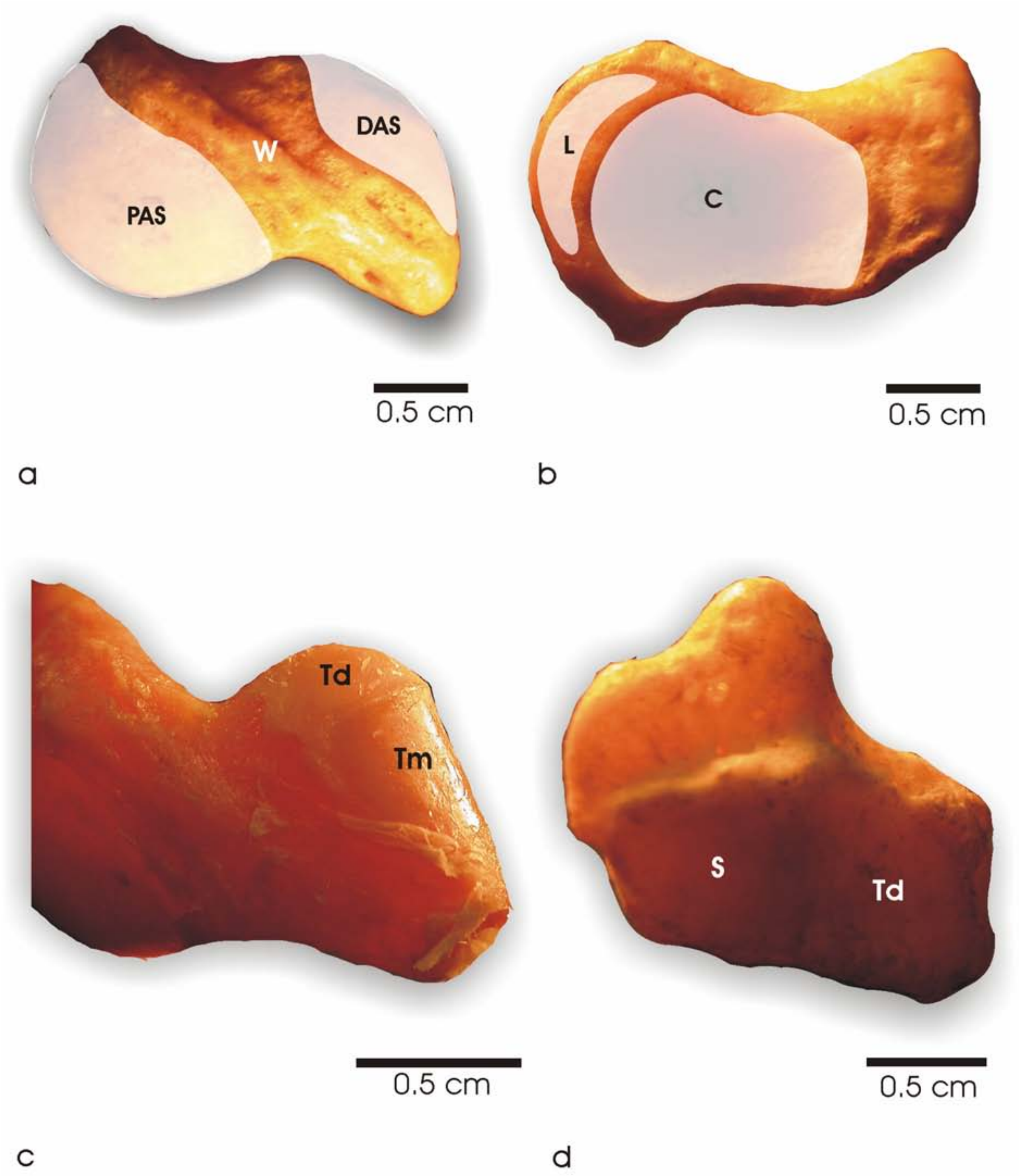

Figure 1.16 Definition of articular surfaces. a - dorsal radial perspective with proximal (PAS) and distal (DAS) articular surfaces. The area between these articular surfaces is the scaphoid waist (W); b - ulnar aspect of the scaphoid with the articular facets for the lunate (L) and capitate (C); c - articular facets are distinct from articular surfaces as the facets are functional divisions of a surface. The distal articular surface of the scaphoid is divided into articular facets for the trapezium (Tm) and trapezoid (Td); d - similarly, the proximal-ulnar articular surface of the trapezium is divided in articular facets for the scaphoid (S) and the trapezoid (Td).

To facilitate clear description of the osseous features of the scaphoid, a detailed nomenclature was adapted and modified from other studies (Berger, 2001; Compson et al., 1994). Proximal and distal poles designated either end of the scaphoid. A single scaphoid tubercle formed the distal-radial projection of the scaphoid. The ulnar aspect was demarcated by two distinct articular facets. The most distal of the ulnar facets was the capitate facet, whilst the most proximal was the lunate facet (figure 1.16).

The dorsal aspect of the scaphoid was marked by a variable number of bony projections. Where a single projection was observed, it was designated a scaphoid crest (figure 1.17). The crest terminated at the proximal-ulnar margin of the dorsal aspect of the scaphoid at the ulnar eminence of the crest and the radial eminence of the crest, near the scaphoid tubercle. When three projections were observed they were designated proximal, intermediate and distal crests (figure 1.17). Each crest traversed the dorsal aspect of the scaphoid in proximal-ulnar to distal-radial direction. The proximal crest terminated at the proximal-ulnar margin of the dorsal aspect of the scaphoid at the proximal-ulnar tubercle and receded into the proximal groove (see below). The intermediate crest emerged from the proximal groove and either fused with the distal crest or receded into the distal groove. The distal crest emerged from the distal groove and terminated at the radial eminence of the crest. Distal to a single scaphoid crest and to either side of an intermediate scaphoid crest lay two invaginated regions of bone. Each of these regions contained numerous nutrient foraminae not present anywhere else on the scaphoid. When single they were designated a scaphoid groove, and when double they were designated proximal and distal scaphoid grooves, and always followed the course of the scaphoid crests (figure 1.17). Where only a single scaphoid crest was observed, the concavity of the scaphoid groove

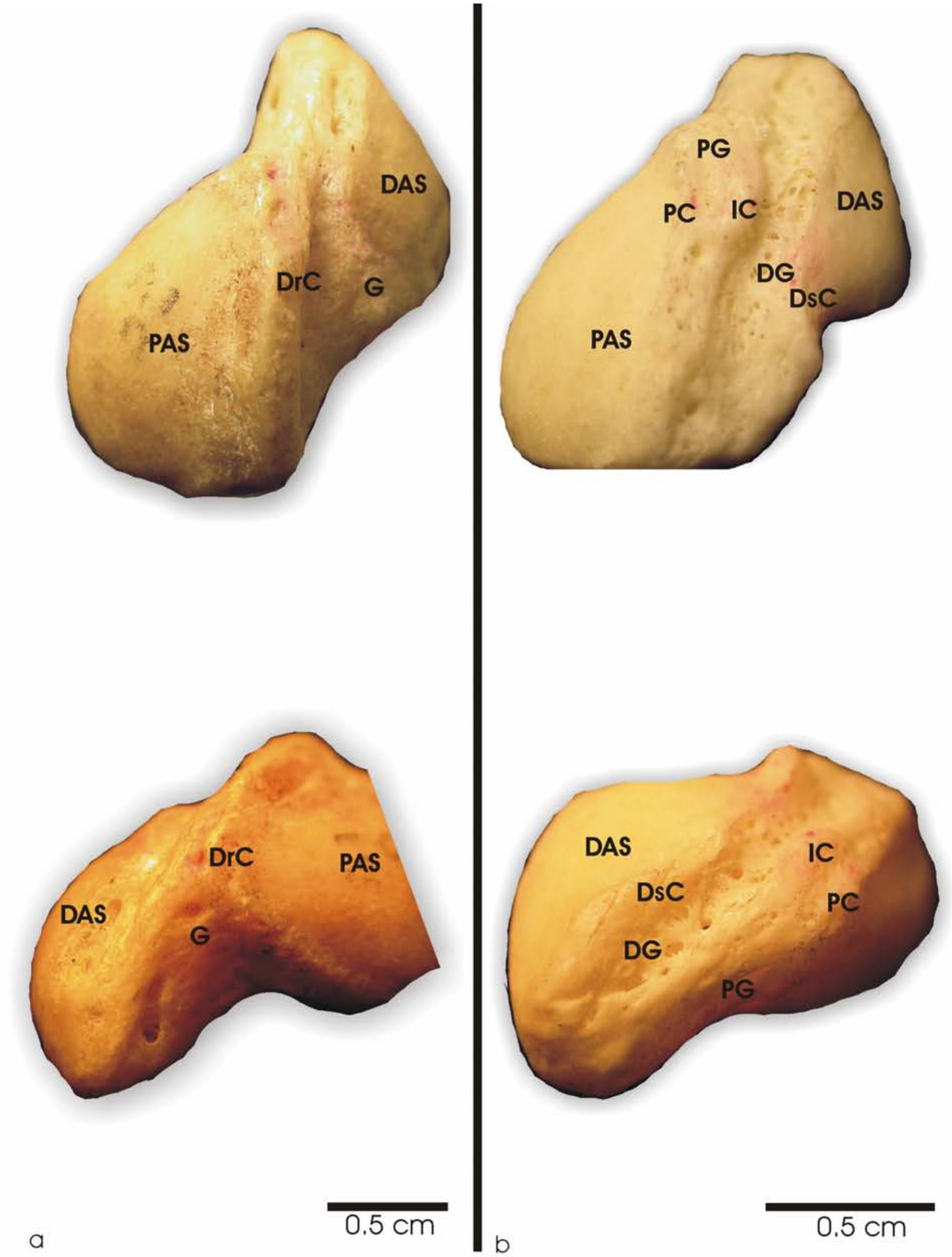

Figure 1.17 Dorsal landmarks of the scaphoid. a - single dorsalcrest (DrC) and groove (G) dividing the proximal (PAS) and distal (DAS) articular surfaces; b - proximal (PC), intermediate (IC) and distal (DsC) crests bordering proximal (PG) and distal (DG) grooves and separating the proximal (PAS) and distal (DAS) articular surfaces.

merged distally into the distal articular surface. Where three scaphoid crests were observed, the proximal and distal crests bordered the grooves, and hence separated them from the proximal and distal articular surfaces.

The ulnar aspect of the scaphoid was dominated by two articular facets. The capitate articular facet was the larger and most distal of the two facets (figure 1.18). The lunate articular facet was smaller than and proximal to the capitate articular facet. The lunate articular facet is also considered part of the proximal pole of the scaphoid. The capitate articular facets clearly differed between scaphoids. Some facets were elongated and shallow, whilst others were ovoid to c-shaped and deep. The shallow facets occupied much of the ulnar aspect of the scaphoid, whilst the shallow facets were concentrated proximally on the ulnar aspect of the scaphoid (figure 1.18). There was no perceivable difference in the lunate articular facets.

The trapezium is a complex bone with multiple articular surfaces and numerous bony protuberances (figure 1.19). Many studies describe different combinations of landmarks to varying degrees of detail. The trapezium is characterised by large proximal and distal aspects. Both are predominately articular. The proximal aspect has a large articular surface with separate facets for the scaphoid and trapezoid, the latter of which may be more ulnar than proximal. For descriptive purposes and in view of the close relationship between the articular facets, it is considered part of the proximal aspect. The palmar margin of the proximal aspect is modified as the floor of the tunnel for the flexor carpi radialis tendon. The palmar margin has three eminences to which the fibrous floor of the tunnel for the flexor carpi radialis tendon may attach. They were designated radial,

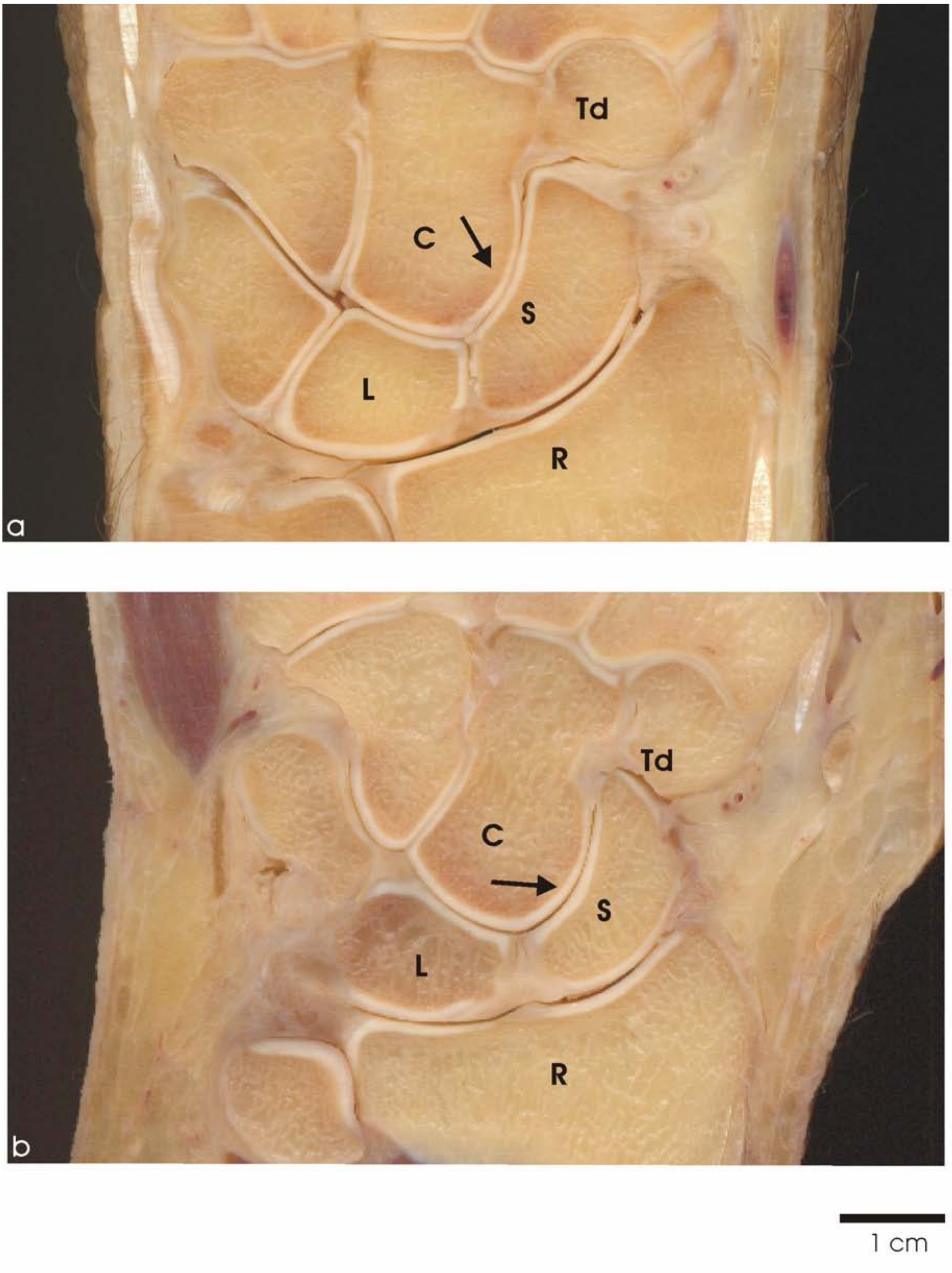

Figure 1.18 Variation of the capitate articular facet. a - the type one scaphoids had a shallow, long capitate articular facet area (arrow). This may allow the scaphoid (S) to be translated against the capitate (C) as it is rotated about its longitudinal axis; b - the type two scaphoids had a deep, broad capitate articular facet (arrow). This may limit translation and rotation of the scaphoid (S) but facilitate flexion/extension of the scaphoid; R - radius, L - lunate, Td - trapezoid; both images of coronal band-saw sections of embalmed wrists.

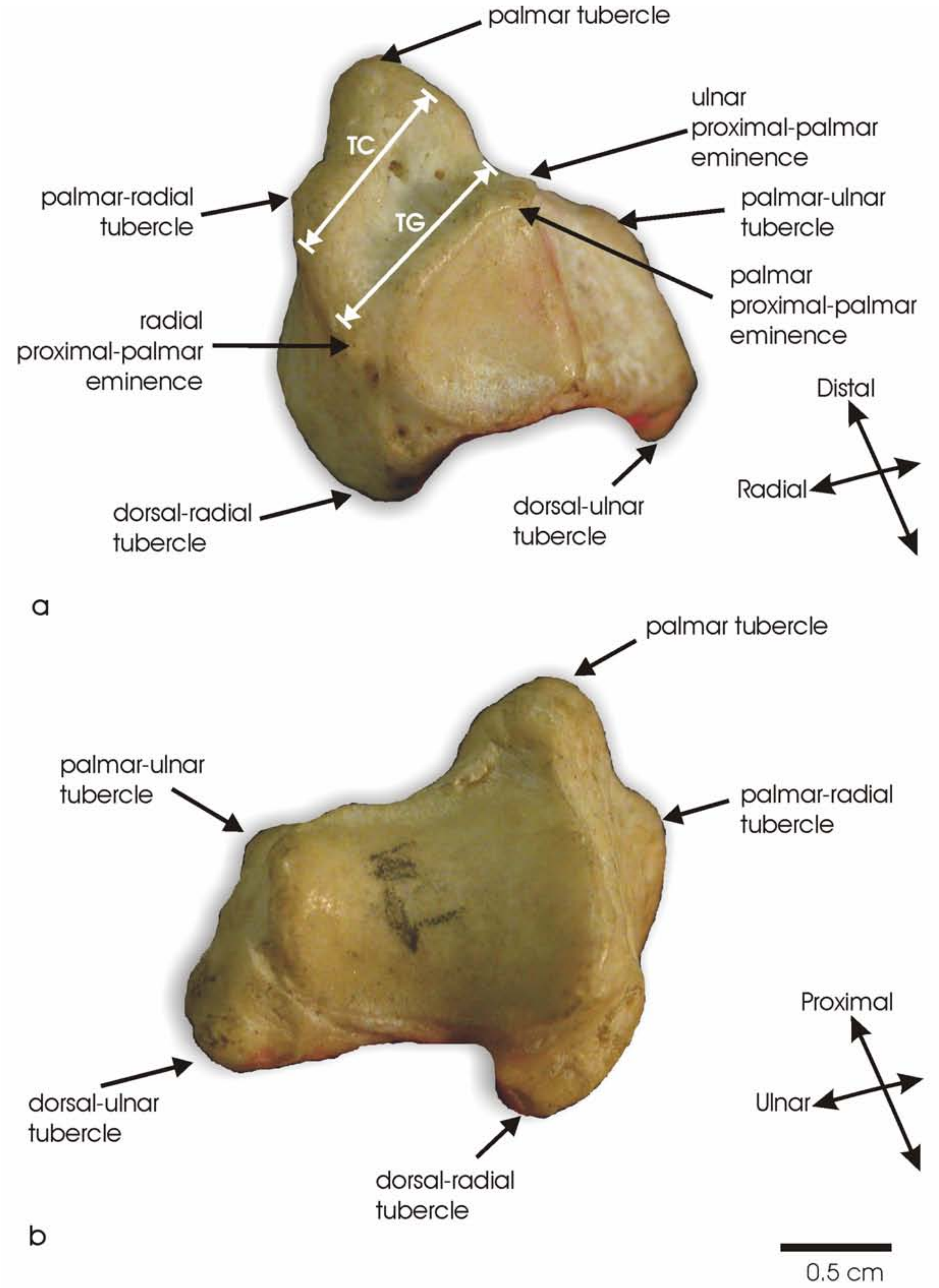

Figure 1.19 Trapezium Nomenclature. a - Proximal-radial perspective. The trapezial crest (TC) may be accentuated by palmar and palmar-radial tubercles. Likewise, the palmar margin of the scaphoid/trapezoid facets may be accentuated by radial proximal-palmar, palmar proximal-palmar and ulnar proximal-palmar eminences. The trapezial groove (TG, for the flexor carpi radialis tendon) lies between the trapezial crest and the palmar margin of the scaphoid/trapezoid facets. The radial and ulnar margins of the dorsal aspect are accentuated by the dorsal-radial and dorsal-ulnar tubercles. A palmar-ulnar tubercle may accentuate the dorsal margin of the ulnar pole of the trapezium; b - distal aspect from which the marginal tubercles can be observed.

palmar and ulnar proximal-palmar eminences. Dorsal-ulnar and palmar-ulnar eminences were also present along the ulnar margin of the proximal aspect.

The distal aspect has a large articular surface for the first metacarpal. The projections visible from this aspect originate from either the palmar or dorsal aspects. The palmar and dorsal aspects are smaller that the proximal and distal aspects, and are non-articular. The palmar aspect has a large invagination, the trapezial groove, through which the tendon of flexor carpi radialis muscle is passed. The distal margin of the palmar aspect is enlarged radially by the trapezial crest. The crest may be further accentuated by ulnar and radial crest eminences to which various ligaments may be attached. The thin ulnar margin of the palmar aspect is dominated by the palmar-ulnar tubercle. The dorsal aspect has a greater area than the palmar aspect. The radial and ulnar margins of the dorsal aspect are enlarged into dorsal-ulnar and dorsal-radial tubercles. Between these tubercles is a slight concavity termed the first metacarpal fossa. The radial and ulnar poles have no landmarks apart from the overlap of the marginal landmarks described for each of the trapezial aspects.

1.4.2 Scaphoid Morphology

The sample population of 100 scaphoids were divided into two types based on the macroscopic differences observed on the dorsal aspect of each scaphoid. Type one scaphoid (n = 40; 40%) were characterised by a single crest on the dorsal aspect of the scaphoid. Type two scaphoids (n = 60; 60%) had three crests on the dorsal aspect of the scaphoid. The two groups were tested for significant morphological differences in order to theorise functional differences between the groups.

1.4.2.1 Scaphoid Length and Crest Height

The maximal proximal pole to distal pole and dorsal-ulnar tubercle to scaphoid tuberosity lengths were measured (figure 1.20). The mean type one tubercle length (23.22±2.01 mm) was significantly greater than the mean type two tubercle length (21.58±2.63 mm; $p < 0.05$; figure 1.21). The mean type one pole length (21.76±1.191 mm) was significantly greater than the mean type two pole length (21.243±2.210 mm; $p < 0.05$; figure 1.21).

Within-type analyses were conducted. The type one mean tubercle length (23.22±2.01 mm) was significantly greater than the type one mean pole length (21.76±1.191 mm; $p < 0.05$; figure 1.21). The Pearson's correlation coefficient was only slightly significant ($r = 0.513$) for type one lengths. The type two mean tubercle length (21.58±2.63 mm) was not significantly greater than the type two mean pole length (21.243±2.210 mm; $p > 0.05$; figure 1.21). The Pearson's correlation coefficient suggested a significant relationship between the type two measures ($r = 0.784$).

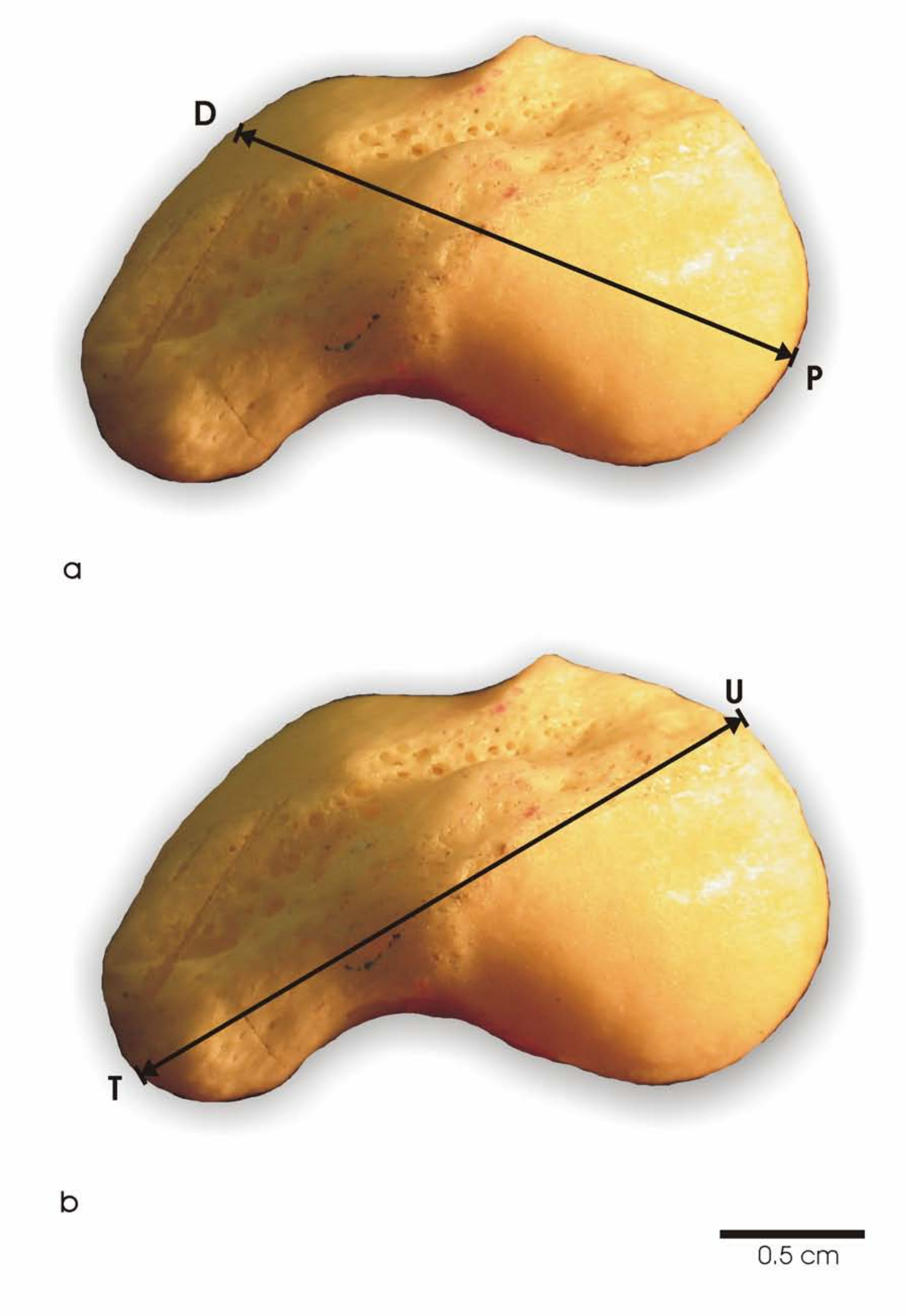

Figure 1.20 Scaphoid length measures. a - maximal proximal pole to distal pole length; b - maximal ulnar eminence to tubercle length; P - proximal pole, D - distal pole, U - ulnar eminence, T - tubercle.

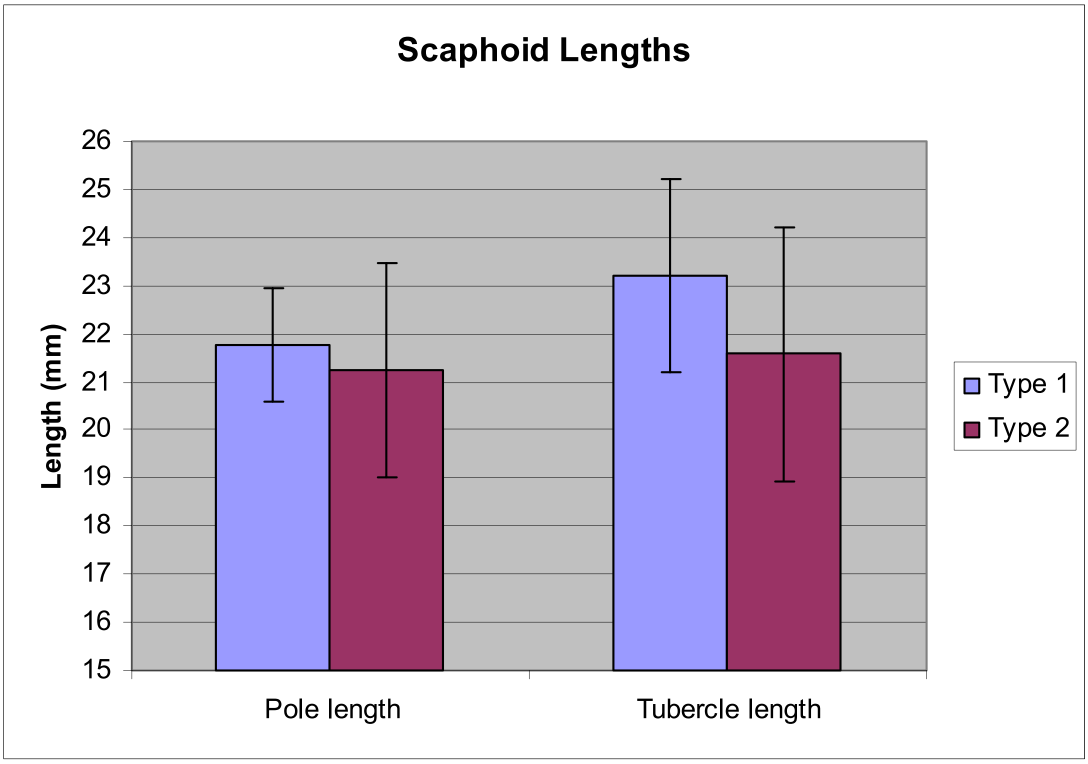

Figure 1.21 Scaphoid lengths. Mean values for maximal proximal pole to distal pole length, and maximal dorsal-ulnar tubercle to scaphoid tuberosity length.

Crest heights were measured at three points along each crest of the type one scaphoids, and at the mid-point of each crest of the type two scaphoids (figure 1.22). The mean crest height of type one scaphoids (2.64±0.092mm) was significantly greater than the mean crest height of type two scaphoids (1.015±0.114mm; $p < 0.05$; figure 1.23). Similarly, the mean relative crest height (crest height / scaphoid pole length) of type one scaphoids (0.121±0.0002mm/mm) was significantly greater than the mean relative crest height of type two scaphoids (0.049±0.0002mm/mm; $p < 0.05$; figure 1.24).

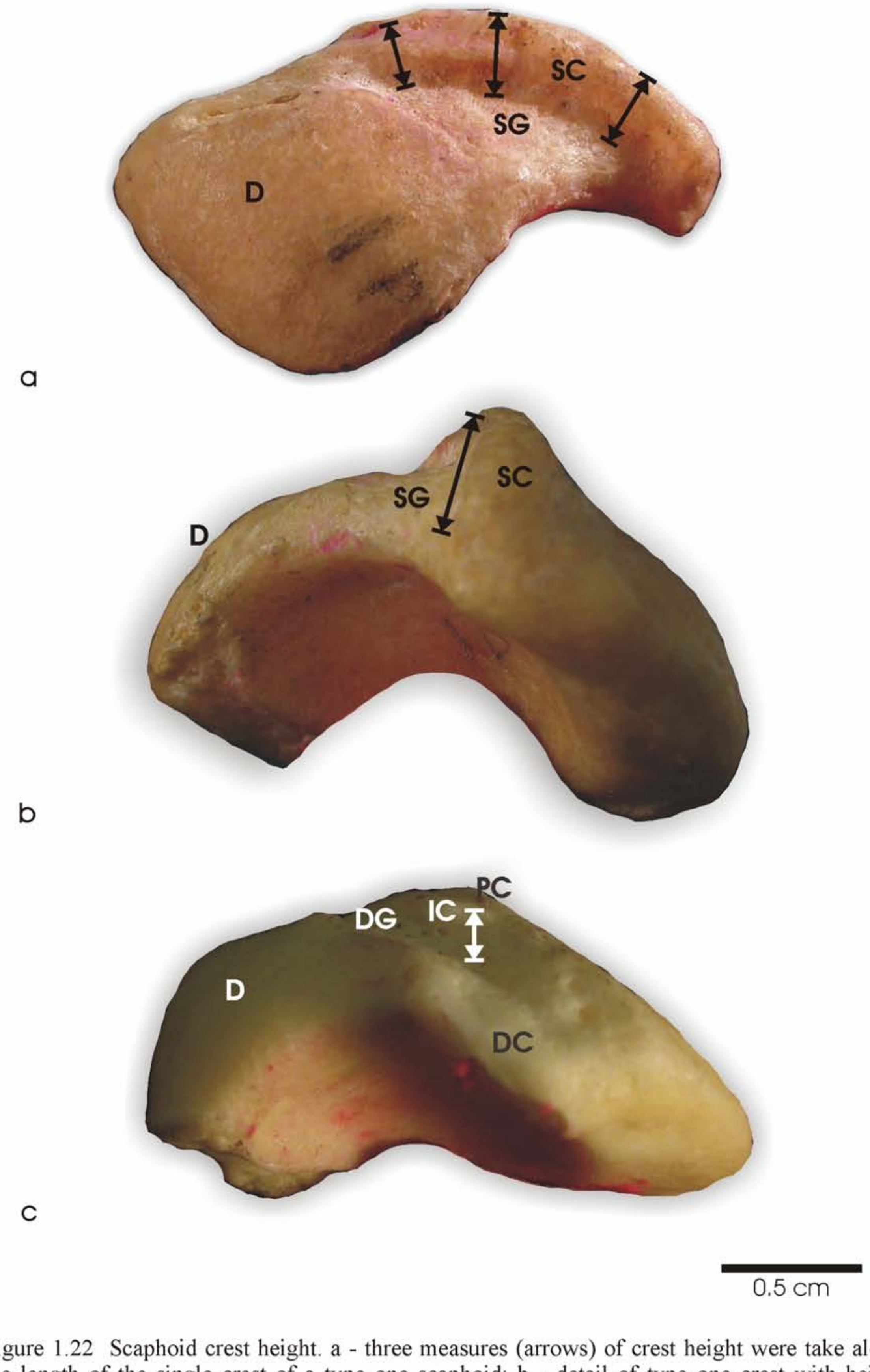

Figure 1.22 Scaphoid crest height. a - three measures (arrows) of crest height were take along the length of the single crest of a type one scaphoid; b - detail of type one crest with height measured (arrow); c - the three crests of a type two scaphoid were measured once each (arrow) to yield three measures from each scaphoid; D - distal articular surface, SG - scaphoid groove, SC - scaphoid crest, DG - distal groove, DC -distal crest, IC - intermediate crest, PC - proximal crest.

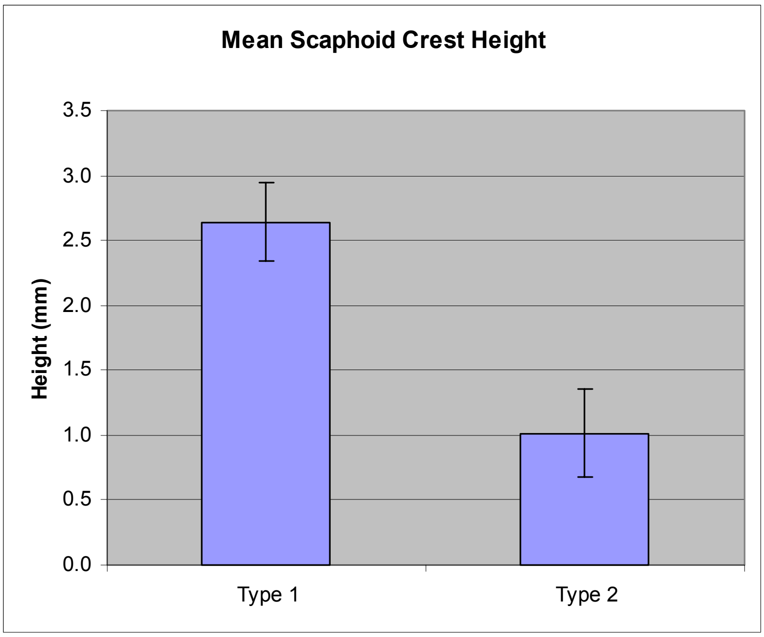

Figure 1.23 Mean scaphoid crest height. Mean height of the scaphoid crest for each type calculated from proximal, intermediate and distal measures of each crest.

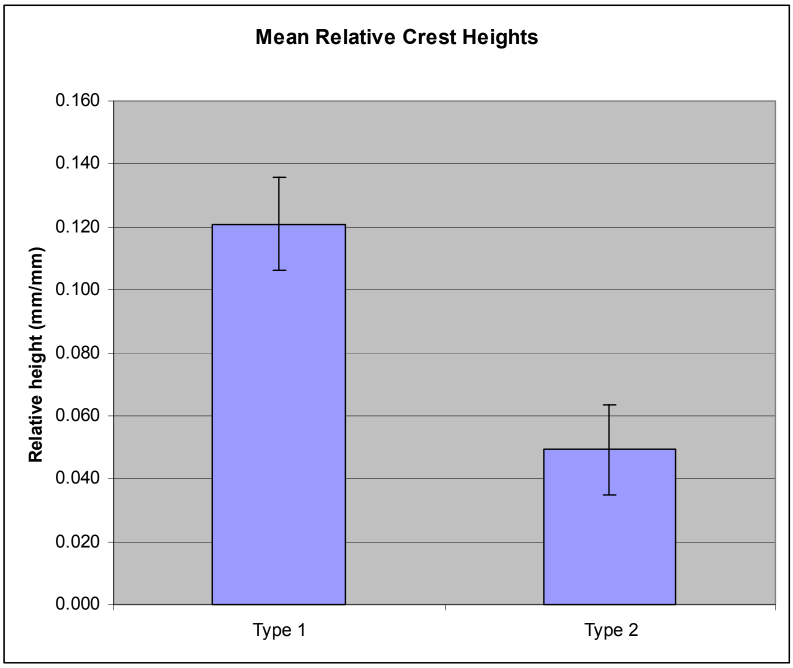

Figure 1.24 Mean relative crest height. Mean crest height divided by the pole length of each scaphoid to generate the height in relation to the length of the scaphoid.

1.4.2.2 Articular Surfaces and Facets

The mean capitate articular facet length of the type one scaphoids (14.309±0.589mm) was significantly greater than the mean capitate articular facet length of the type two scaphoids (11.99±1.31mm; $p < 0.05$; figure 1.25). The mean relative capitate articular facet length (capitate facet length / scaphoid pole length) of the type one scaphoids (0.654±0.05mm/mm) was significantly greater than the mean relative capitate facet length of the type two scaphoids (0.513±0.05 mm/mm; $p < 0.05$; figure 1.26).

The mean lunate articular facet length of the type two scaphoids (3.023±0.627 mm) was not significantly greater than the mean lunate facet length of the type one scaphoids (2.838±0.59 mm; $p > 0.05$; figure 1.25). The mean relative lunate facet length (lunate facet length / scaphoid pole length) of the type two scaphoids (0.147±0.031 mm/mm) was not significantly greater than the mean relative lunate facet length of type one scaphoids (0.122±0.022 mm/mm; $p > 0.05$; figure 1.26).

The area of the distal articular surface and the lunate and capitate facets were calculated for each type of scaphoid. The mean distal articular surface area of type one scaphoids (89.0±26.866 mm^2) was significantly greater than the mean distal articular surface area of type two scaphoids (71.625±31.388 mm^2; $p < 0.05$; figure 1.27). The mean relative distal articular surface area (distal articular surface area / scaphoid pole length) of type one scaphoids (5.024±1.089 mm^2/mm) was significantly greater than the mean relative distal articular surface area of type two scaphoids (2.788±0.788 mm^2/mm; $p < 0.05$; figure 1.28).

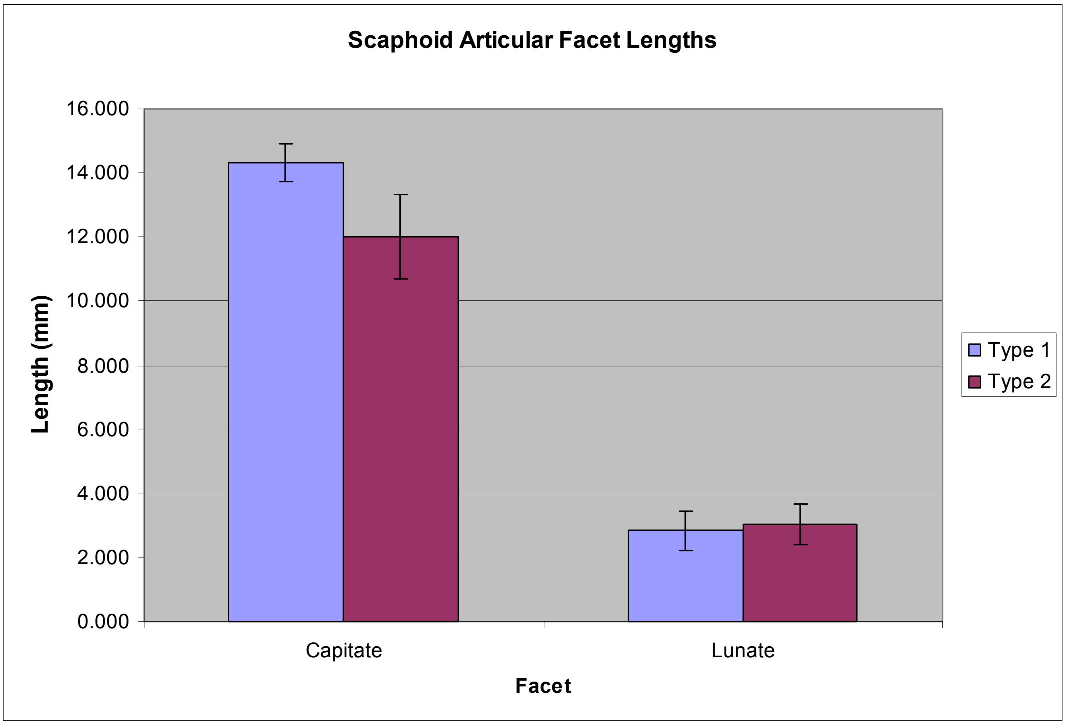

Figure 1.25 Mean articular facet length. The maximum proximal-distal lengths of the capitate and lunate articular facets of each scaphoid type were measured.

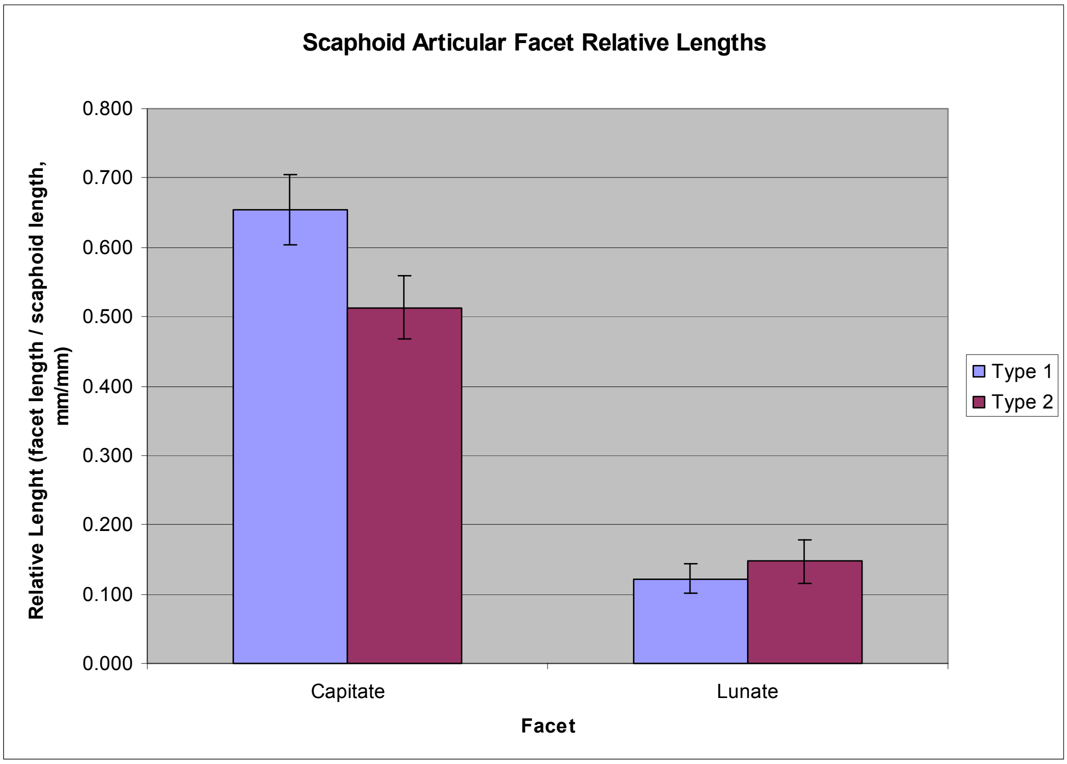

Figure 1.26 Mean relative articular facet length. The maximum proximal-distal lengths of the capitate and lunate articular facets were measured relative to the scaphoid pole length.

The mean capitate facet area of the type one scaphoids (104.945±15.143mm^2) was significantly greater than the mean capitate facet area of the type two scaphoids (77.586±31.076mm^2; $p < 0.05$; figure 1.27). The mean relative capitate facet area (capitate facet area / scaphoid pole length) of the type one scaphoids (4.832±0.561mm^2/mm) was significantly greater than the mean relative capitate facet area of the type two scaphoids (3.78±0.923 mm^2/mm; $p < 0.01$; figure 1.28).

The mean lunate facet area of the type two scaphoids (19.965±6.697 mm^2) was not significantly greater than the mean lunate facet area of the type one scaphoids (19.1±5.682 mm^2; $p > 0.05$; figure 1.27). The mean relative lunate facet area (lunate facet area / scaphoid pole length) of the type one scaphoids (1.031±0.162 mm^2/mm) was not significantly greater than the mean relative lunate facet area of the type two scaphoids (0.909±0.299 mm^2/mm; $p > 0.05$; figure 1.28).

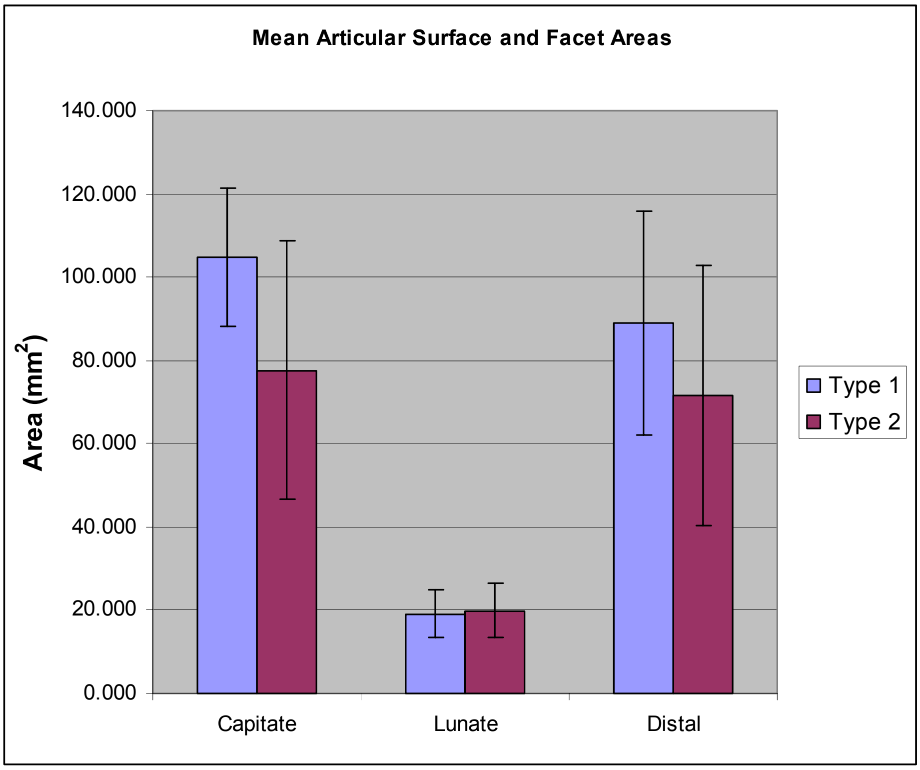

Figure 1.27 Mean articular surface and facet areas. The areas of the distal articular surface, the capitate facet and the lunate facet of each scaphoid type were measured.

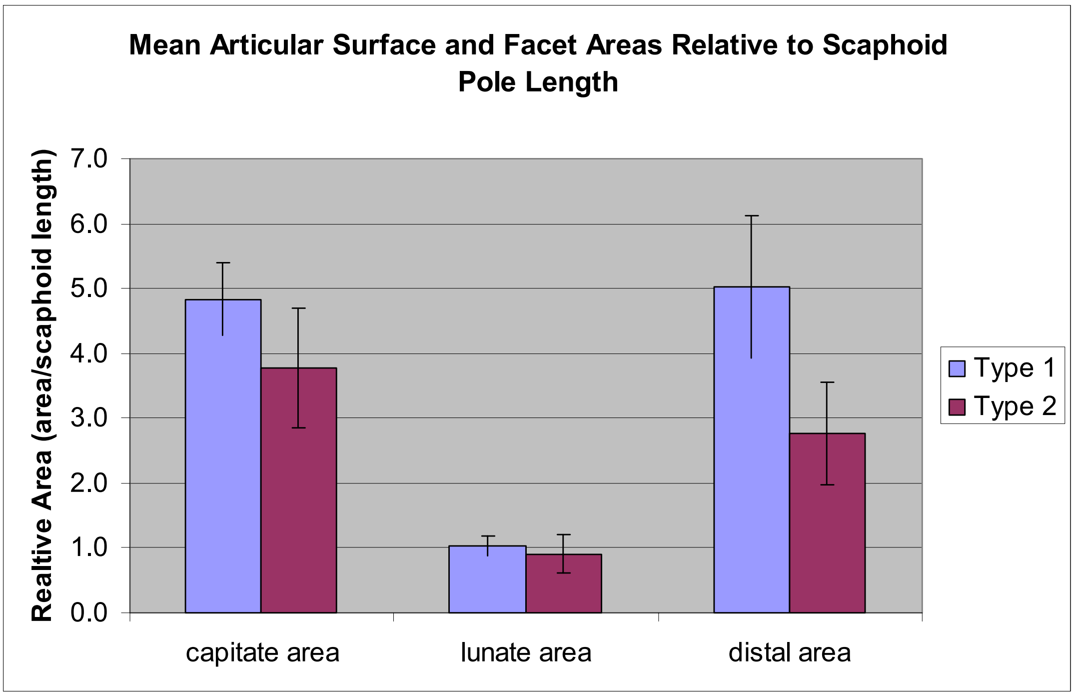

Figure 1.28 Mean articular surface and facet areas relative to scaphoid pole length.

Indices of the ulnar aspect articular facet relative areas (relative lunate facet area / relative capitate facet area) where calculated. The mean values of the indices were compared to determine the ratio of lunate articular facet area to capitate articular facet area. The mean facet index of type two scaphoids (0.250±0.11) was significantly greater than the mean facet index of type one scaphoids (0.217±0.056 ; $p < 0.05$; figure 1.29).

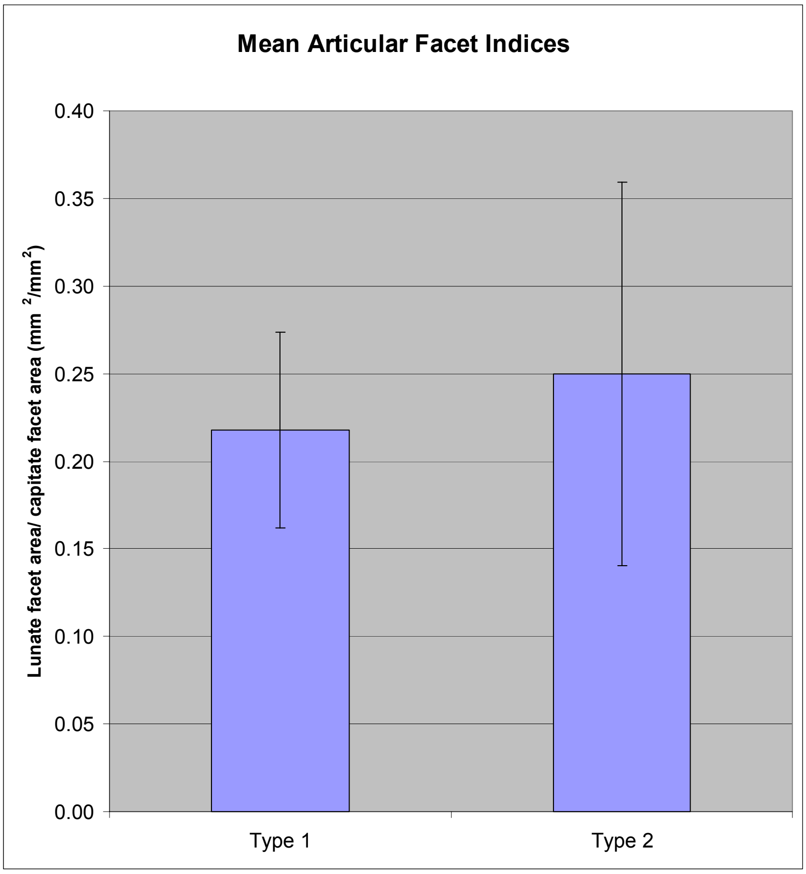

Figure 1.29 Mean relative articular facet indices. The relative lunate facet area was divided by the relative capitate facet area to yield the ulnar facet indices.

The relationship between scaphoid articular surfaces and facets was examined further by the calculation of Pearson's correlation coefficient. Type one scaphoids did not have a significant correlation between capitate and lunate facet relative area ($r = 0.331$), nor was there a significant relationship between capitate facet and distal articular surface relative areas ($r = 0.219$). There was a significant relationship between the distal articular surface and the lunate facet relative areas in type one scaphoids (r = 0.858). Type two scaphoids did not have a significant correlation between capitate and lunate facets relative areas (r = -0.208), nor was there a significant relationship between capitate facet and distal articular surface relative areas (r = 0.024) or between the distal articular surface and the lunate facet relative areas (r = -0.111).

1.5 Discussion

1.5.1 Nomenclature

The morphological variation of the scaphoid has been investigated. The investigation was aided by the development of a detailed nomenclature of the osseous features of the scaphoid. Furthermore, a detailed nomenclature for the trapezium was proposed to facilitate accurate discussion in other sections of this thesis. The other carpal bones discussed in this study did not require more detailed descriptions than those demonstrated in the introduction. The terminology used was in accordance with the guidelines of the Federative Committee on Anatomical Terminology (1999). In addition to the recommendations of the FCAT (1999), several rules for description of anatomical specimens were proposed. Most notable was the distinction between surfaces and aspects. It was determined that both sides of structures and regions within a side (such as an articular region) were commonly termed surfaces. This may lead to confusion in cases where a side of a structure may have multiple specialised regions, ie. the ulnar side of the scaphoid has two articular regions. To avoid this, the complete sides of structures were termed aspects (ie. the ulnar aspect of the scaphoid, the palmar aspect of the hand), and specialised regions surfaces (ie. the distal articular surface of the scaphoid). In discussion of articular surfaces, it may be common to refer to articular facets, but the term facet was reserved for articular surfaces divided into functional sub-areas (ie. the ulnar articular surface of the scaphoid has lunate and capitate articular facets). More landmarks were identified, particularly on the scaphoid and the trapezium, providing for accurate means of describing both the bones and the structures attached to and surrounding the bones. It is hoped that this promotes more accurate conveyance of information from author to reader.

1.5.2 Scaphoid Morphology

1.5.2.1 Methodology

The aim of this study was to determine whether different scaphoid morphologies existed in a sample population. *In vivo* kinematic studies had previously identified two distinct types of scaphoid motion (Moojen *et al*, 2002b; Moritomo *et al*, 2000a; Wolfe *et al*, 2000) but the patterns observed have not been related to anatomical variations in the reviewed literature. Identification of variant scaphoid morphologies may facilitate discussion of the functional significance of the variations in relation to the kinematic studies.

Gross examination of the sample population identified a distinct difference between scaphoids. The most obvious difference was the dorsal aspect. Type one scaphoids had a single crest and groove, whilst type two scaphoids had three crests and two grooves between the crests. Size differences between scaphoids were analysed by the measurement of the maximal length of each scaphoid. The scaphoid tubercle was obviously highly variable in shape, and had been reported as such by others (Compson *et al*, 1994; Moritomo *et al*, 2000b). The margins of the tuberosity were difficult to determine (Compson *et al*, 1994) so a comparison of two length measures was used. Maximal proximal pole to distal pole length was measured to determine the length of each scaphoid between the polar articular surfaces. Dorsal-ulnar tubercle to scaphoid tubercle length was measured to determine the contribution of the scaphoid tubercle to length of the scaphoid. A significant difference between the two lengths may suggest a prominent scaphoid tubercle.

The height of the scaphoid crests was measured to determine any difference between the types of scaphoid. Three measures of height were made at separate points for each scaphoid: ulnar, median and radial points along the single crest or the three crests. They were averaged for each specimen and these means were again averaged to give the mean crest height for each type. To remove the influence of scaphoid size (big scaphoids with big crests and small scaphoid with small crests) relative heights were calculated from the raw data. The heights relative to the pole length of the scaphoid provided a means of assessing the height of the crests irrespective of the scaphoid size. This method was utilised for all other measures to remove the influence of size. Measures of area (for the three mid-carpal articulations) were also assessed relative to length of the scaphoid, providing the unusual notion of "millimetres squared per millimetre".

Morphological analyses of 100 scaphoids were conducted and suggested that two distinct morphologies exist. The majority of specimens used in this study were not of known sex, so a detailed investigation of sexual dimorphism was not conducted. Minor analyses (not presented) suggest that sexual dimorphism does not appear in the characteristics examined. These anatomical findings contrasted previous kinematic results (Craigen and Stanley, 1995) where some degree of sexual dimorphism in carpal motion was reported, but are not examined in this study. The two morphologies identified suggest that there are two types of scaphoid motion, as the shape of the articular surfaces, the orientation of the articulations, and the specialisations of the ligament attachment sites determine how the joints may be moved (Hamrick, 1996). This suggestion is supported in the literature by kinematic studies of the carpus (Moojen *et al*, 2002a). The data reported suggest that there are several distinguishing elements for each type of scaphoid. On gross examination the clearest identifier is the dorsal aspect of the scaphoid.

1.5.2.2 Scaphoid Lengths and Crest Heights

Measures of various dimensions of scaphoids in each group were made. The type one scaphoids were significantly longer than the type two scaphoids. The type one scaphoids had significantly greater mean tubercle lengths than mean pole lengths, whilst there was not a significant difference in mean tubercle and pole lengths for the type two scaphoids. This suggests that the type one scaphoids had a prominent tuberosity, whilst the type two scaphoids had a less distinct tuberosity. Compson *et al* (1994) suggest various scaphoid tubercle shapes. The more prominent scaphoid tubercle of the type one scaphoids may provide greater area or angle for ligament attachment and may alter the mechanical positioning of the scaphoid by its supporting structures. The mean and relative crest heights of type one scaphoids were significantly greater than those of type two scaphoids. This suggests that the single crest of a type one scaphoid is more prominent than the three crests of a type two scaphoid. This may influence the function of ligaments attached to the dorsal aspect of the scaphoid.

The amount of bone to which a ligament attached is suggestive of the degree of force transmitted through the ligament (Benjamin and Ralphs, 1998; Forster, 1984; Gao *et al*, 1996). Greater attachment area or volume of bone suggests greater force transmission, which, in turn suggests stronger ligaments. Strength may be represented as thicker ligamentous fibres or greater angles (arc of tension) through which the ligament transmits force efficiently. The crest of the type one scaphoids may provide a single line of prominent bone for ligamentous attachment where the ligamentous fibres would be aligned in a specific plane. Forces through this plane may be optimally transmitted by the ligament and may then be considered to have been transmitted to the ligament at an angle within the optimal "arc of tension" of that ligament (figure 1.30a). Forces transmitted at angles outside the arc of tension may not be completely transmitted by the ligament, transmitting more force to neighbouring structures and increasing the likelihood of tissue damage. The arc of tension may be determined by the combined angles of the ligamentous fibres, and the area of attachment. A ligament with uniform fibre angle and small attachment areas may have an acute arc of tension, whilst a ligament with less uniform fibre angles and large areas of attachment may have an obtuse arc of tension (figure 1.30b). The former ligament may only be an effective force transmitter for an acute arc of forces and be more susceptible to rupture, whilst the latter ligament may be effective over an obtuse arc of forces and be less susceptible to rupture (figure 1.30c).

The function of ligaments attached to the single crest of the type one scaphoids may be influenced by the height and width of the crest. The height of the single crest may enable greater depth of attachment than a low crest. The ligaments may then have an obtuse arc of tension in a near-sagittal plane (figure 1.31). The narrow area that the single crest provides may limit the width of ligament attachment. The arc of tension may therefore be acute in a near-transverse plane (figure 1.31). Motion of the type one scaphoid may then be considered to be the most stable when such motion is along the line of attachment, the crest. Flexion/extension of the scaphoid about the transverse axis of the scaphoid may be limited due to the narrow area to which ligaments may be attached. Ligaments attached along the complete length of the crest may become taut when loaded and prevent the scaphoid poles from moving in opposite directions, ie. flexion/extension.

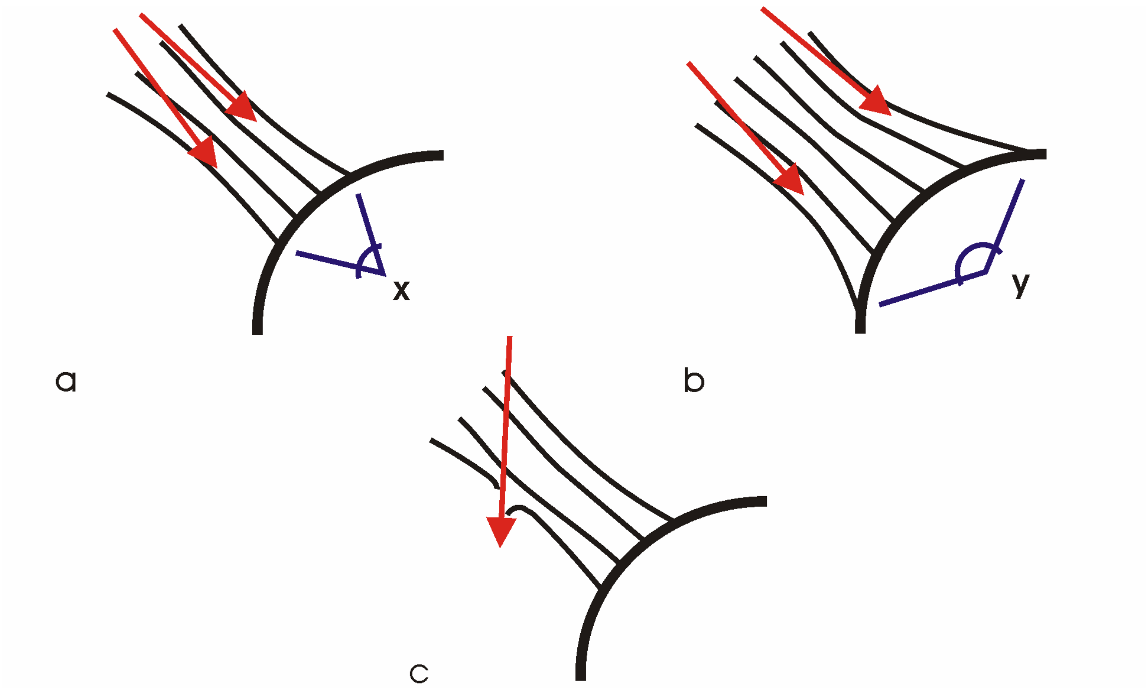

Figure 1.30 Theoretical ligament function. a - narrow ligaments or small attachment sites may limit the angle (x) at which forces (arrows) may be transmitted through the ligament. The arc of tension of this ligament suggests that it may only function efficiently in a narrow range angles; b - broad ligaments, combinations of ligaments or large attachment sites may increase the arc of tension (y). This ligament may function efficiently despite a greater variety in force angle (arrows); c - force (arrow) not transmitted within the arc of tension may not be efficiently transmitted through the ligament and may even result in rupture of the ligament if the force or angle is too severe.

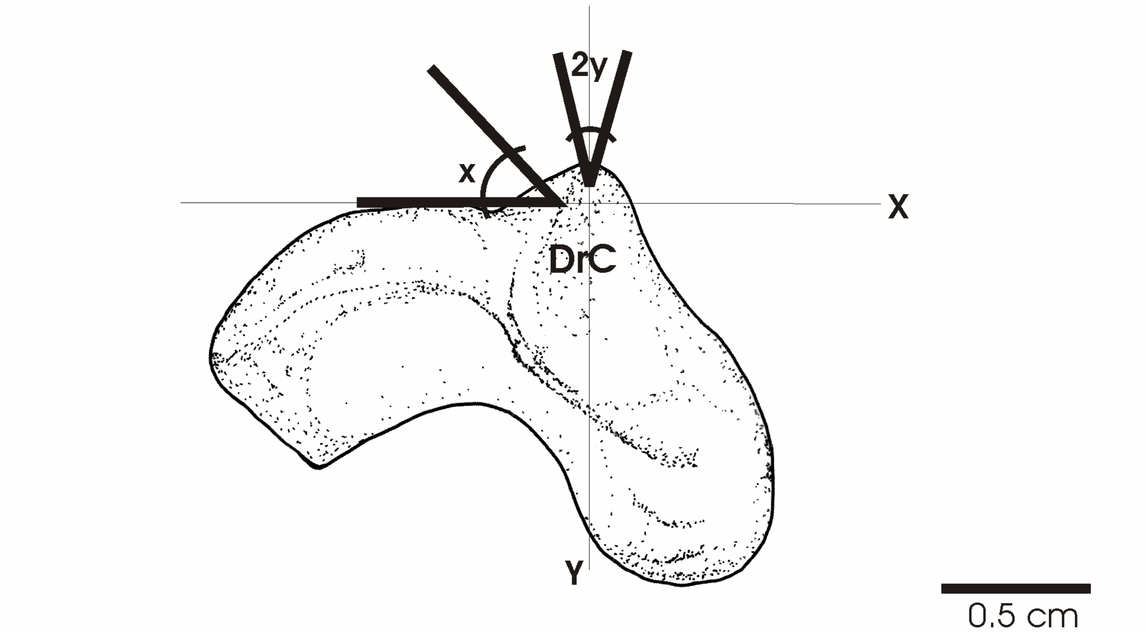

Figure 1.31 The single crest of type one scaphoids. Ligaments may be attached to the dorsal crest (DrC) of the scaphoid. The height of the crest may facilitate a large arc of tension (x) for ligaments attached to the crest in a near-sagittal plane. The narrow width of the crest may reduce the arc of tension (2y) for ligaments attached to the crest in a near-transverse plane. The potential arcs of tension may be measured from axes (planes) perpendicular to the ligament attachments, such the arc x may be measured from the plane X, and the arc 2y from the plane Y.

The generation of uniform tension through the complete band of ligamentous fibres may enable the entire scaphoid to move in one direction, ie. rotation about the longitudinal axis of the scaphoid. This movement may be limited by the maximal tension of the ligaments attached to the crest. This may stabilise the scaphoid whilst allowing movement in a single plane. The angle of the crest may facilitate some lag in tension of the fibres from one end of the crest to the other, allowing a small degree of flexion/extension of the scaphoid. These suggestions are consistent with kinematic analyses of scaphoid motion, where scaphoid rotation is combined with small degrees of flexion/extension (Moojen *et al*, 2002b; Nuttal *et al*, 1998; Wolfe *et al*, 2000).

The high single crest of the type one scaphoids may influence ligament function in a different manner. The ligaments attached to the crest may vary in length and angle such that the percentage of loaded fibres increases as the scaphoid is moved to the extremes of its range of rotation (figure 1.32a). The ligaments may be lax when the scaphoid is in neutral position and then tighten as the scaphoid is internally rotated. Tension in these fibres as the scaphoid is moved to the extremes of its range of rotation may passively contribute to external rotation of the scaphoid, such as when the internally rotated scaphoid is returned to its neutral position. Tension in the ligamentous fibres may also passively contribute to the maintenance of contact between the shallow capitate facet of the scaphoid and the head of the capitate as the scaphoid is translated about the head of the capitate (figure 1.32b). The effect of this passive contribution by a ligament may be likened to the effect of an active contribution by the serratus anterior muscle. This muscle pulls the medial margin of the scaphoid anteriorly to maintain the scapular relationship with the ribs as the scapula is protracted around the ribs. Without this action (such as after impaction of

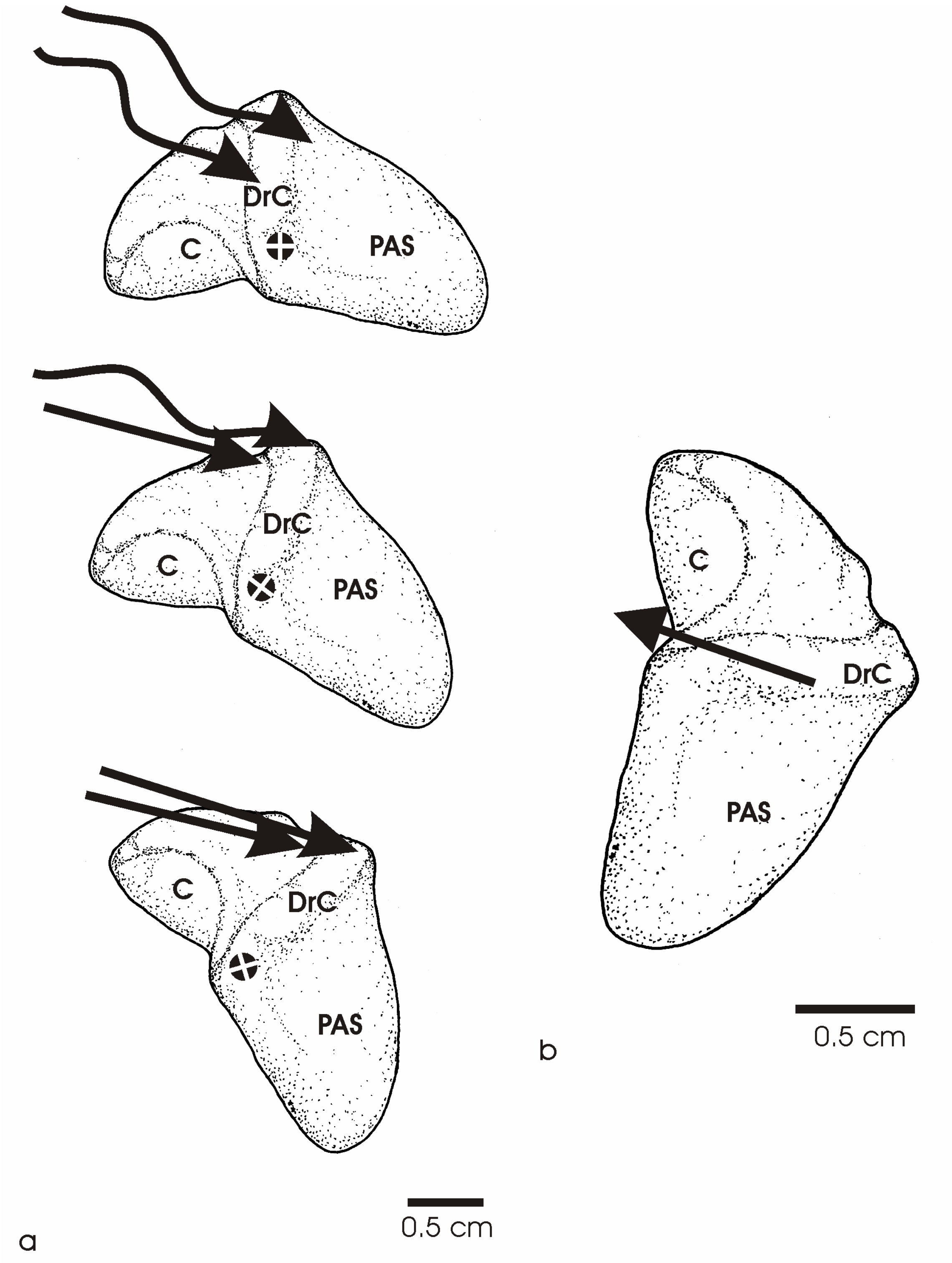

Figure 1.32 Rotation of the type one scaphoid. a - Internal rotation about the longitudinal axis of the scaphoid progressively tighten ligaments (arrows) attached to the dorsal crest (DrC) of the scaphoid. In neutral position (top) all ligaments may be lax. A small degree of rotation (middle) may tighten the shorter ligaments (arrows) to stabilise the movement. Towards the extreme of internal rotation the longer ligaments may also tighten, retarding the scaphoid movement. The height of the crest may facilitate this rotation by increasing the angles within which the fibres are taut; b - the ligaments attached to the dorsal crest (DrC) of the scaphoid may also passively pull (arrow) the capitate articular facet of the scaphoid against the head of the capitate, maintaining contact between the two surfaces; PAS - proximal articular surface, SC - scaphoid crest, C - capitate articular facet.

the long thoracic nerve) the medial margin of the scapula may be pulled posteriorly by other muscles. Similarly, the scaphoid may be pulled away from the capitate if the tension in the ligament is not generated. The may be observed clinically as instability of the scaphoid (Hand, 1999; Kleinman, 2001; Watson *et al*, 1993).

The heights of the three crests observed on type two scaphoids were significantly smaller than those of type one scaphoids. The high, narrow crest of the type one scaphoids was contrasted by the type two scaphoids' low crests spread over a wider area. This suggests that the ligaments that may be attached to the crests of the type two scaphoids may also differ from those attached to the type one scaphoids. The type two scaphoids may have a broad band of ligaments attached to the crests. As the crests are staggered across the dorsal aspect of the scaphoid, the ligaments may be attached to the crests in a staggered pattern. The proximal crest is the most ulnar, whilst the distal crest is the most radial, increasing the arc in which ligaments may be attached to the dorsal aspect of the scaphoid. This may further increase the arc of tension in a near-transverse plane (figure 1.33a). This arrangement of ligaments may facilitate flexion/extension of the scaphoid. The variable ligament lengths, determined by the staggered crests to which they may be attached, may permit significant lag in the loading of the ligamentous fibres. This may allow the poles of the scaphoid to be moved in opposite directions in the same plane, such as the distal pole being moved palmarly and the proximal pole being moved dorsally, ie. flexion. The low height of the crests may not facilitate great depth of the ligamentous attachments. This may result in an acute arc of tension in a near-sagittal plane (figure 1.33b). The type two scaphoids may therefore be unstable in all but slight rotation about the longitudinal axis of

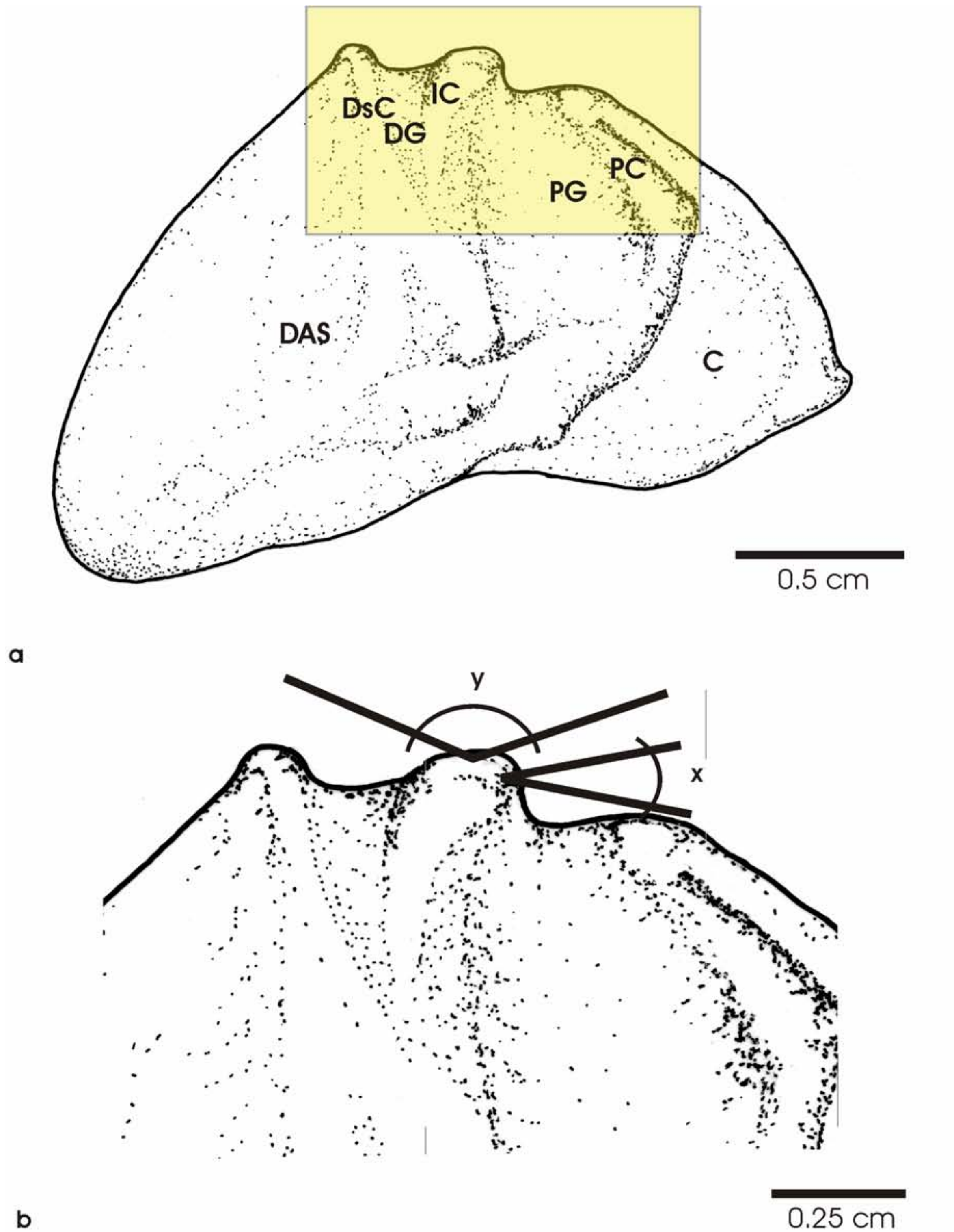

Figure 1.33 The three crests of the type two scaphoids. a - The proximal (PC), intermediate (IM) and distal (DsC) crests divide the proximal (PG) and distal (DG) grooves. The low crest heights and the width which the three crests occupy contrasts the arrangement of the type one scaphoids; b - close up of the region highlighted in a). The possible angle (x) of ligament attachments in the near-sagittal plane is acute due to the low crest height, whilst the possible angle (y) in a near-transverse plane is obtuse. The obtuse near-transverse angle may facilitate greater stability in flexion/extension movements of the scaphoid; DAS - distal articular surface, C - capitate articular facet.

the scaphoid. These suggestions are supported by kinematic studies (Moojen *et al*, 2002b; Nuttal *et al*, 1998; Wolfe *et al*, 2000).

1.5.2.3 Articular Surfaces and Facets

The area of the distal articular surface, the lunate articular facet and the capitate articular facet were measured. The mean relative distal articular surface area of the type one scaphoids was significantly greater than that of the type two scaphoids. The distal articular surface of the type one scaphoids was elongated dorsally (figure 1.34a). This description is consistent with reviewed descriptions of the distal articular surface (Compson *et al*, 1994). This may suggest that the proximal articular surfaces of the trapezium and trapezoid are pulled proximally across the distal articular surface in radial deviation of the wrist. Kinematic studies (Moojen *et al*, 2002b; Moritomo *et al*, 2000a) suggest that the movement of the distal pole of the scaphoid is limited, even during flexion/extension movements of the scaphoid. The ligamentous support of the distal pole of the scaphoid may restrict the movement of the distal pole (Boabighi *et al*, 1993; Drewniany *et al*, 1985). The full range of scaphoid flexion/extension may then be more reliant on proximal pole movements (Moojen *et al*, 2002b; Moritomo *et al*, 2000a; Wolfe *et al*, 2000). However, if the scaphoid is rotated about its longitudinal axis the elongated distal articular surface of the scaphoid may be utilised in radial deviation. In this case the scaphoid may be slightly flexed to position the trapezium and trapezoid dorsally on its distal articular surface. Once more dorsal to the scaphoid, the trapezium and trapezoid can be pulled down the elongated distal articular surface of the scaphoid. Internal rotation of the scaphoid may move the scaphoid crest from dorsal to radial, reducing the potential of it

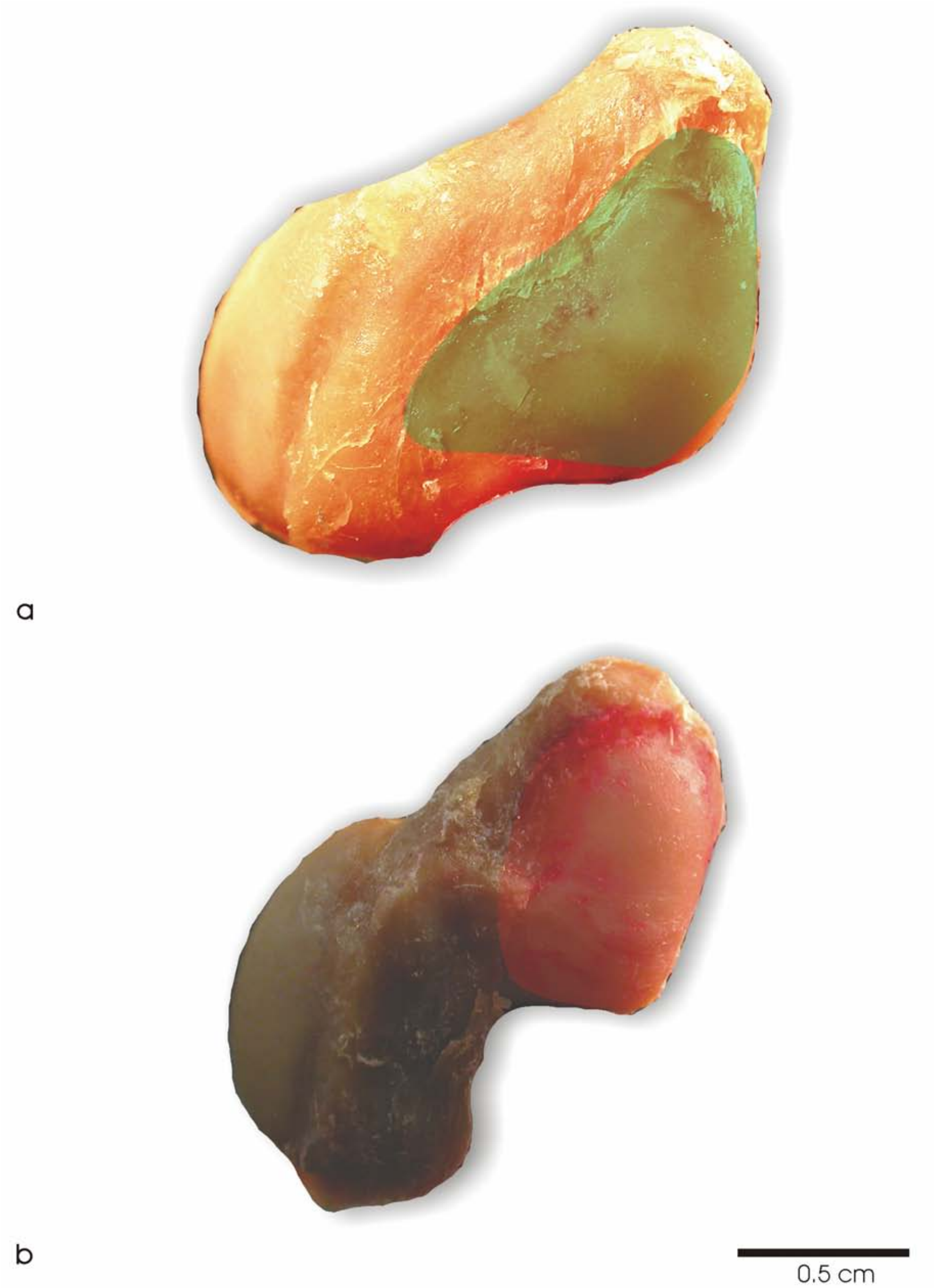

Figure 1.34 Variation of the scaphoid distal articular surface. a - type one scaphoid with distal articular surface (green) elongated across the dorsal aspect of the scaphoid; b - type two scaphoid with no elongation of the distal articular surface (red).

acting as an obstacle to the proximal movement of the trapezium and trapezoid. The internal rotation of the scaphoid may also position the distal articular surface of the scaphoid for optimal congruency with the proximal articular surfaces of the trapezium and trapezoid. This may be likened to the glenoid-humeral joint, where external rotation of the humerus moves the greater tuberosity of the humerus away from the acromion process of the scapula to facilitate full abduction of the shoulder. To facilitate further motion the scaphoid may be translated proximal and ulnar to its neutral position, following the convex curvature of the capitate head.

The small distal articular surface of the type two scaphoids may be suggestive of flexion/extension of the scaphoid. Kinematic analyses of the wrist suggest that distal pole of the scaphoid is moved significantly less than the proximal pole of the scaphoid during flexion/extension (Moojen *et al*, 2002b; Moritomo *et al*, 2000a). This is represented anatomically by the small distal articular surface that is not elongated across the dorsal aspect of the scaphoid (cf. type one scaphoids; figure 1.34b). This description of variation of the distal articular surface is supported by other studies (Berger, 2001b; Compson *et al*, 1994). Radial deviation of the wrist may then be reliant on flexion of the scaphoid to provide space into which the trapezium and trapezoid may be moved. As the distal articular surface of the scaphoid is not elongated the trapezium and trapezoid cannot be moved into a more dorsal position relative to the scaphoid, and will be pushed upon the distal pole of the scaphoid as radial deviation is initiated. The proximal pole of the scaphoid must be extended (flexing the scaphoid) to allow the distal scaphoid-trapezium-trapezoid complex to be moved into a more proximal space. This exaggerated movement of the proximal pole of the scaphoid has been observed *in vivo* (Moojen *et al*, 2002b). For this movement to happen without forcing the scaphoid to translate proximal and ulnar (around the capitate head) to its neutral position, movement of the scaphoid against the capitate must be limited to predominately flexion/extension. This may be achieved by ligamentous restraints or the articulation between the scaphoid and the capitate.

The mean relative capitate facet area and length of the type one scaphoids were significantly greater than those of the type two scaphoids. The large, elongated and shallow capitate facet of the type one scaphoids may facilitate rotation of the scaphoid about its longitudinal axis. The shallow capitate facet may facilitate rotation of the scaphoid by not restricting dorsal to palmar movements of the scaphoid. This may allow the scaphoid to be moved palmarly when internally rotated, and dorsally when externally rotated. Congruency between the two articular surfaces may be maintained passively by the ligaments discussed previously. The length of the capitate facet may facilitate translation of the rotated scaphoid, as the capitate head is unlikely to occupy the entire facet at any one position. The capitate facet may be likened to a long trough in which the capitate head may slide. In a neutral position the capitate head may be articulated proximally with the capitate articular facet of the scaphoid. When the scaphoid is translated proximal and ulnar around the capitate the capitate head may be articulated distally with the capitate articular facet of the scaphoid.

The capitate articular facet of the type two scaphoids was round and deep, quite different to the elongated, shallow facet of the type one scaphoids. Although the mean relative capitate facet area of the type two scaphoids was significantly smaller than the type one scaphoids, the difference in volume may be more significant than that reported. The measures of both facet areas were taken from the maximal dimensions of the facets. The volume of the type one facets may be considered as the sum of a small number of slices similar in each to other. The volume of the type two facets may be considered as the sum of a large number of slices progressively smaller in area than the last slice. The greatest area of the type two facets may come from the most ulnar slice, whilst the smallest area may come from the most radial slice. The capitate articular facet of the type two scaphoids may be considered a cylindrical pyramid with an ulnar base and a radial apex. The entire deep capitate articular facet may be congruent with the head of the capitate, limiting the range and direction of possible scaphoid movements (Hamrick, 1996). The type two scaphoids may then be prevented from being translated across the surface of the capitate head. To facilitate radial deviation the only movement of the scaphoid that may provide space for the trapezium and trapezoid is flexion of the scaphoid. The articulation between the capitate head and the deep capitate articular facet of the scaphoid may provide a fulcrum about which the scaphoid may be moved into flexion/extension.

There was no significant difference between the mean relative lunate articular facet areas of the type one and type two scaphoids. However, the slight difference between facet areas may be functionally significant, as in contrast to the previous measures of articular surface/facet area, the type two values were greater than the type one values. The measurements of lunate articular facet area may have been the least accurate of the measures. Identification of the margins of the lunate articular facet was difficult on many dry bones. Multiple measures of the specimens provided consistent results, but this may have been influenced by the more accurate measurement of the wet scaphoid specimens. The slight difference may be significant in relation to the suggested movements of each scaphoid type. If the type one scaphoids are rotated about their longitudinal axes and translated against the capitate there is less need for articulation between the scaphoid and lunate. Small articular surfaces upon the scaphoid and lunate pressed against each other may be sufficient for the transmission of force through the proximal row of carpal bones. If the type two scaphoids are flexed/extended, and particularly if the majority of this movement is at the proximal pole of the scaphoid, the articulation with the lunate may be subject to a greater range of motion, demanding a greater articular surface (Hamrick, 1996). This speculation may be resolved by a more extensive study of wet scaphoid-lunate articulations.

The difference between lunate articular facet areas of the type one and type two scaphoids may be further supported by the calculation of scaphoid ulnar aspect articular facet indices. Division of the mean relative lunate articular facet area by the mean relative capitate articular facet area yields the indices. The indices are suggestive of the relationship between the lunate and capitate articular facets for each scaphoid type. The type two indices were significantly greater than the type one indices, suggesting that the type two lunate articular facets may be more significant contributors to the articular facet areas of the ulnar aspect of the scaphoid. That the type two lunate articular facet may be significantly larger than the type one facet in relation to capitate facet area suggests that scaphoid-lunate interaction in wrists with a type two scaphoid is more significant than scaphoid-lunate interaction in wrists with a type one scaphoid. These differences may be most obvious in pathological degeneration of wrist function, such as scapholunate advanced collapse (SLAC) wrist. Once the scaphoid-lunate joint is damaged, ulnar deviation of a wrist with a type one scaphoid may exacerbate the dysfunction by pulling the scaphoid away from the lunate. Less damage may be caused by combined movements of the scaphoid and lunate, such as proximal row translation. A wrist with a type two scaphoid may be more likely to exacerbate the dysfunction in both radial and ulnar deviation of the wrist due to flexion/extension of the scaphoid. Flexion/extension of the scaphoid is reported to oppose the flexion/extension of the lunate (Craigen and Stanley, 1995; Moojen *et al*, 2002a; Nakamura *et al*, 2000; Sarrafian *et al*, 1977; Wolfe *et al*, 2000).

The morphological analyses of the scaphoid suggest that there are two distinct types of scaphoid. The morphological differences between the two types also suggest that the movement of the two types of scaphoid may be different. The type one scaphoids were characterised by a single high crest obliquely orientated across the dorsal aspect, a large, elongated distal articular surface, large, elongated and shallow capitate articular facet, and a small lunate articular facet. It was suggested that the type one scaphoids were rotated about their longitudinal axis and translated proximally and ulnarly around the capitate head to facilitate radial deviation of the wrist. The type two scaphoids were characterised by three low crests obliquely orientated across the dorsal aspect, a small distal articular surface, a short, deep capitate articular facet and a slightly larger lunate articular facet than type one scaphoids. It was suggested that the type two scaphoids were flexed/extended with the deep articulation with the head of the capitate acting as a fulcrum about which the scaphoid is moved.

1.6 Conclusions

A detailed nomenclature of the scaphoid and trapezium was proposed to facilitate investigations of the osseous anatomy and the anatomical structures that support the carpus. The morphological investigation of the scaphoid suggested that two distinct morphologies exist. The morphologies suggest that one type of scaphoid is rotated about its longitudinal axis during wrist motion, and the other is flexed and extended about its transverse axis during wrist motion.

The improved understanding of scaphoid morphology and its variation may improve interpretation of kinematic data. This may ultimately improve the understanding of wrist function and promote enhancement of treatments for wrist dysfunction.

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Chapter 2

Histological Tissue Differentiation

2.1 Introduction

The anatomical study of the wrist has been largely focussed on the fibrous support of the carpal bones. The differentiation between ligament and joint capsule has been debated as the interpretation of gross results is often reliant on separating force-bearing ligaments from joint capsule. In order to accurately differentiate between ligament and joint capsule the two tissues must be investigated. The means of differentiating between the two need to be established and quantified so that objective descriptions of the carpal ligamentous support may be made.

Ligament, as with tendon, is primarily a specific grouping of collagen fibres (Benjamin and Ralphs, 1997). Collagen fibrils are collected into fibres, collections of fibres form bundles, bundles form fascicles and the fascicles form a ligament or tendon (Benjamin and Ralphs, 1997). General differentiation between ligament and tendon is based on cellular populations and fibre density. Tendon contains a greater number and variety of cells, and has a greater fibre density, reflected by the dense extracellular matrix (Benjamin and Ralphs, 1997). Tendon and ligament, especially in a histologic section, are simply and readily differentiated in most cases by their anatomical position (Flint, 1983; Forster, 1984). In the wrist, ligaments are commonly termed intrinsic or extrinsic in reference to their position relative to the joint capsule (Johnstone *et al*, 1995), where intrinsic is considered to be deep to the capsule, and extrinsic considered part, or thickenings, of the capsule. Tendons in the wrist are commonly superficial to the extrinsic ligaments, and separated from the ligamentous layer by various connective tissues, making distinctions between tendon and ligament clear.

In addition to the bundling of collagen, ligament and tendon have a series of connective tissue layers that ensheath the fascicles and ligament/tendon as a whole. Smaller groups of collagen fibrils (fibres, bundles) are ensheathed by the cytoplasmic processes of the fibroblasts from whence they were produced and are maintained, whilst collections of these smaller groups (fascicles) are ensheathed in a loose connective tissue sleeve, the endoligament/endotendon (figure 2.1). The entire structure (ligament/tendon) is ensheathed by an epiligament/epitendon (figure 2.1), which is similar to and continuous with the endoligament/endotendon, until both terminal ends are attached to another structure (generally bone for ligament and muscle/bone for tendon). The internal sheaths (endoligament/endotendon) enable bundles and fascicles to slide against each other with greatly reduced friction, whilst the external structures (epiligament/epitendon) provide the same friction-reducing capacity between the ligament/tendon and the surrounding tissues. Epiligament/epitendon is continuous with the periosteum/epimysium at the termination of the ligament/tendon (Benjamin and Ralphs, 1999). The distinct tissues of the ligament/tendon are therefore further separated from surrounding tissues by these protective sheaths. This suggests that identification of these sheaths may facilitate, for example, differentiation between ligament and capsule. This may be particularly important in macroscopic investigation of the wrist (figure 2.2a). However, reliable macroscopic differentiation may be limited to larger ligaments. Identification of the sheaths may be readily achieved histologically, and may contribute to improved accuracy in differentiating between ligament and joint capsule. Identification of these bounding structures enables the margins between ligament and joint capsule to be identified histologically (figure 2.2b). As the endo- and epiligament ensheath the ligament and its components, they are expected to be visible regardless of tissue block orientation (figure 2.3). Their identification may be further facilitated by a collagen-differentiating stain, a stain that colours collagen fibres

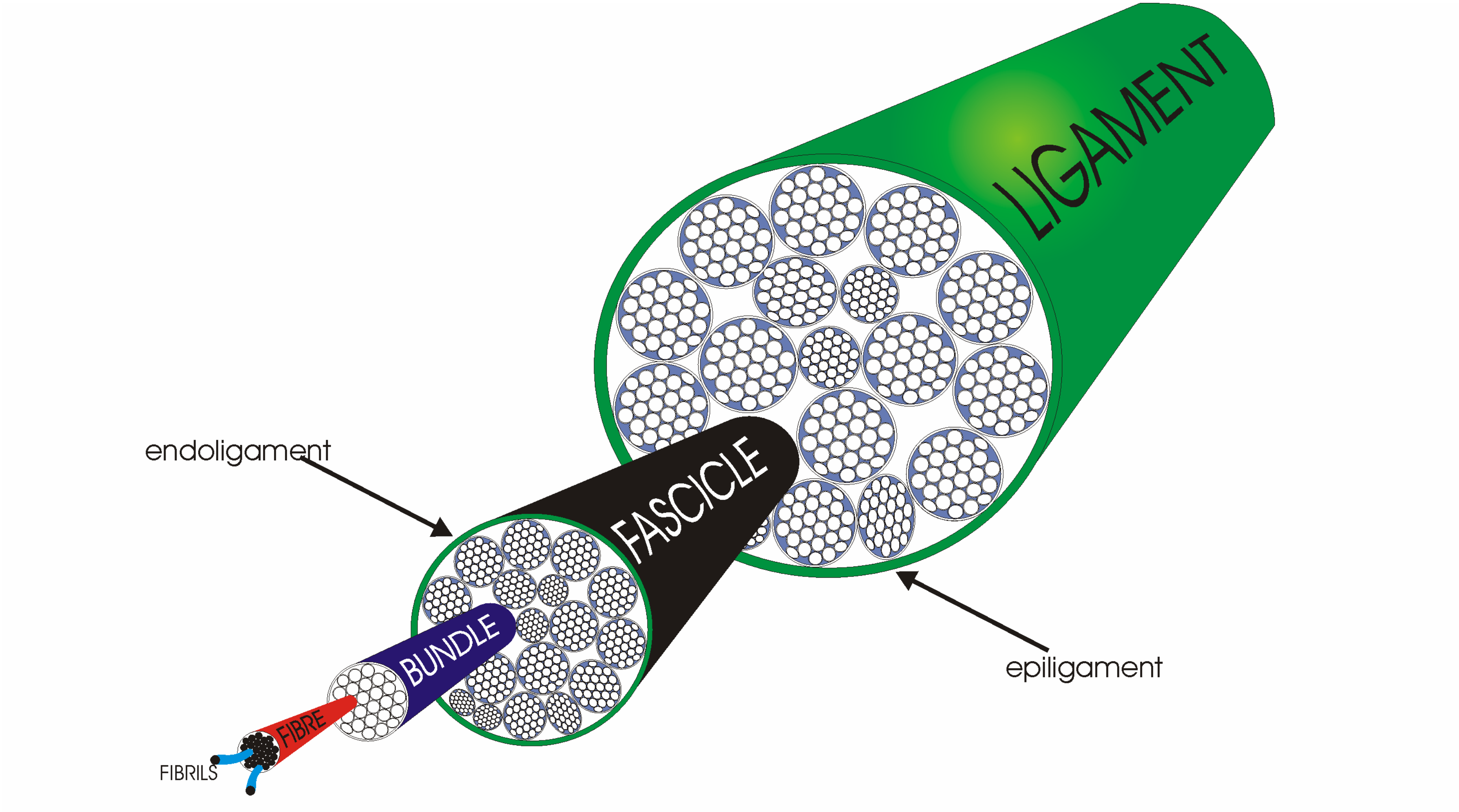


Figure 2.1 Structural divisions of a ligament. Collagen fibrils, surrounded by fibroblastic processes (not shown) are grouped into fibres, which are visible using light microscopy (Benjamin and Ralphs,1997); numerous fibres are grouped into bundles, separated from neighbouring bundles the same fibroblastic processes (Benjamin and Ralphs, 1998); numerous bundles are grouped into fascicles are separated from each other by endoligament (black); numerous fascicles form a ligament, which is separated from other tissues by an epiligament (green), which is continuous with the endoligament.

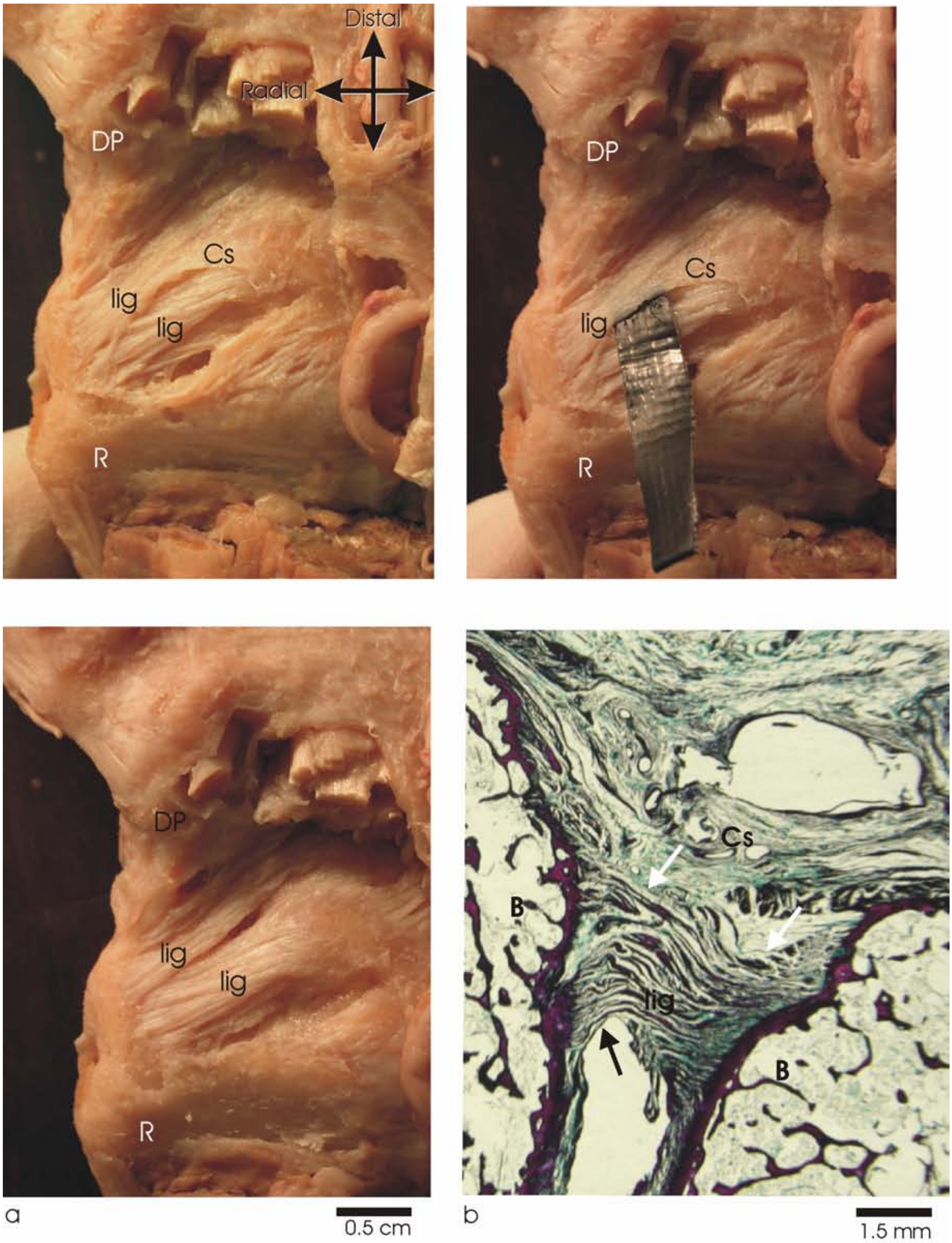
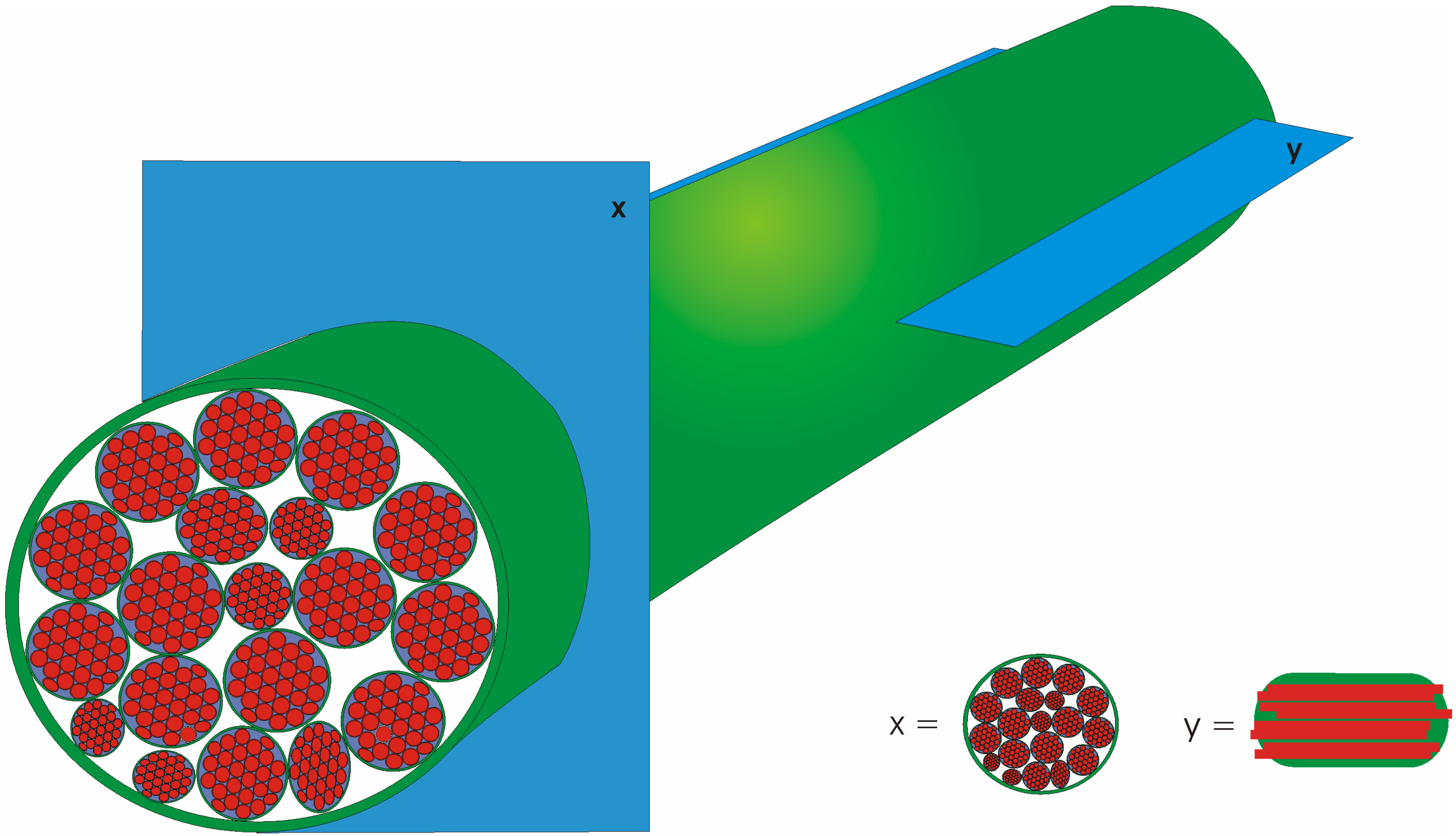
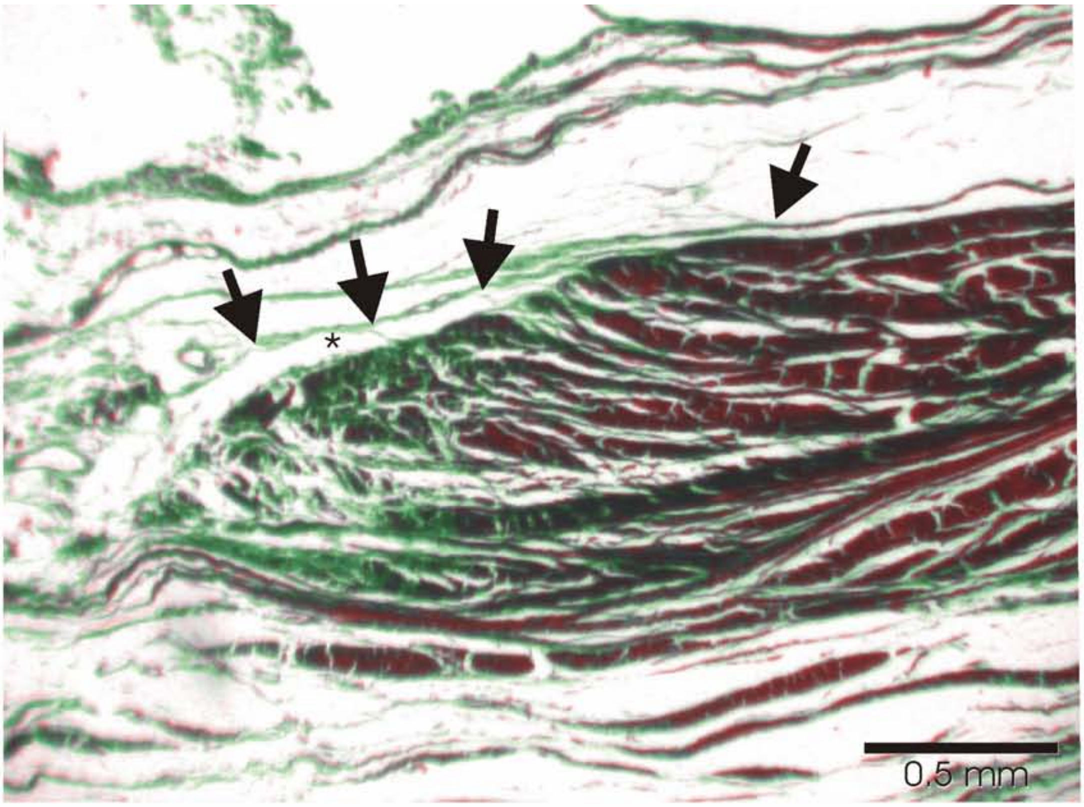


Figure 2.2 Differentiating ligament from capsule. a - Palmar aspect of the wrist illustrating the difference between ligament and capsule that is not always discernible; top left - two ligaments (lig) and a thin layer of capsule (Cs), top right - marker separating deep ligament from capsule and superficial ligament, illustrating the difficulty in determining the margins of each tissue, bottom left - capsule dissected out to reveal the perceived margins of each ligament; R - radius, DP - distal pole of scaphoid. b - histological section illustrating the difference between ligament (lig) and joint capsule (Cs). The margins of the ligament are demarcated by the epiligament (arrows); Modified Masson's Trichrome.



a

Figure 2.3 a- Ligament identification. Schematic ligament (fascicles in red) encapsulated by epiligament (green) as seen in two sections; x - transverse section of specimen; y - longitudinal section of specimen



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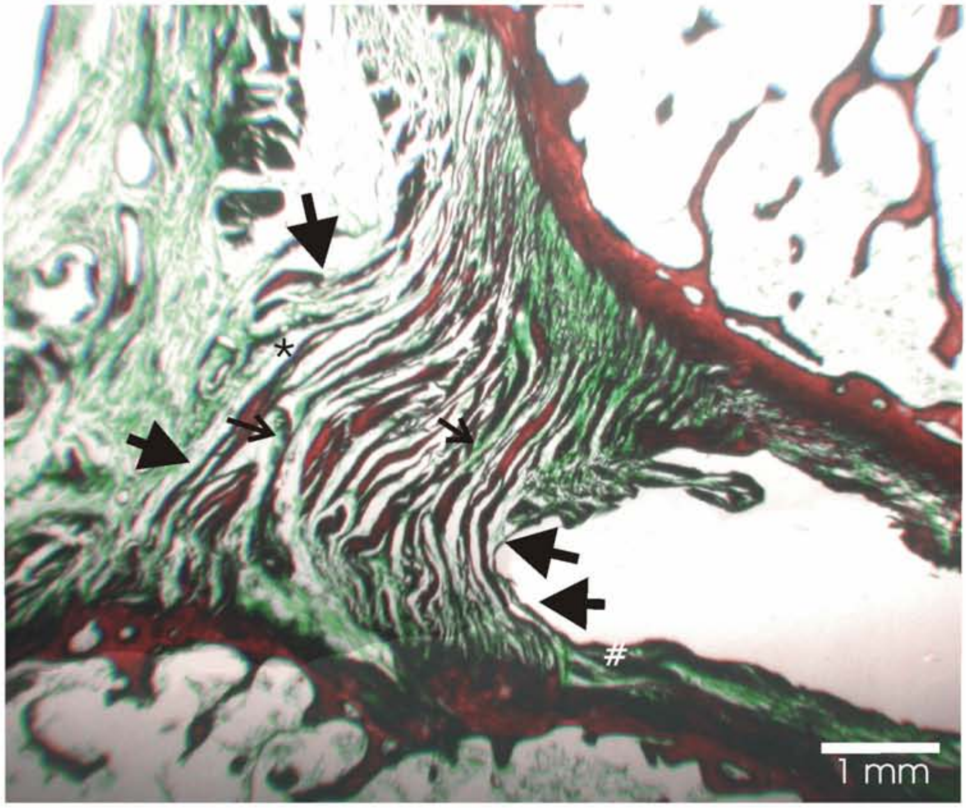


c

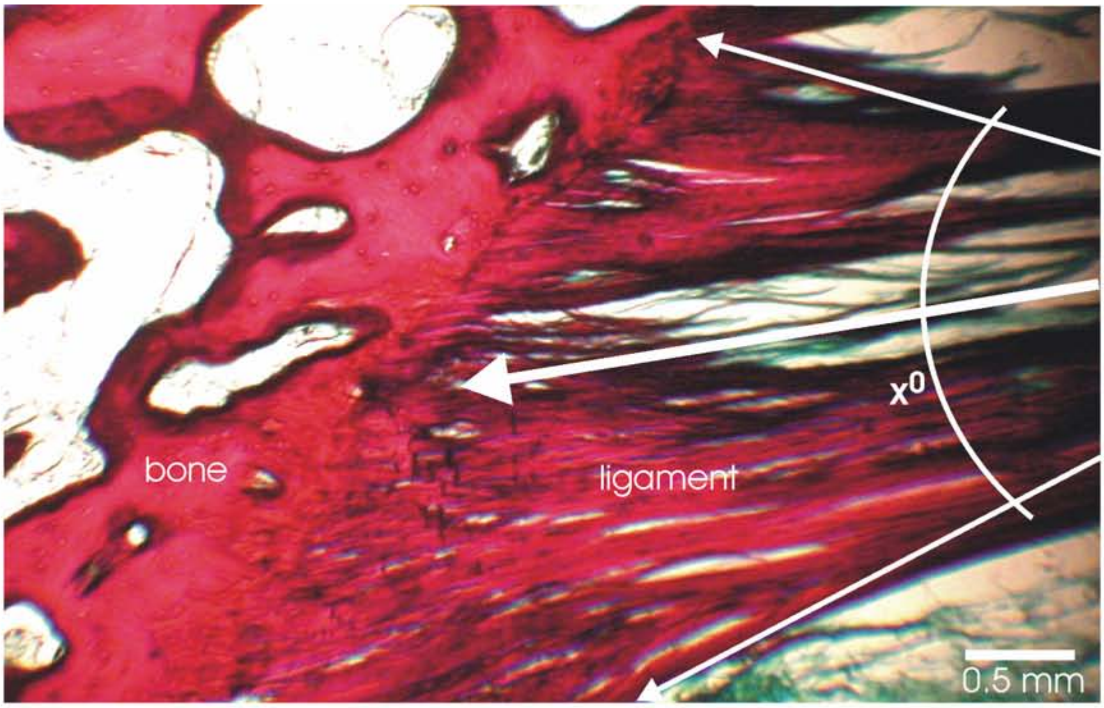
Figure 2.3 continued Ligament identification. Modified Masson's Trichrome stains bone and ligament red, all other connective tissues are green, allowing differentiation between ligament and capsule. Epiligament (closed arrow heads) is seen around the ligament, whilst endoligament (open arrow heads) is seen between ligamentous fascicles and bundles. b - transverse section of ligament; c - longitudinal section of a ligament, also illustrating the continuity between epiligament and periosteum (#); * artefactual space.

differently to other substances, such as Masson's trichrome (figure 2.3bc, and Appendix IV).

Although it has been illustrated that ligament and tendon may differ structurally, the common structural patterns of ligament and tendon suggest similar function. The clearest common function between ligament and tendon is force transmission. The ensheathment of similar structures in both facilitates gliding movements of the fibres, allowing them to stretch and bend against each other and the parallel arrangement of fibres allows forces to be channelled in specific directions. These flexible and directed structures are specialised for the passage of forces from one end of their structure to the other (Benjamin and Ralphs, 1998; Cooper and Misol, 1970). Along this path some of the force is lost through absorptive movements of the ligament/tendon, decreasing the loading of the structure to which the terminus of the ligament/tendon is attached (Benjamin and McGonagle, 2001; Clarke and Stechschulte Jr, 1998). Evidence of ligament/tendon function can therefore be seen not only in the tissues themselves, but in the tissues to which they are attached. Specifically relevant for this study are the adaptive properties of bone to variable loading. Bone thickness is reduced (bone is resorbed) when loading decreases, and increased when loading increases (De Ricqles *et al*, 1990; Kahn and Partridge, 1990; Lanyon, 1990; Sayers *et al*, 1987; Simmons, 1990). This may indicate not only the type of tissue that is attached to it, but the severity of force transmitted through it in relation to the neighbouring bone to which other tissues are attached. Structural differences between ligament and tendon may give further clues to understanding the design and positioning of ligaments. Fascicular spiralling has been reported along the length of tendons (Benjamin and Ralphs, 1997), but not in ligaments. Such a difference in fascicle orientation may suggest functional differences; for example, the spiralling fascicles within a tendon may assist with the transmission of greater force, aid in storage of elastic energy, and increase the optimal range of angulation for force transmission

(Benjamin and Ralphs, 1997). Conversely, the parallel orientation of ligamentous fascicles may lower the amount of force to failure (fracture), limit the storage of elastic energy and narrow the angle for optimal force transmission (ie. when all fibres are tensed). This may well limit the function of a single ligament, necessitating multiple ligaments at graduated angles to provide adequate support for some joints. A single ligament may then be considered to be functional in a very narrow arc through which the fibres are tensed by the load placed upon them, whilst beyond this arc they may be considered ineffective load bearers (figure 2.4a). The anatomical arrangement of ligaments about a joint may suggest what forces are supported and therefore what movements are possible at that joint (Short *et al*, 2002b).

In contrast to ligament and tendon, joint capsule is not clearly defined microscopically (figure 2.4b). The fibres of a joint capsule are not parallel, and cannot channel force in a specific direction. The lack of organisation of the fibres also reduces the load to fail, as few fibres can contribute to the absorption or transmission of force, contrasted by the near-uniform involvement of fibres in a ligament/tendon. It may then be suggested that the bone to which the capsule is attached indicates how the capsule is involved in force transmission through the carpus. Significantly large forces passing through the capsule, the force would reach the bone having very little absorbed and/or a fraction of the force focussed on a small area of bone. The higher loading upon the bone may result in responsive thickening of the capsular bone. Alternatively, if the area had sufficient ligamentous support the mechanical properties of the ligaments would reduce the load upon enthesial bone and possible reduce the required bone thickness (Hoogbergen *et al*, 2002; Lanyon, 1990; Sayers *et al*, 1987; Vashishth *et al*, 2003). As joint capsule lacks the structure necessary for adequate force transmission, it is clinically important to clearly identify what structures (or regions of structures, such as bones) are capable of supporting a



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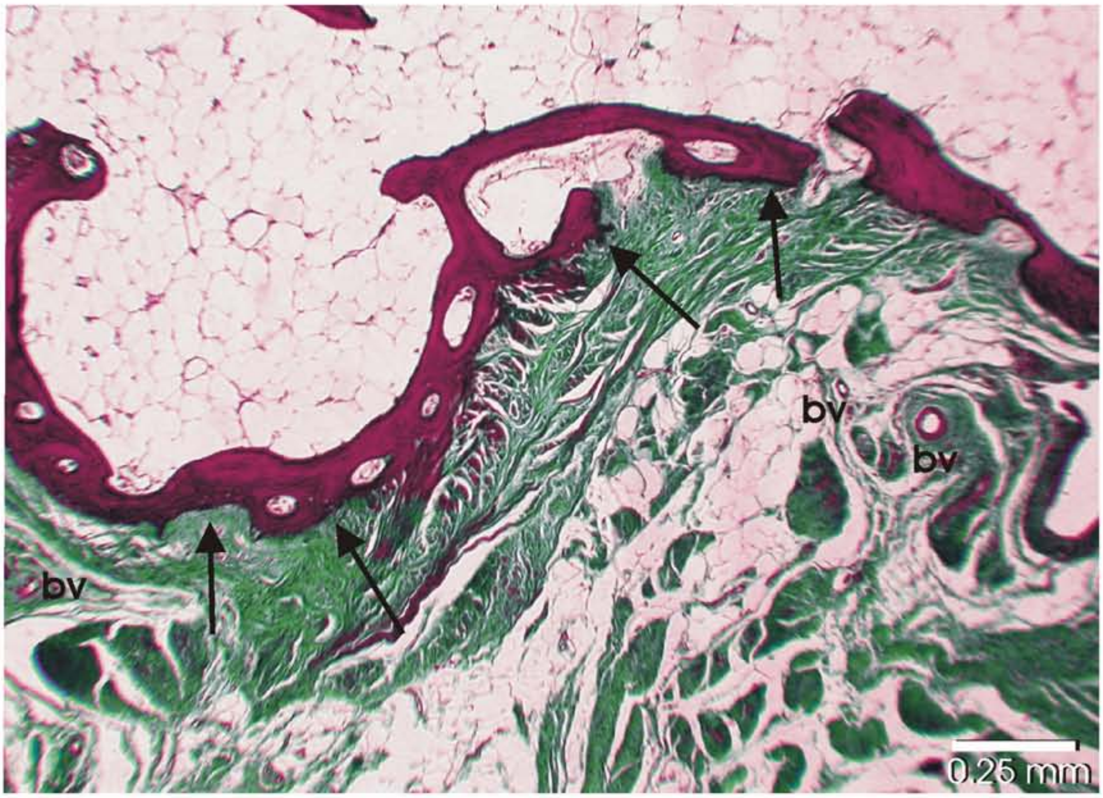


Figure 2.4 Tissues and force transmission. a - forces parallel to ligamentous fibres are spread across the bone (bold arrow), but the effectiveness of this mechanism is limited by the size and angle of the ligament, and the area of attachment. This creates an arc of optimal function for each ligament (x^0), outside of which force transmission is less effective (outside thin arrows)This "arc of tension" may be determined by measuring the angle (x^0) between lines (thin arrows) drawn from either margin of the ligament attachment to the mid-point of the ligament; b - joint capsule is composed of dense irregular connective tissue (green) and provides no means of directed force across the bony surface. Capsule is therefore not suited to force transmission but provides adequate support to other structures, such as blood vessels (bv). No structural modification near to the skeletal (red) attachment (arrows) confirms the inability to direct force to the bone; Modified Masson's Trichrome.

loads and which are not. Reconstructive procedures for wrist dysfunction are of particular interest, as the complexity of the carpus and its ligamentous support, coupled with a large, compartmentalised joint capsule (Berger, 1996; Berger, 1997; Garcia-Elias, 2001), makes structural identification difficult macroscopically and to a lesser extent, arthroscopically (Abe *et al*, 2003).

The region of bone (or other tissue) to which ligaments or tendons are attached is termed an enthesis (Benjamin *et al*, 2002; Suzuki *et al*, 2002) (figure 2.5). This specialised region enables forces transmitted through a ligament/tendon to be modified before reaching the supporting tissue, which is usually bone. The relationship between ligament/tendon and the supporting tissue, and hence the degree and type of force modification, is varied (Benjamin *et al*, 2002; Benjamin and Ralphs, 1998; Fournie, 1993). Site-specific differences have been observed by several authors (Benjamin *et al*, 2002; Canoso, 1998; Milz *et al*, 1998; Milz *et al*, 2001; Mine and Kawai, 1995; Misawa *et al*, 1994) and are commonly related to functional differences. More specifically, these functional differences may be translated into differences in the habitual loading of each specific tendon/ligament. Large habitual loads may be accommodated by increased enthesial bone thickness, increased enthesial fibrocartilage, sesamoid bones or bursae (Benjamin and Ralphs, 1999; Canoso, 1998). Conversely, small habitual loads may be expected to have thinner enthesial bone, less fibrocartilage and may be less likely to have other specialisations. Such differences suggest structural variation at the point of attachment, regardless of the tissue to which the tendon/ligament is attached. This suggestion is supported by the commonly reported mechanical principle that transmitted forces accumulate where two substances meet (Benjamin *et al*, 2002; Cooper and Misol, 1970; Forster, 1984). Much has been reported of the mechanisms that deal with the accumulation of forces at the musculotendinous junction, but this will not be discussed

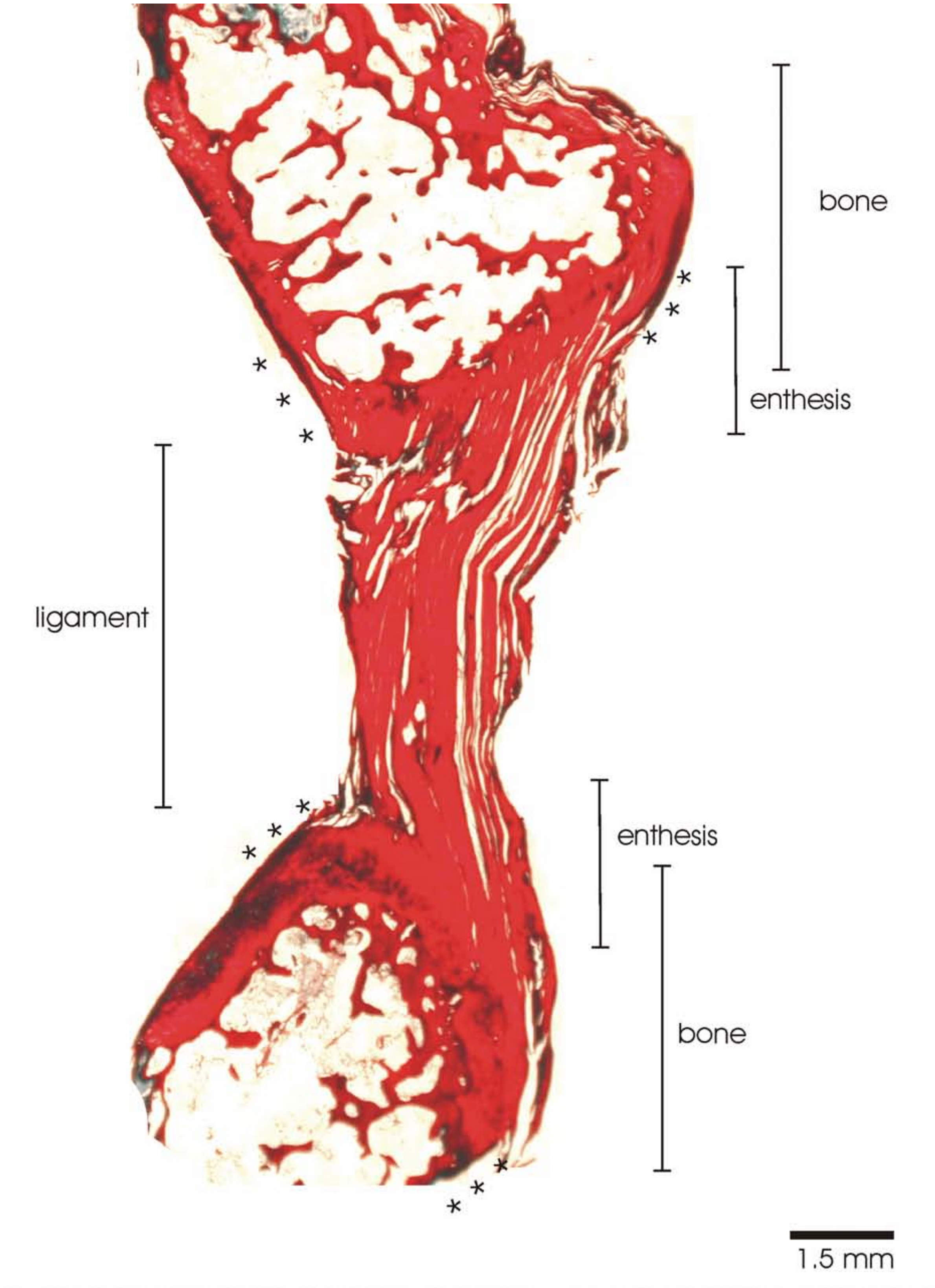


Figure 2.5 The Enthesis. The ligament is attached between two bones and the margins of these two tissues do not cross. The enthesis is not a tissue, but a combination of tissues grouped as a functional unit. There is therefore an enthesis at either terminus of a ligament that is composed of ligament, bone and supporting tissues such as endo-/epi-ligament. This specialised region can be modified to adapt to loading conditions of the constituent tissues, such as using fibrocartilage as an intermediate between ligament and bone where habitual loading is high. The adjacent para-enthesial regions (*) may be modified to further enhance the load bearing capabilities of the area. These modifications may include thickening of the para-enthesial bone and the development of bursae.

here. The tendon/ligament-bone junction, however, is of great interest. Much of the data reported focus on tendinous insertions. High rates of muscular trauma and the lengthy rehabilitation required following such injury requires better understanding of the entire musculoskeletal unit. Large ligaments, such as the patellar ligament, also have been the subject of many publications, but smaller ligaments are often left out. Despite this, it is clear that better understanding of the structure and function of particular ligamentous regions, such as the wrist, will increase understanding of their role in stabilising a particular area, and therefore promote increased effectiveness of clinical care for dysfunction in the area. In particular, joint reconstructions assume that the artificially placed graft will match the biological strength of the original. However, variations in ligament/tendon entheses suggest that one ligament/tendon may not satisfactorily replace another due to morphological differences.

Entheses have been characterised in accordance with morphological features and perceived functional roles, yet a consensus on enthesial nomenclature has not yet been reached (Benjamin *et al*, 2002). The simplest morphological characterisation provides two types of entheses, fibrous and fibrocartilaginous (Benjamin *et al*, 2002). Fibrous entheses consist of the collagen fibres of the tendon/ligament being attached either superficially into periosteum (in a juvenile individual, or when habitual loading is low), or deeply into the bone (in a mature individual, when habitual loading is high) (figure 2.6a). Fibrocartilaginous entheses contain a transitional area that creates four distinct zones (figure 2.6b). Proximal to the attachment are the fibres of the tendon/ligament; these are followed by a region of uncalcified fibrocartilage, then a region of calcified fibrocartilage, and finally bone. It may be considered (Benjamin *et al*, 2002; Canoso, 1998; Frowen and Benjamin, 1995; Gao *et al*, 1996) that the transitional zones of fibrocartilaginous entheses absorb and dissipate forces transmitted through the tendon/ligament, thus relieving the a

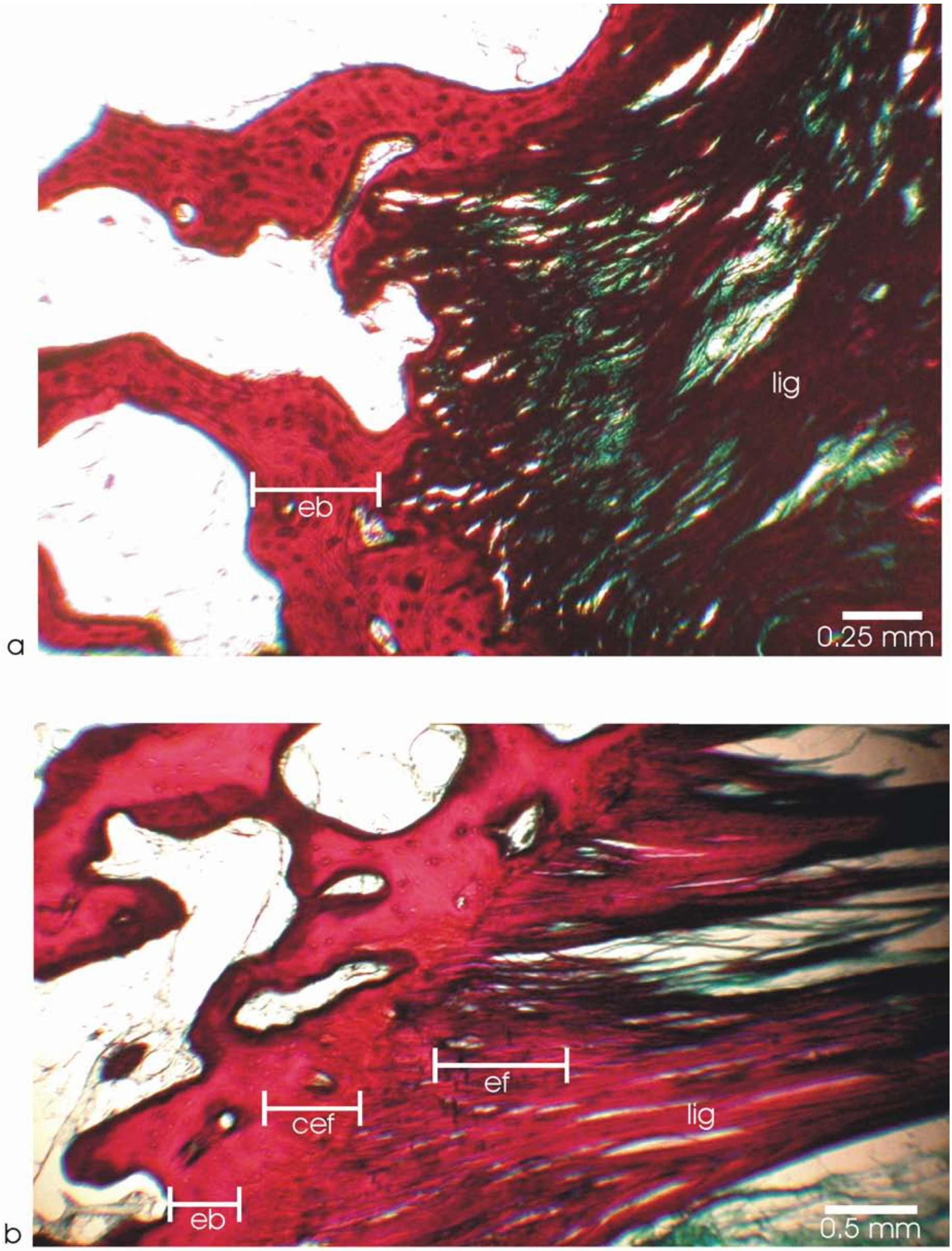


Figure 2.6 Enthesial Structures. a - ligament attached directly to bone; b - Ligament attached to bone with fibrocartilaginous enthesis; eb - enthesial bone, ef - enthesial fibrocartilage, cef - calcified enthesial fibrocartilage, lig - ligament; Modified Masson's Trichrome.

underlying bone of the full mechanical force. This notion is further supported by analyses of enthesial bone strength (Benjamin *et al*, 2002).

Studies (Gao *et al*, 1996; Kumai *et al*, 2002; Maffulli, 1990) suggest that enthesial bone has poor resistance to mechanical loading, and as such may account for the commonly observed avulsion fractures associated with joint trauma. However, this weakness may differ greatly with location, as do other enthesial structures (Benjamin *et al*, 2002; Canoso, 1998; Fournie, 1993). In addition to the specialisations of fibrocartilaginous entheses, to counter the poor mechanical strength of enthesial bone, other structures are positioned around the enthesial region (Benjamin *et al*, 2002) (figure 2.7). Most notable amongst these additional structures are bursae, which act to reduce the frictional impact on the bone (and other tissues, such as tendon) adjacent to the enthesial bone (Benjamin *et al*, 2002). In summation of these factors, the enthesis and its surrounding structures have been termed an “enthesis organ” (Benjamin *et al*, 2002). These para-enthesial regions may also have increased areas of cortical bone to cope with high habitual loading of the region. The para-enthesial regions are likely to have increased areas of cortical bone as the enthesial structures are unable to influence force transmission away from the enthesial region (Benjamin *et al*, 2002) (figure 2.8a). Therefore, any force that is transmitted through the region in any manner other than directly through the enthesis is likely to apply greater forces to the para-enthesial cortices (figure 2.8b). Any typical ligament can serve as an example of this; a force directed longitudinally along the fibres of the ligament is transmitted through to the bone. During this passage some of the force is absorbed by the ligament, reducing the subsequent load upon the bone (figure 2.9a). Force directed transversely through the ligament is not transmitted to either enthesis, nor is it dispersed across the terminus of either enthesis. Such a force is not absorbed or transmitted, so none of the mechanical strength of the ligament is utilised, and the ligament is most likely to fail

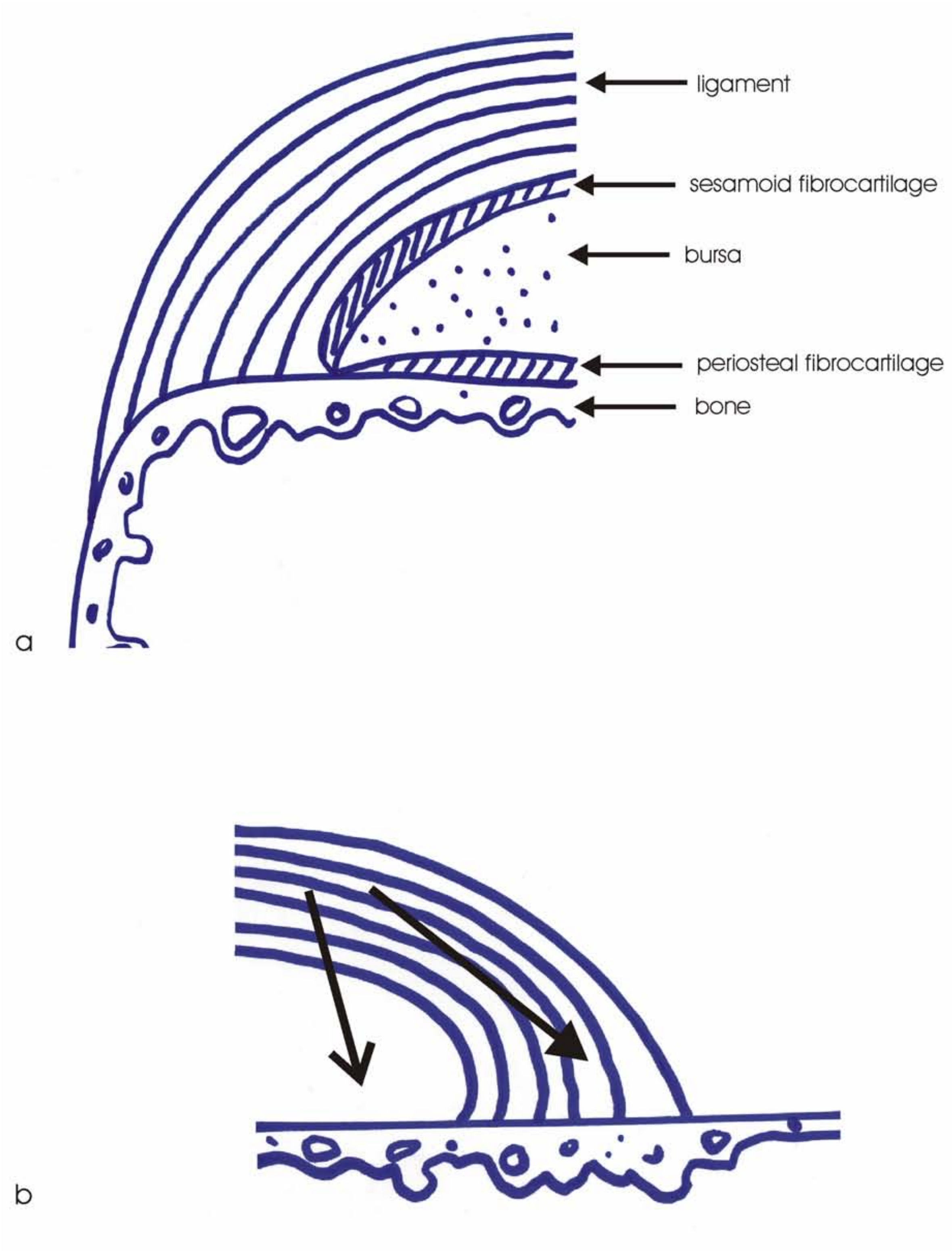
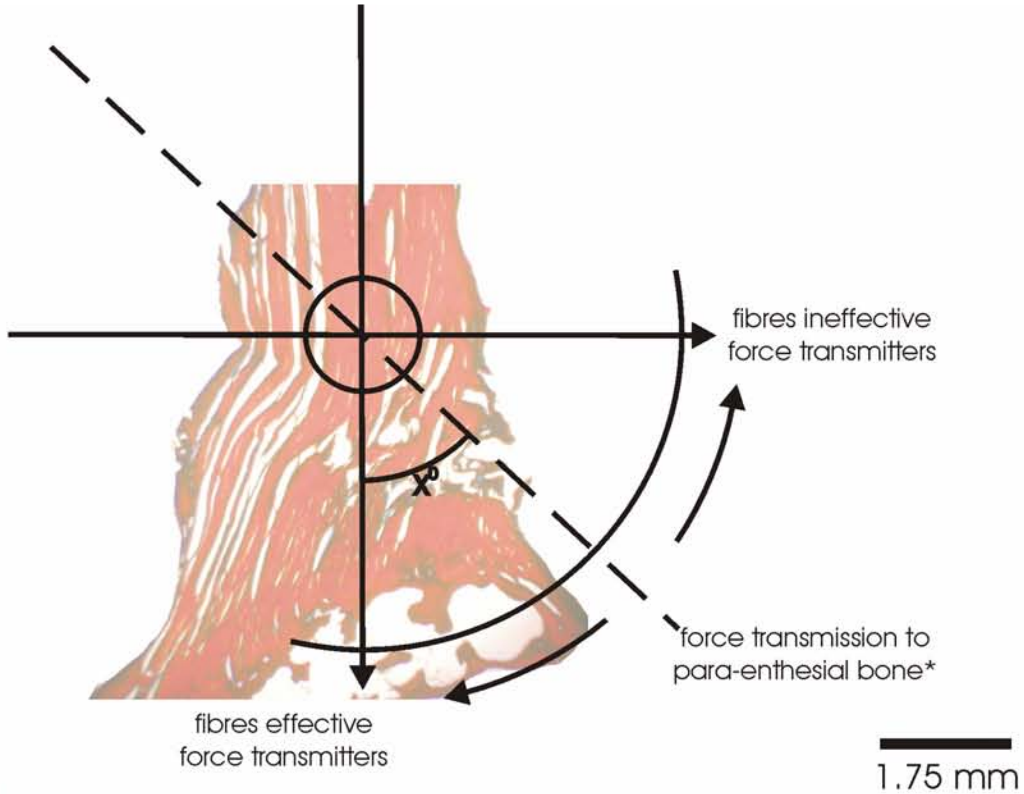


Figure 2.7 Para-enthesial support structures. a - in addition to enthesial adaptations, the para-enthesial region may contain structures to aid in force transmission. These may include layers of fibrocartilage (sesamoid or periosteal), and bursae to limit frictional damage (after Benjamin and Ralphs, 1997); b - para-enthesial force transmission may be suggested by thickening of para-enthesial bone, which may suggest poor alignment or function of ligamentous support in the area. In this case force normally transmitted along the ligamentous fibres (closed arrowhead) may be directed obliquely across the ligament and focused upon an area of para-enthesial bone (open arrowhead).



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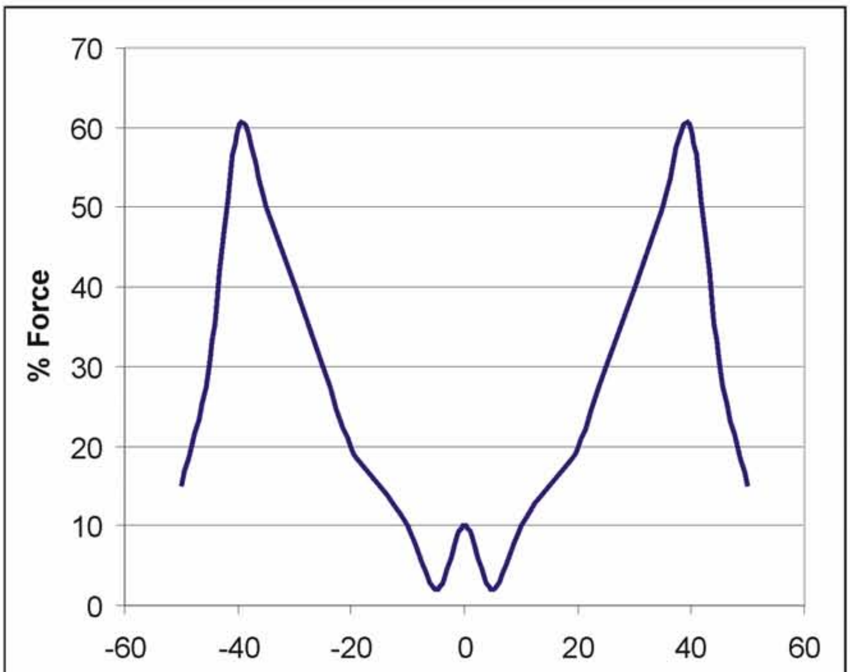

b

Figure 2.8 Enthesial force transmission. a - forces transmitted parallel to ligamentous fibres may be partially absorbed within the ligament, reducing the load upon enthesial bone. This load is spread across the enthesial bone surface, further reducing the overall load upon the bone; b - theoretical force distribution upon enthesial and para-enthesial bone with differing angle of transmission through a ligament. Zero degrees equates to a force transmitted parallel to the ligamentous fibres.

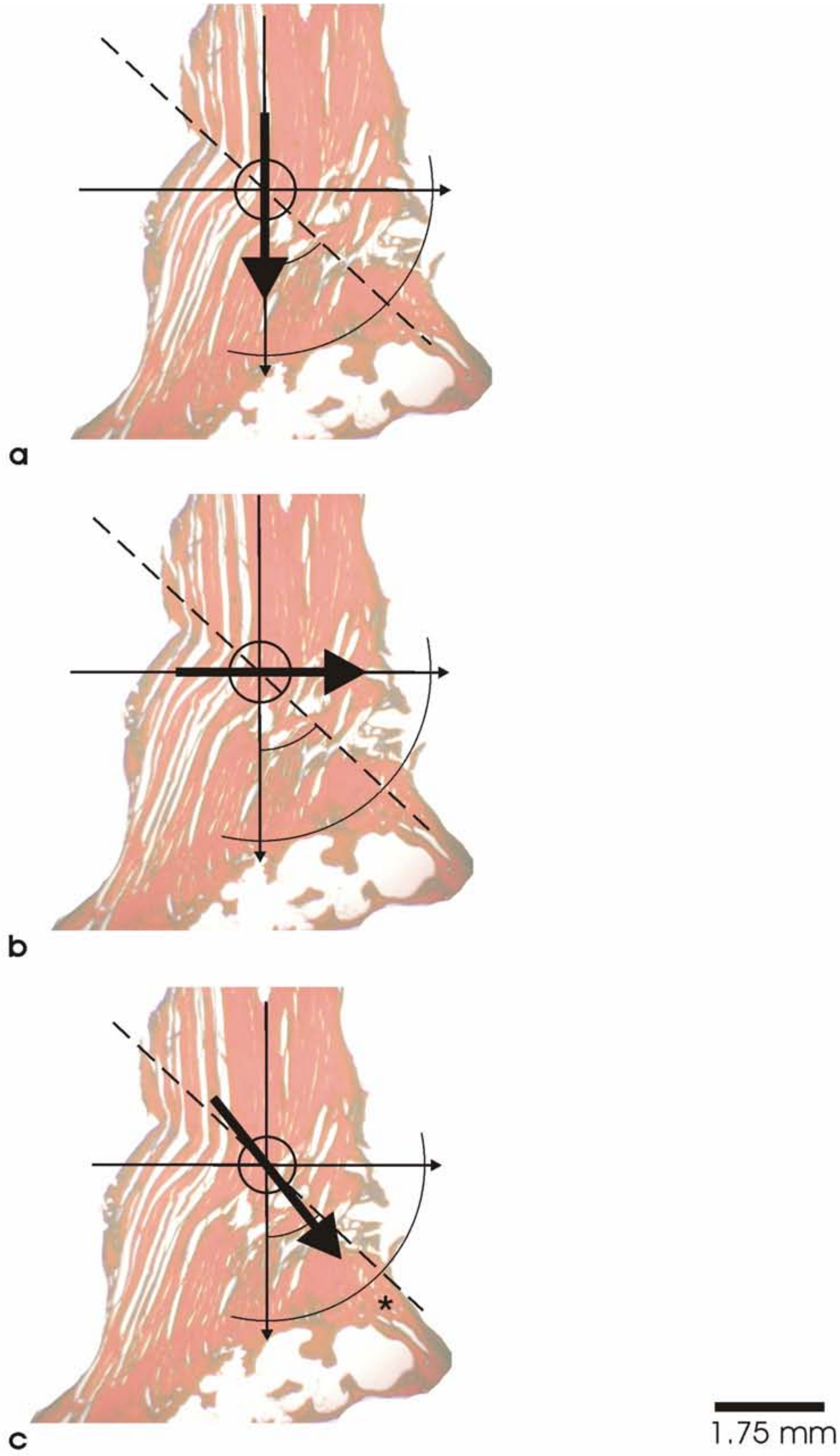

Figure 2.9 Enthesial force transmission. a - forces transmitted parallel to ligamentous fibres are dispersed evenly across the enthesial bone surface; b - forces transmitted perpendicular to the ligamentous fibres are not dispersed across the enthesial bone surface, nor are they focused upon a region of para-enthesial bone; the force is either absorbed by the ligament or by mechanical damage to the ligament and/or juxtaposed supporting tissues; c- forces transmitted at an angle oblique to the ligamentous fibres are partially dispersed across the enthesial bone surface, and partially focused (*) upon a region of para-enthesial bone.

(figure 2.9b). If the force is not transmitted longitudinally, but obliquely, through the ligament, then a percentage of the force will be transmitted to a point beyond the enthesis (figure 2.9c). This force will have been transmitted by fewer fibres (less absorption) and will not have been dispersed by the enthesis, and hence will be focussed upon a small area of para-enthesial bone. In response to this scenario the para-enthesial cortices may be of greater area, which is suggestive of a greater capability to absorb and transmit force (Benjamin *et al*, 2002). Furthermore, if para-enthesial cortices develop greater area in response to forces that are not transmitted through the entheses, regional differences in the para-enthesial area may be observed. Anatomical design and environmental factors (such as limb use) may limit the angles at which force may enter a region, and hence influence para-enthesial cortical development. Greater cortical thickness around an enthesis may suggest greater force transmission in one direction, or a narrow range of degrees, in comparison to many directions or a wide range of degrees (figure 2.10). To counter the reliance on bone adaptation to para-enthesial loading, a structure such as the wrist may counter variable angles of loading by the development of a more expansive ligament array. Potential weak spots in the fibrous support of a joint (capsular) may develop more specific stabilisers (ligament) to minimise that potential for para-enthesial force transmission (figure 2.10b).

Many regional differences have been reported throughout the body, particularly of tendinous entheses, suggesting that these tissues undergo local specialisation to suit the habitual loading of their region (Benjamin *et al*, 2002; Canoso, 1998; Francois *et al*, 2001; Kumai and Benjamin, 2002; Kumai *et al*, 2002; Milz *et al*, 1998; Milz *et al*, 2001). Under different loading conditions, different features have been observed at entheses and in the structures in the immediate vicinity of the entheses (Canoso, 1998). Some features, such as large fibrocartilaginous regions, bursae and increased enthesial dimensions are suggestive

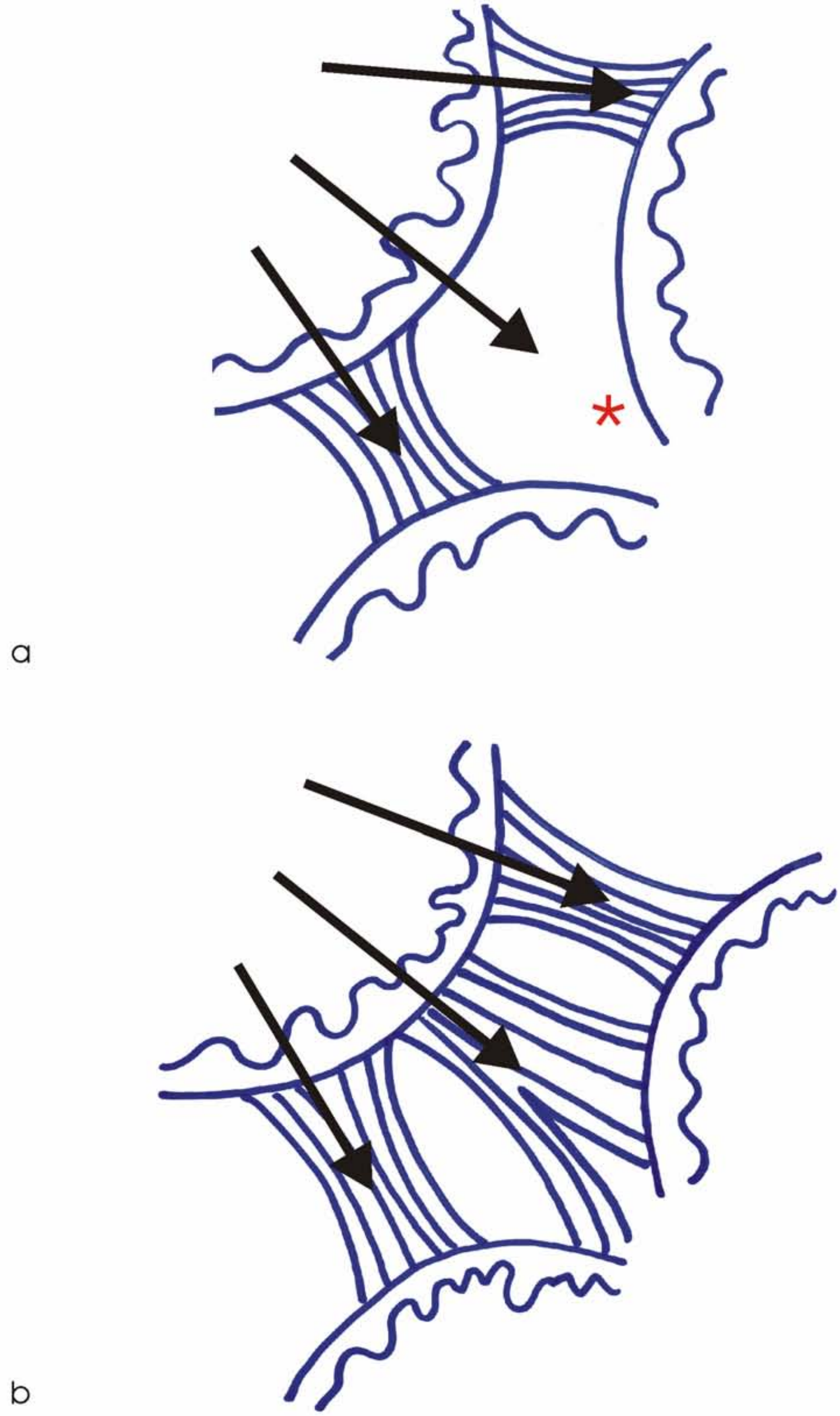

Figure 2.10 Adaptation to load. a - gaps between ligaments may place para-enthesial bone under increased stress, especially where the "normal" pattern (outer arrows) of force transmission has been altered (middle arrow). This may produce a "weak spot" in the structures (*) where damage is more likely to occur; b - additional ligamentous support may eliminate such a weak spot by aiding in the even transmission of forces to the bone.

of increased loads, whilst little fibrocartilage, no supporting structures and limited enthesial dimensions are suggestive of less loading upon the region (Benjamin and Ralphs, 1998). These reports and understanding of the detailed structure of ligament/tendon suggest that a similar understanding of wrist ligamentous structure is required. It may be hypothesised that ligaments under greater habitual loading may contain fibrocartilaginous epitheses, whilst those under less habitual loading may simply have fibrous epitheses. Accessory structures, such as bursae, or increased enthesial dimensions may indicate greater loading upon a particular ligament and hence increase the importance of retaining the support of that ligament. Less evidence of critical structures may imply expediency of certain ligaments, and hence clarify the patterns of surgical repair. In surgical repair or modification of these ligamentous supports it is therefore important to have a good understanding of the structural support a particular ligament is endowed. Attempting to subject a fibrous epithesis to the higher habitual loading expected of a fibrocartilaginous epithesis may place undue stress on the structure post-operatively. If this were the case, an attempted return to normal function may result in failure of the ligament. Proper consideration should therefore be given to the functional design of the ligaments supporting the wrist.

If force transmission routes were focussed upon bone of insufficient thickness, adaptation of the bone to those forces may occur. This is most likely in young healthy persons (Bailey and Mansell, 1997; Belmonte-Serrano *et al*, 1993; Young *et al*, 2002), but less likely the older the person. Adaptation is highly unlikely in those with systemic arthritic disorders (Belmonte-Serrano *et al*, 1993), the population of whom are most likely to be recommended for reconstructive wrist surgery (Pellegrini, 1992; Rogers and Watson, 1990; Rothschild, 1996).

The orientation of the ligamentous support of the wrist must be understood in order to establish clear comprehension of carpal mechanics. In order to reduce the subjectivity of dissection-based investigations, histological evidence may assist in discrimination between ligament and joint capsule. Failure to acknowledge the gross similarity of these tissues may rationalise the great degree of observed difference in the literature.

Ligament and joint capsule are histologically distinct tissues (Benjamin and Ralphs, 1998; Canoso, 1998). Epiligament separates the dense-regular connective construct of a ligament from the dense-irregular joint capsule. The dominant component of epiligament is loose connective tissue (Benjamin and Ralphs, 1998). Despite this, with the exception of large ligaments, there is very little to differentiate ligament from joint capsule macroscopically. The variation to Masson's Trichrome staining technique (Appendix IV) clearly demarcates the division between soft connective tissues and bone. Furthermore, ligament and capsule are differentiated by both fibre orientation and density, and staining (another measure of fibre density). Structurally, the division between ligament and joint capsule may be demarcated by the epiligament (Benjamin and Ralphs, 1997). The epiligament differs in structure from both joint capsule and ligament, and hence provides an accurate marker for dividing the two tissue types. The bone to which various connective tissues are attached can therefore be measured with some degree of accuracy.

There has been little published discussion of cortical bone variation at various types of junctions. Of the few discussions, most suggest a trend between cortical bone area and the type of tissue that is attached to the bone (Benjamin *et al*, 2002; Canoso, 1998; Cooper and Misol, 1970; Fournie, 1993; Hahn *et al*, 1997; Hoogbergen *et al*, 2002; Suzuki *et al*, 2002). This relationship has not been examined any further than a suggestion in the reviewed literature. However, pathological reports provide useful discussion of the role cortical bone plays at an enthesis. When habitual loading increases to such an extent that some part of the enthesial organ is disrupted, a metabolic response is mounted in the cortical bone (Kumai and Benjamin, 2002). If this occurs in the plantar fascia, a heel spur is formed (Kumai and Benjamin, 2002). If force is pathologically increased through a joint, as in many arthroses, osteophyte formation results (Resnick, 1984). All of these metabolic responses are the body's attempt to reinforce the apparently failing strength of the particular structure. From this it may then be extrapolated that non-pathological bone displays similar responses to loading, in this case the habitual load transmitted through a ligament, joint capsule, or articular surface via the articular cartilage. It may then be hypothesised that joint capsule will transmit very little force, and hence the cortical bone to which it is attached will be smaller in area than the bone to which other tissues are attached (figure 2.11). The force that reaches the cortical bone to which ligament and articular cartilage are attached may well determine the area of cortical bone observed. This relies greatly on the absorptive capability of articular cartilage. It may be hypothesised that the forces transmitted across a joint surface, and hence through the articular cartilage are:

1. large but greatly absorbed by the articular cartilage, making no difference to the area of cortical bone observed,
2. large enough that cartilage cannot absorb a significant proportion of the force, resulting in increased cortical bone area,
3. either of the above, but the force transmitted through ligament is greater, resulting in greater cortical bone area for ligamentous attachment than for cartilaginous attachment.

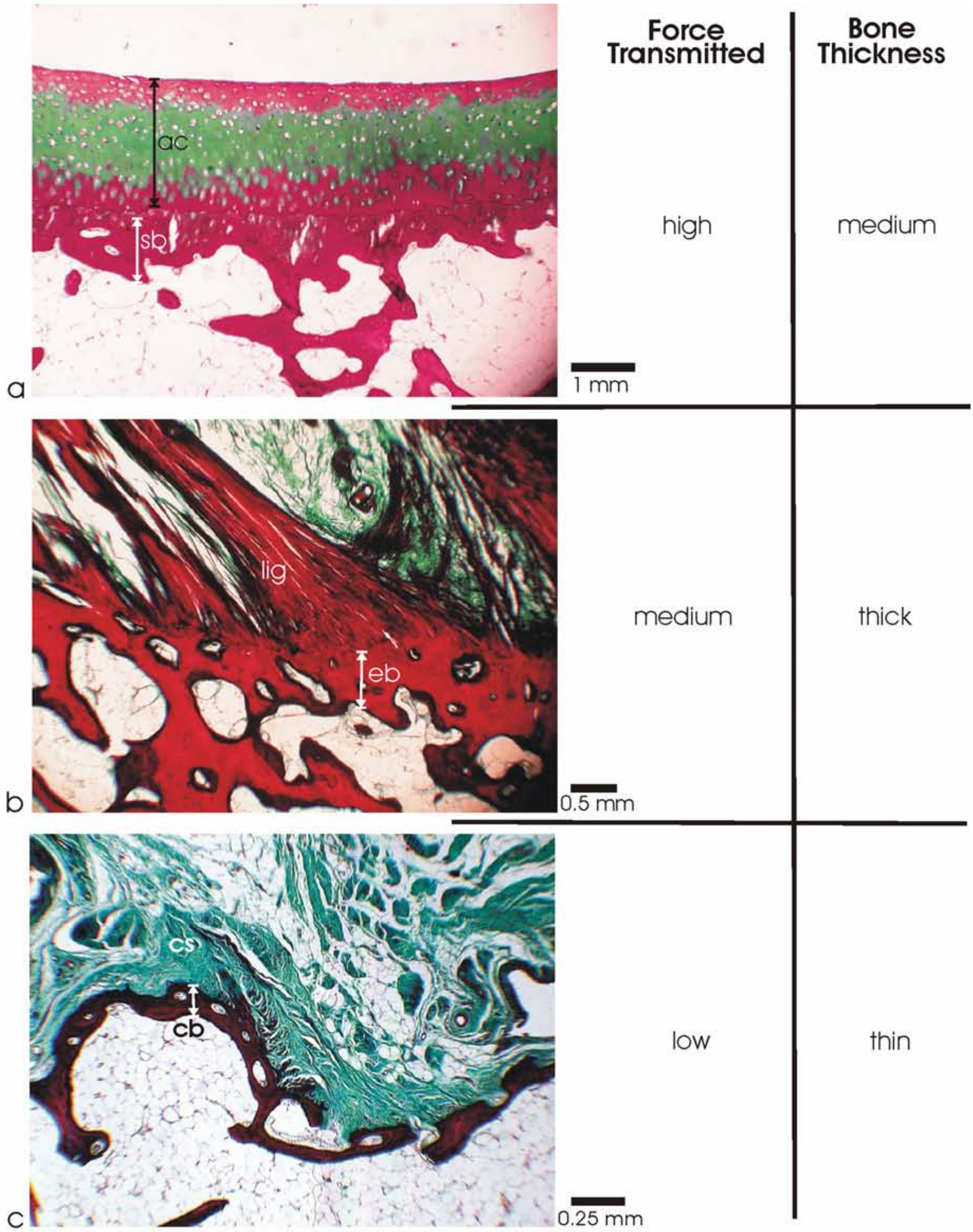

Figure 2.11 Theoretical effect of force transmission on enthesial bone thickness. a - subchondral bone (sb) is protected from the repetitive heavy loading of the joint by the layer of articular cartilage (ac). The ability of cartilage to absorb force has been well documented (see text for references), suggesting that the thickness of subchondral bone may not need to be great; b - Ligament (lig) transmits force from one side of a joint to another, and focuses that force upon the enthesial bone (eb) at the ligamentous terminus. Enthesial modifications may dampen the force, but the enthesial bone is still expected to be thickened in response to the loading; c - joint capsule (cs) is not designed for force transmission, suggesting that force is not focused on the bone to which capsule is attached (cb). This capsular bone is expected to be thinner than subchondral and enthesial bone in most cases; all photos Modified Masson's Trichrome.

A result indicating greater cortical bone area for articular cartilage attachment would suggest greater force through the joint surface than ligament, and increased requirement for cortical support due to the greater force transmission. To the contrary, a result suggesting greater cortical bone area for ligamentous attachment would suggest greater force transmission through ligament than joint surface, or greater efficiency of force absorption by articular cartilage. The latter scenario cannot be quantified through the proposed investigation, but numerous reports attest to the considerable absorptive capabilities of articular cartilage (Bullough and Jagannath, 1983; Fulkerson *et al*, 1987; Mankin, 1982; Mankin, 1993; Shrive and Frank, 1995; Weiss, 1979).

The enthesial support afforded the intercarpal joints is rarely discussed but may be of some significance in identifying those at risk of wrist dysfunction. If particular areas of the carpus are supported by less cortical bone than others, then altering the loading patterns through surgical intervention may have negative results on post-operative wrist function. This concept is quite pertinent to current surgical practice, as removal of carpal components and fusion of others may increase force transmission through regions with inappropriate cortical support. Functional regions may therefore be defined for the carpal bones observed. The regions will suggest where a bone is best able to absorb or transmit force (articular and ligamentous regions), and where special mechanisms do not exist for force absorption or transmission (capsular regions). The definition of these regions may assist in the design or modification of surgical procedures for wrist dysfunction.

2.1.1 Aims

The aims of this component of the study are to determine an accurate means of differentiating between ligament and joint capsule in the wrist. Localised specialisations for each of the observed tissue types will be quantified and analysed to determine whether the difference between the tissues can be quantified. It is hoped that a multi-dimensional approach may provide a conclusive means of tissue differentiation. The observed variations will be documented for each of the carpal bones sectioned.

2.2 Materials

Cadaveric specimens were arbitrarily selected from the Ray Last Anatomy Laboratory, Department of Anatomical Sciences, the University of Adelaide. Permission for their use, as granted by the Head of the Department of Anatomical Sciences, was covered by the Anatomy Act of South Australia (1983). All specimens were previously embalmed through the normal procedures of the Ray Last Anatomy Laboratory (see Appendix I).

Paired specimens (right and left hands, n = 30 hands) were split into two groups. The left hand of each pair was analysed by gross dissection, the analysis of which is discussed elsewhere (see Chapter 3). The right hand of each pair was processed for histological analysis. Thus, 15 right hands were analysed histologically.

2.4 Methods

The specimens reserved for histological analysis were processed individually to enable fine control over each step of the process (see Appendix II). Individual processing also enabled the protocol to be completed at much faster rate, reduced the volume of reagents required and eased the logistical strain of the procedure.

The selected specimens were cut in similar fashion to minimise the amount of tissue to process, and to allow each specimen block to be accurately orientated on the sliding microtome. Each specimen was cut in transverse section through the proximal third of the metacarpals, and through the distal radio-ulnar joint, thus creating a single block containing the entire carpus. This block was cut in half in the coronal plane and in the sagittal plane, dividing it into four blocks. For each case, the radio-dorsal and radio-palmar blocks were processed whilst the ulnar-dorsal and ulnar-palmar were reserved for future examination.

The selected blocks were decalcified, double-embedded in paraffin wax and cast in individually-manufactured moulds, as described in Appendix II. The sectioning and staining processes, and their rationale, are described in Appendices III and IV respectively. Digital images of each slide were taken as described in Appendix V.

For individual histological images, bone was divided into regions in accordance with the type of tissue attached to the bone. Bone was either deemed subchondral (supporting articular cartilage), enthesial (a ligamentous attachment site), or capsular (a joint capsule attachment site) (figure 2.12). The length of each functional area was

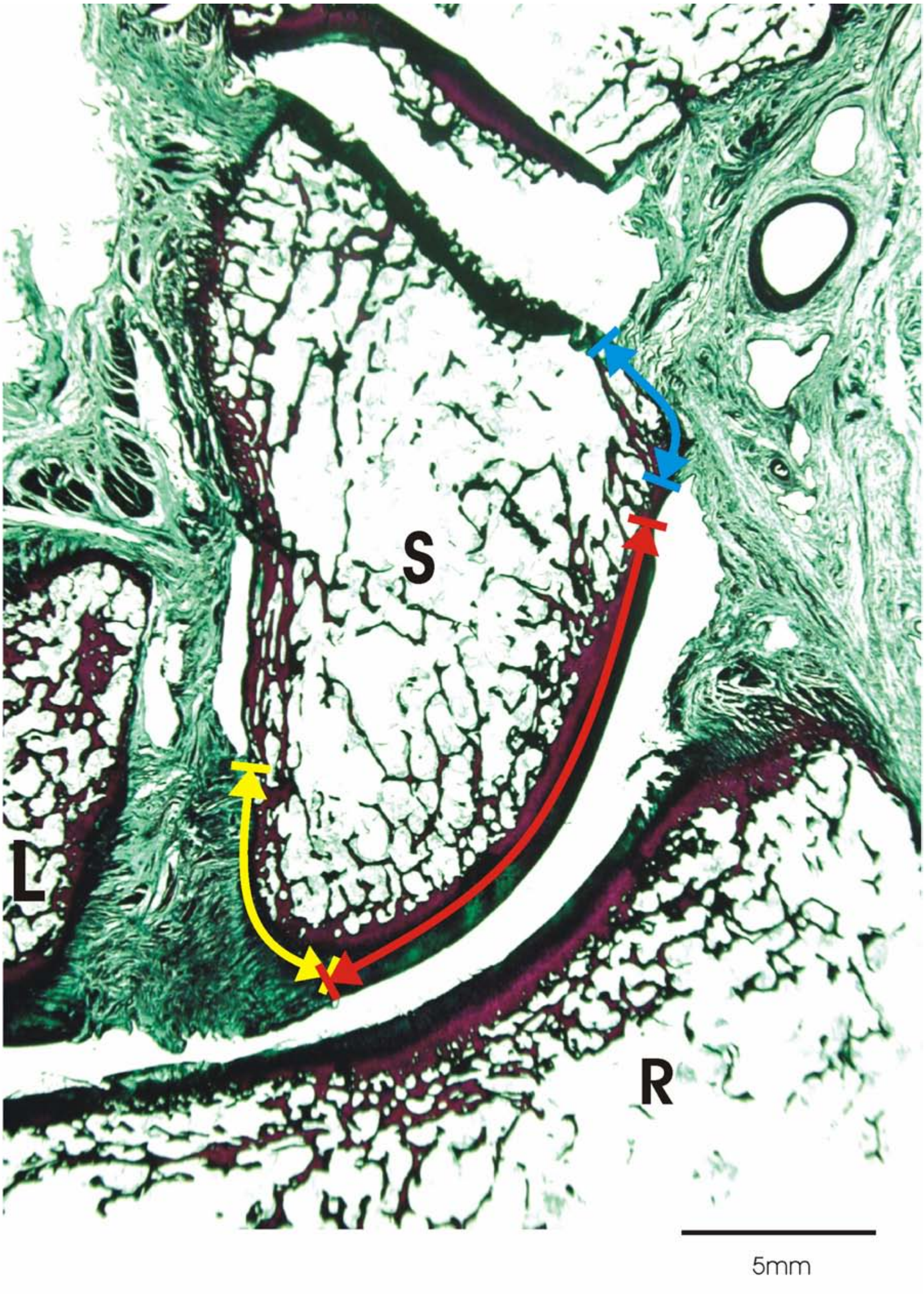

Figure 2.12 Osseous attachment of various tissues. Yellow arrow - ligamentous attachment, red arrow - cartilaginous attachment, blue arrow - capsular attachment; S - scaphoid, L - lunate, R - radius, Modified Masson's Trichrome (see Appendix IV), x10.

measured digitally, followed by a measure of the area and perimeter of the bone in each division. All of the digital measurements were done using Image J (Rasband, 2002), as described in Appendix VI.

The measures for each division were collated and analysed. All original measurements were used to generate mean values for each of the collations to be analysed. Statistical analyses were then used to establish the relationship between various tissues and the bone to which they are attached. The same analyses were then performed for individual bones, and anatomical margins of each bone.

Descriptive statistics were used to produce a general description of the data in each of the analyses. Single factor analysis of variance (ANOVA) was then used to determine the statistical significance of the suggested relationships between bone area and its role in providing articular support, attachment sites for ligaments or attachment sites for the joint capsule. The same procedure was used to determine any statistical significance between carpal bones (scaphoid vs trapezium vs lunate), and between regions of a single carpal bone (eg. radial aspect of scaphoid vs ulnar aspect of scaphoid).

2.4 Results

2.4.1 General Data

Three histologically distinct tissue types were attached to bone in the specimens observed (figure 2.13). The length of each attachment site in each histological section was measured. The greatest length of bone per section was devoted to articular surfaces (subchondral) (7.606±2.745mm). This mean was significantly greater than that for ligament (enthesial) and capsule (capsular) attachment lengths ($p < 0.05$). There was no statistically significant difference ($p > 0.5$) between the mean lengths for capsular (4.554±2.355mm) and ligamentous (enthesial) (4.368±1.738mm) attachment sites (figure 2.14).

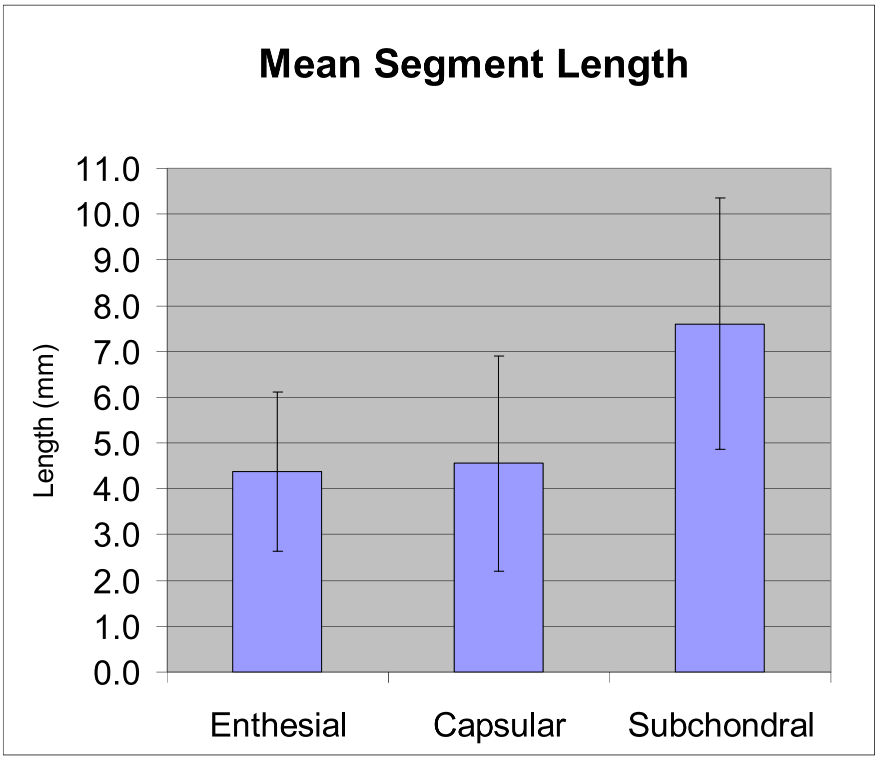

Figure 2.14 Mean Segment Length. Average length of bone to which various tissues are attached.

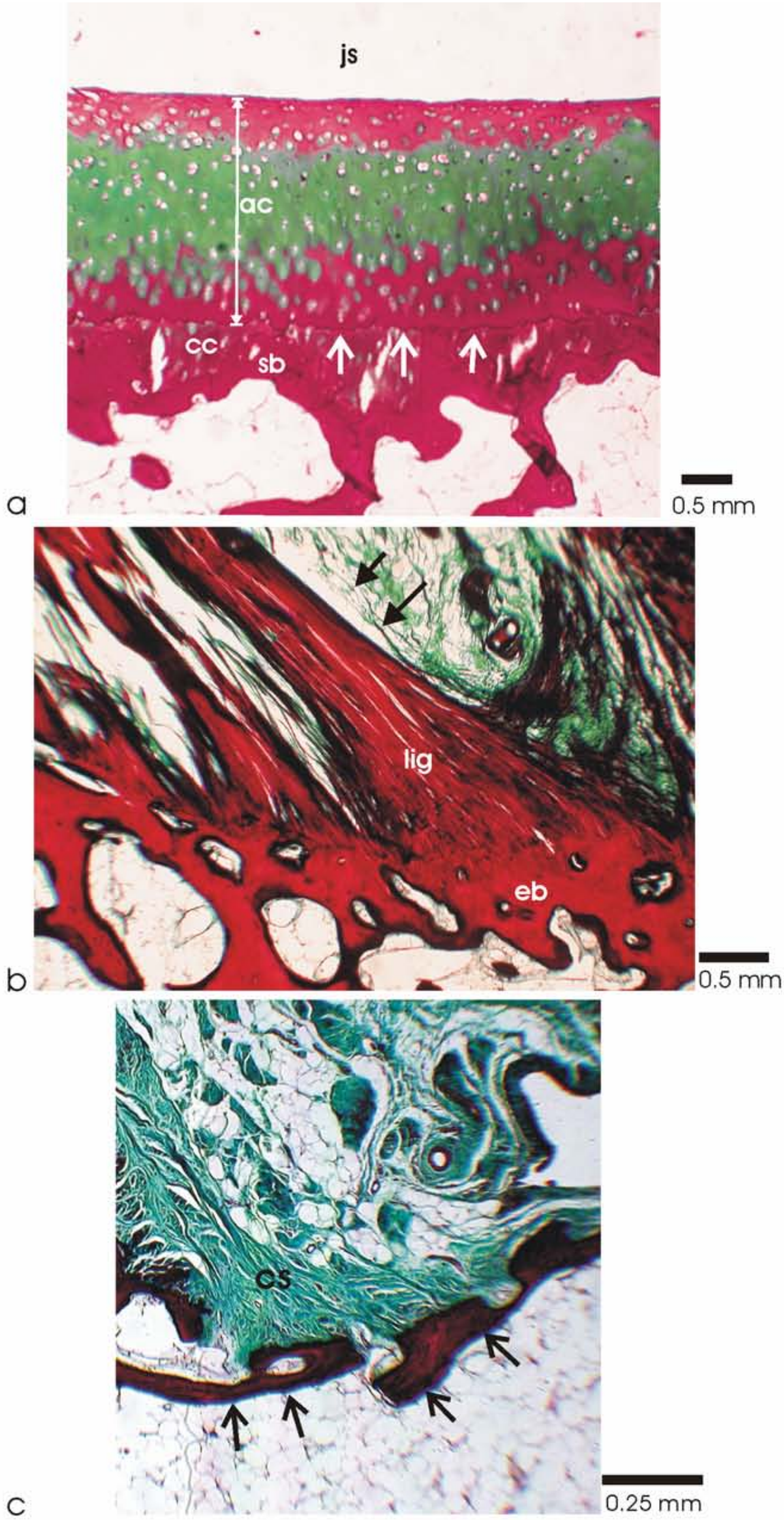

Figure 2.13 Histological differentiation of tissue types. a - articular cartilage (ac) and the underlying subchondral bone (sb), identified by adjacent joint space (js), chondrocytes, and separated from calcified cartilage (cc) and subchondral bone by the tidemark (open arrows); b - ligament (lig) attached to enthesial bone (eb), forming the enthesis. The ligament (stained red), with parallel fibres, was separated from joint capsule (green) by a thin layer of loose connective tissue, the epiligament (closed arrows); c - joint capsule (cs) was attached to capsular bone (open arrows) without any structural modifications, and was characterised by the irregular arrangement of the fibres; Modified Masson's Trichrome.

The mean perimeter of subchondral bone was larger (16.399±5.963mm, $p < 0.05$) than capsular (9.662±4.942mm) and enthesial (10.057±3.896mm) bone. There was no statistically significant difference between the mean perimeters of capsular and enthesial bone ($p > 0.5$) (figure 2.15).

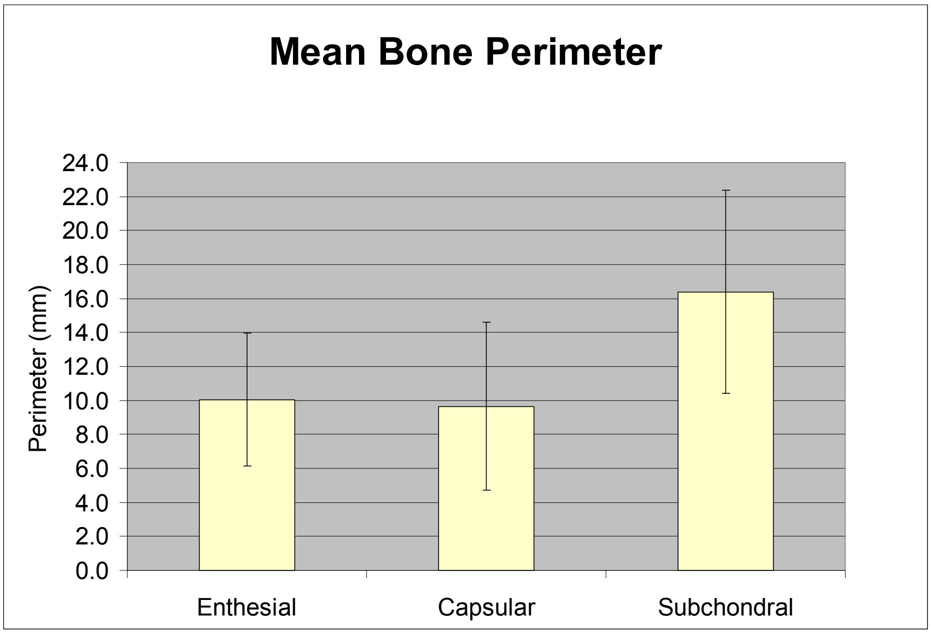

Figure 2.15 Mean Bone Perimeter. Average perimeter of bone to which various tissues were attached.

The mean area of subchondral bone was larger (2.39±1.17mm^2) than enthesial bone (1.975±1.21mm^2), but the statistical significance of this difference was marginal ($p < 0.056$). Mean enthesial bone area was greater than mean capsular bone area (0.799±0.587mm^2), with a high degree of statistical significance ($p < 0.05$) (figure 2.16).

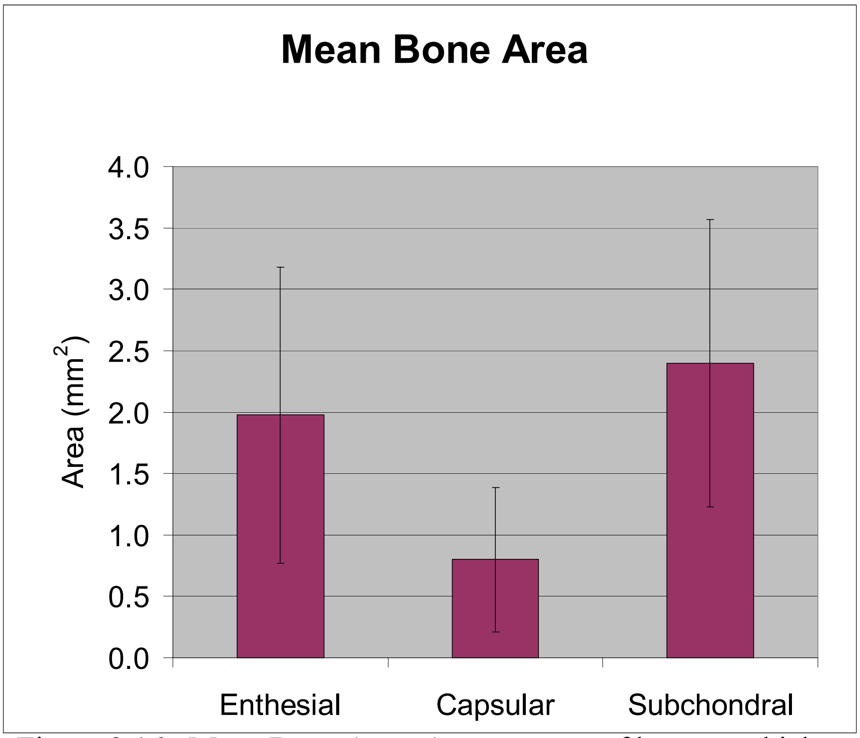

Figure 2.16 Mean Bone Area. Average area of bone to which various tissues are attached.

The relative areas of bone were calculated as a function of the lengths of bone measured (figure 2.17). These relative indices therefore gave a measure of the area of bone (mm^2) per millimetre of tissue attached to the bone. The mean relative area of enthesial bone (0.4403±0.167mm^2/mm) was larger than that of subchondral bone (0.3127±0.083mm^2/mm). The difference was statistically significant ($p < 0.05$). The mean relative area of subchondral bone was greater than that of capsular bone (0.1739±0.088mm^2/mm), and the difference was statistically significant ($p < 0.01$).

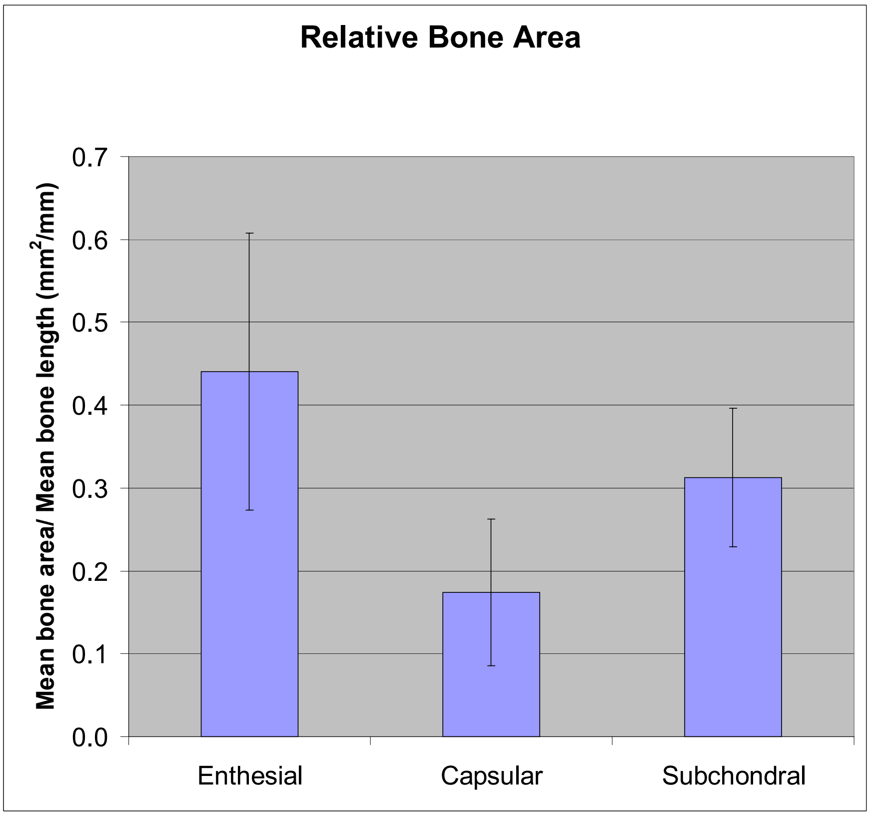

Figure 2.17 Relative Bone Area. Mean bone area divided by mean cortical bone length to which various tissues are attached.

2.4.2 Scaphoid Data

Data were pooled for each carpal bone to assess between bone differences. The scaphoids measured averaged significantly greater subchondral bone lengths (7.94±3.54mm) than enthesial (3.91±1.60mm; $p < 0.05$) or capsular (3.94±2.24mm; $p < 0.05$) bone lengths, whilst enthesial and capsular bone lengths were not significantly different ($p > 0.05$). Similarly, bone perimeter measures were significantly greater for subchondral bone (17.19±7.65mm), against enthesial (9.15±3.66mm; $p < 0.05$) and capsular (8.18±4.86mm; $p < 0.01$) bone perimeters, whilst there was no difference ($p > 0.05$) between enthesial and capsular bone perimeters (figure 2.18).

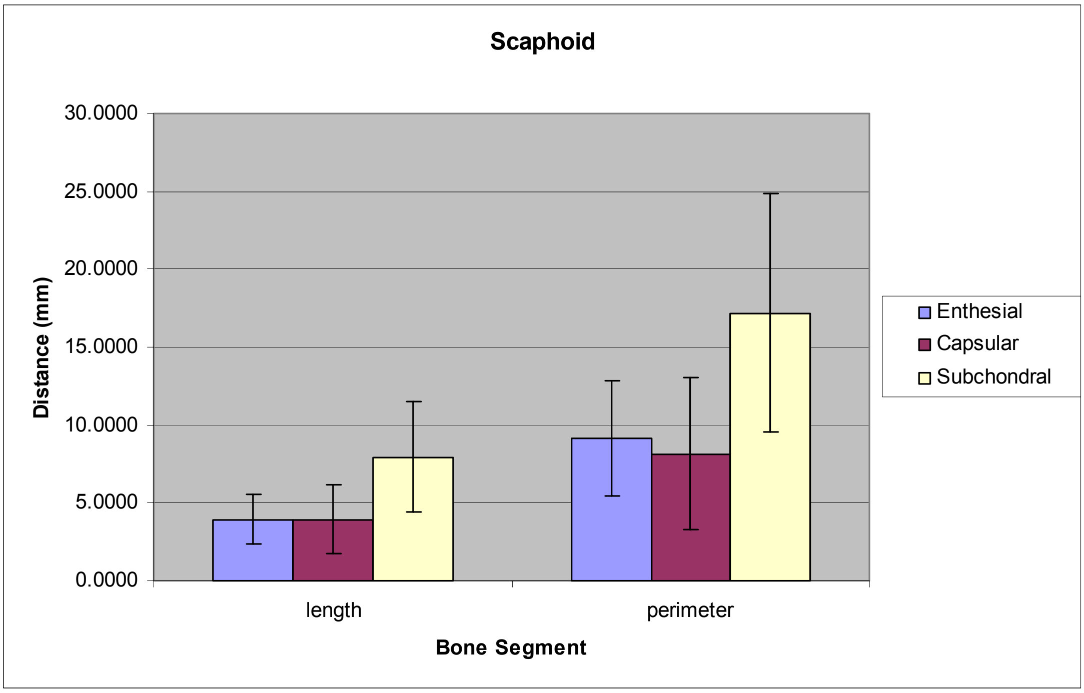

Figure 2.18 Scaphoid cortical bone measurements. Mean measures of bone segment length and perimeter to which various tissues were attached.

2.4.3 Trapezium Data

Subchondral bone lengths (7.96±1.75mm) were greater than enthesial (4.56±1.88mm) or capsular (5.46±2.37mm) bone lengths, but the difference was only statistically significant ($p < 0.05$) between subchondral and enthesial bone lengths. Similarly, perimeter measures for subchondral bone perimeters (17.21±3.70mm) were greater than enthesial (10.53±4.31mm) and capsular (11.89±4.47mm) bone perimeters, but the difference was only statistically significant ($p < 0.05$) between subchondral and enthesial bone perimeters (figure 2.19).

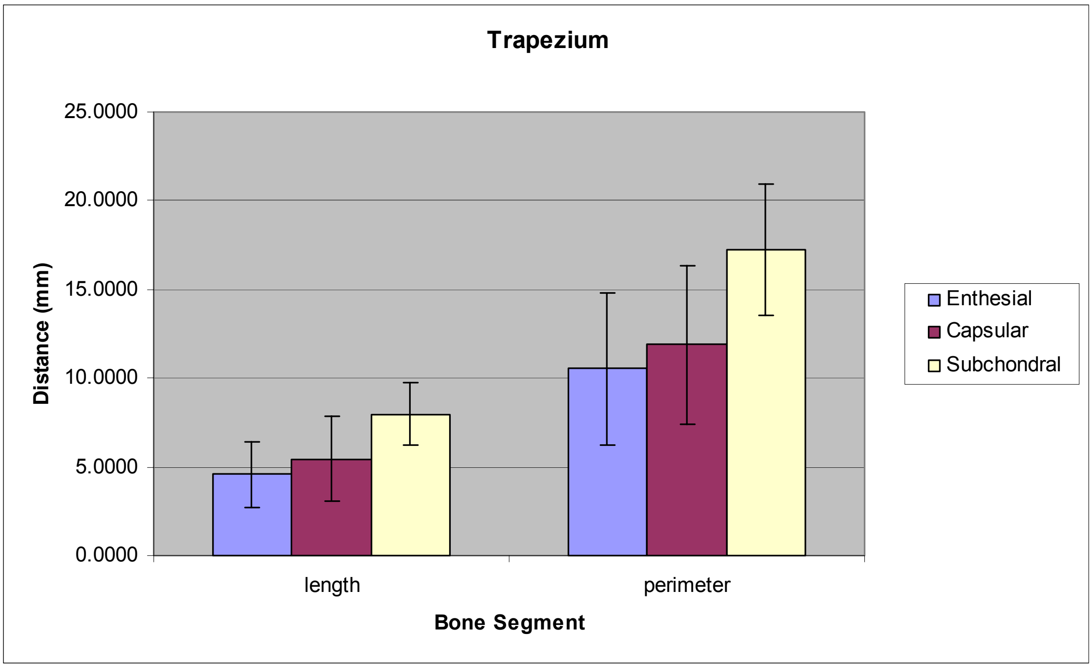

Figure 2.19 Trapezium bone measurements. Mean measures of bone segment length and perimeter to which various tissues were attached.

2.4.4 Lunate Data

Enthesial bone lengths (5.67±0.97mm) were greater than subchondral (4.72±0.83mm) and capsular (3.75±0.72mm) bone lengths, but the difference was only statistically significant ($p < 0.01$) between enthesial and capsular bone lengths. Similarly, perimeter measures for enthesial bone (12.36±1.81mm) were greater than subchondral bone (9.72±0.97mm) and capsular (7.54±1.87mm) bone perimeters. Enthesial bone perimeters were significantly greater than subchondral ($p < 0.05$) and capsular ($p < 0.01$) bone perimeters, whilst subchondral bone perimeters were significantly greater than capsular bone perimeters ($p < 0.05$) (figure 2.20).

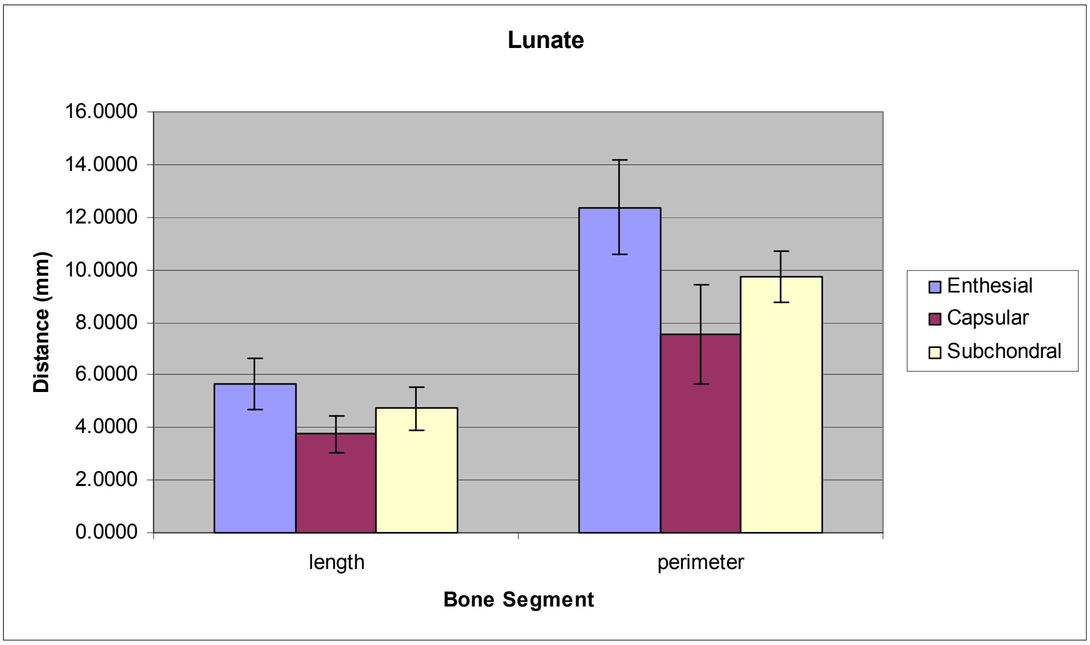

Figure 2.20 Lunate bone measurements. Mean measures of bone segment length and perimeter to which various tissues were attached.

2.4.5 Area and Relative Area Measures

Measures of area were made for the bone to which the various tissues were attached (figure 2.21). The mean area for subchondral bone of the scaphoid (2.724±1.44mm^2) was significantly greater than those for the enthesial (1.546±0.889mm^2; $p < 0.05$) and capsular bone (0.633±0.601mm^2; $p < 0.01$) of the scaphoid. Enthesial bone means were significantly greater than the capsular bone means ($p < 0.01$). When mean bone areas relative to segment length were calculated, the relationship between tissue type and bone area changed on the observed scaphoids (figure 2.22). Enthesial bone (0.387±0.127mm^2/mm) had a greater, but not significantly ($p < 0.8$), relative area than subchondral bone (0.342±0.104mm^2/mm). Both enthesial ($p < 0.01$) and subchondral ($p < 0.05$) bone had a significantly greater relative area than capsular bone (0.151±0.054mm^2/mm).

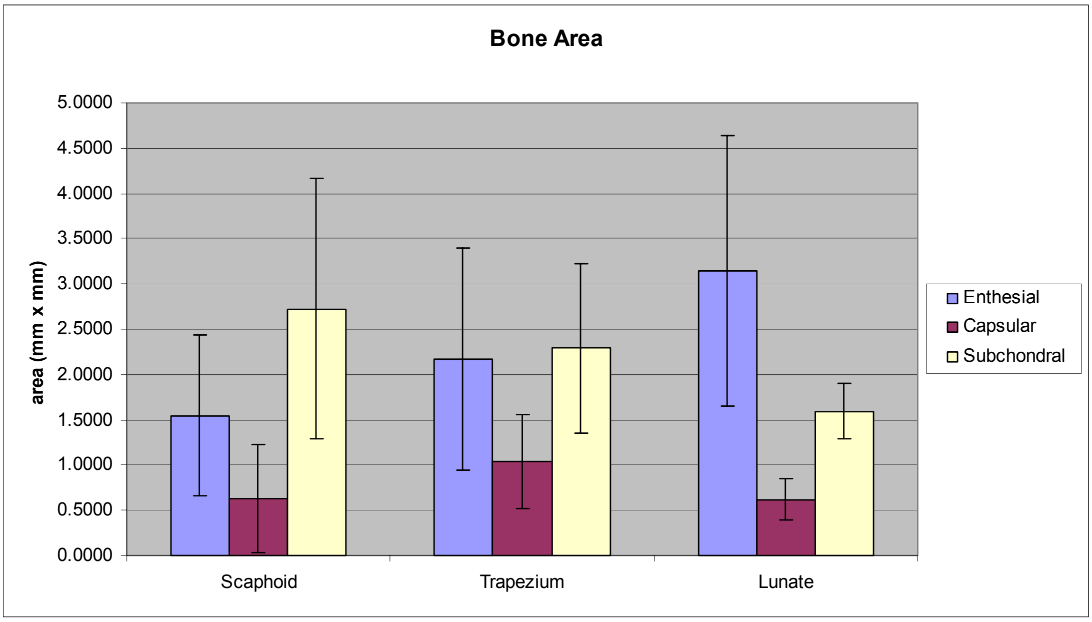

Figure 2.21 Bone area. Mean measures of bone segment area to which various tissues were attached.

The mean area of subchondral bone on the trapezium ($2.288 \pm 0.937 mm^2$) was not significantly greater than that of the enthesial bone ($2.174 \pm 1.229 mm^2$; $p < 0.9$; figure 2.21). However, significant difference was observed between subchondral and capsular bone ($p < 0.05$), and enthesial and capsular bone ($1.040 \pm 0.516 mm^2$; $p < 0.05$) on the trapezium. Mean bone areas relative to segment length altered the relationship between tissue type and bone area on the observed trapezia (figure 2.22). Enthesial bone ($0.475 \pm 0.178 mm^2/mm$) had a significantly greater ($p < 0.05$) mean relative area than subchondral bone ($0.280 \pm 0.061 mm^2/mm$). Enthesial bone also had a significantly greater mean relative area than capsular bone ($0.206 \pm 0.117 mm^2/mm$; $p < 0.05$), whilst the mean relative area of subchondral bone was not significantly greater than that of capsular bone ($p < 0.08$).

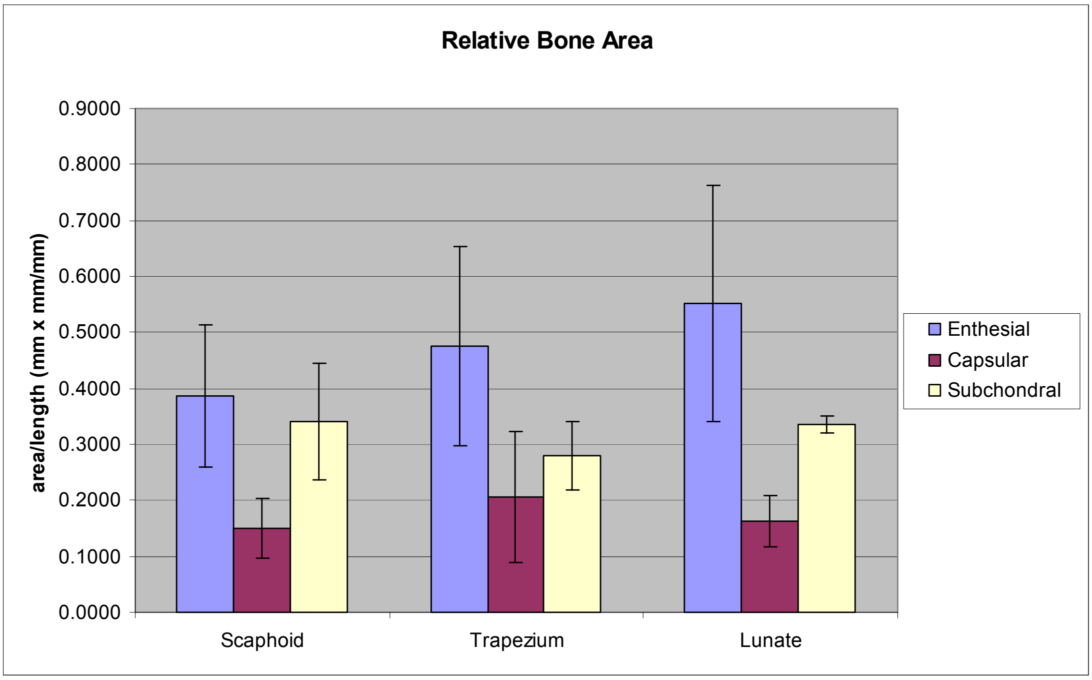

Figure 2.22 Relative bone area. Mean measures of bone segment area relative to mean cortical bone segment length.

The mean area for enthesial bone on the lunate (3.151±1.493mm^2) was significantly greater than that for subchondral (2.174±1.229mm^2; $p < 0.05$) and capsular bone (1.040±0.516mm^2; $p < 0.01$; figure 2.21). Significant difference ($p < 0.05$) was also observed between subchondral and capsular bone on the lunate. Mean bone areas relative to segment length did not alter the relationship between tissue type and bone area on the observed lunates. Enthesial bone (0.552±0.211mm^2/mm) had a significantly greater mean relative area than subchondral (0.336±0.015mm^2/mm; $p < 0.05$) and capsular bone (0.206±0.117mm^2/mm; $p < 0.05$), whilst subchondral bone had a significantly greater mean relative area than capsular bone ($p < 0.05$).

The bone supporting a particular tissue was not similar between carpal bones. The mean area of enthesial bone measured was greatest in the lunate specimens, significantly more than trapezial (2.174±1.229mm^2; $p < 0.05$) and scaphoid specimens (1.546±0.889mm^2; $p < 0.05$). Trapezial specimens had significantly greater mean enthesial bone area than scaphoid specimens ($p < 0.05$). A similar trend was observed in the relative areas of enthesial bone. Lunate specimens (0.552±0.211mm^2/mm) had significantly greater mean relative enthesial bone areas than trapezial (0.475±0.178mm^2/mm; $p < 0.05$) and scaphoid specimens (0.387±0.127mm^2/mm; $p < 0.05$). Trapezial specimens were significantly greater than scaphoid specimens ($p < 0.05$).

There were significant differences between measured areas of subchondral bone. Scaphoids (2.724±1.440mm^2) had greater mean area of subchondral bone than trapezial (2.288±0.937mm^2) specimens, but this difference ($p < 0.08$) was not significant. The mean area measured for scaphoids and trapezia were significantly greater ($p < 0.05$) than the mean area of subchondral bone on the lunates (1.589±0.507mm^2). However, the relative areas of subchondral bone were not significantly different ($p < 0.09$) between any of the bones observed. Likewise, the measured areas ($p < 0.08$) and calculated relative areas ($p < 0.09$) of capsular bone were not significantly different between any of the carpal bones measured.

2.5 Discussion

The carpal bones unite a unique combination of multiple articular surfaces, ligamentous attachments and capsular attachments (Garcia-Elias, 2001). Thus the complex array of structures within the carpus both promotes and hinders investigation. The close proximity of numerous structures (eg. bone, ligament, joint capsule, cartilage) promotes their comparison and the investigation of the relationships between these structures. However, the complexity is often a hindrance to investigation, particularly to gross examination, as many of the structures cannot be readily distinguished from each other (such as ligament and joint capsule). The complex and seemingly indiscriminate construct of the fibrous support of the carpus may therefore have impaired the conclusions of many gross investigations into its arrangement. This suggests that more discerning approaches are required. Histological analyses enable the complexity to be filtered, such that macroscopically indistinct tissues are made histologically distinct with the aid of specific stains. The histologically distinct tissues and their related structures can then be satisfactorily investigated.

Most discussion of carpal function is centred on carpal stability and how instability might be exacerbated, identified, controlled and prevented (Craigen and Stanley, 1995; Kauer, 1986; Moojen *et al*, 2003). Such discussion might address ligamentous arrays within the carpus, the details of which are commonly supported with data from gross investigation alone (Berger, 1997; Feipel and Rooze, 1999; Mayfield, 1984; Taleisnik, 1976). Such data do not account for macroscopic similarities between capsular and ligamentous tissues, and hence are vulnerable to the subjectivity of the investigator. This subjective approach to investigation may account for the great deal of variation in ligamentous arrays reported in the literature. To reduce the subjectivity of such investigations, it is essential to combine macroscopic and microscopic observations in order to differentiate between ligamentous and capsular tissue. The complex and multi-angular orientation of the carpal ligaments limits the viability of a devoted histological investigation within the time, technical and financial restraints of this study, but histological assessment does allow the tissue variations to be observed. It is anticipated that a more elaborate histological study will be attempted.

The histological investigation of carpal ligaments was dependent on the investigator's capacity to accurately identify ligamentous tissue, and to differentiate it from surrounding tissues. Failure to do so with some significant degree of confidence would fail to add any more weight to observations than previous gross investigations. It was therefore essential to clearly establish the difference between the tissue types in question. Ligamentous tissue, the tissue of primary concern in the investigation, constitutes a load-bearing structure (Forster, 1984; Short *et al*, 2002a) , and as such has particular structural requirements. Well documented is the fibrous content of ligament, a dense-regular connective tissue providing a medium for force transmission (Benjamin and Ralphs, 1998). The modified support region of a ligament, the enthesis, remains poorly described, and has not been used as a determinant of function in the carpus in the reviewed literature. Nevertheless, the enthesial adaptation to loading has been widely discussed, mainly in reference to tendinous attachments (Benjamin *et al*, 2002; Canoso, 1998; Milz *et al*, 1998), and occasionally for ligamentous attachments (Itoh, 1989; Milz *et al*, 2001). The consensus amongst this vast range of reports is that load-bearing structures exhibit significant morphological differences to neighbouring non-loading-bearing structures. This is further exacerbated where different tissues are joined, such as entheses (Benjamin *et al*, 2002;

Fournie, 1993). To further facilitate the differentiation between ligament and adjacent tissues in the carpus, a difference in cortical bone area between tissue types was hypothesised.

The carpus is primarily articular (Berger, 1996). Articular surfaces occupied a significantly greater proportion of the surfaces measured, suggesting that most of the carpal bones are devoted to articulation with other bones (figure 2.14). The high proportion of articular surfaces in relation to the total surfaces observed suggests that the carpus is highly reliant on these articulations for the maintenance of wrist stability and range of motion (Hamrick, 1996). The remainder of the surfaces observed were either ligamentous or capsular. There was no significant difference in the lengths of enthesial or capsular bone, which suggests that despite predominance of articular surfaces, the surface area devoted to the attachment of structures that support the joints (ligaments) is no greater than the less specialised capsular surfaces. It is therefore important to establish where these specific areas are, so that the understanding of wrist function may improve, and that they may be preserved or repaired to improve post-operative wrist function.

In order to aid discrimination of ligament from joint capsule in macroscopic observations, histological sections were used to map regions of ligamentous and capsular attachment. It has been reported (Benjamin and Ralphs, 1998; Canoso, 1998; Fournie, 1993; Francois *et al*, 2001; Jiang *et al*, 2002) that the thickness of bone varies according to the function of the bone. Bone thickness may be used to validate the tissue type designations made from histological appearance. The results reported suggest that enthesial bone has the greatest area per unit of measure in the observed specimens (figure 2.22). This area is greater than subchondral, and greater still than capsular bone (figure 2.22). These data suggest that ligaments are positioned to resist specific forces

(Hoogbergen *et al*, 2002; Linscheid and Dobyns, 2002), and therefore must have greater skeletal support for the transmission of these forces (Schuind *et al*, 1995). The role of ligaments may then be to transmit specific forces to the underlying enthesial bone (Benjamin and Ralphs, 1998; Fournie, 1993; Short *et al*, 2002a), a therefore specific arrangements of ligaments will only transmit specific patterns of force. Further evidence of specific force transmission may be observed in the enthesial adaptations. (Benjamin and Ralphs, 1998; Cooper and Misol, 1970; Forster, 1984). For example, where fibrocartilage is observed as part of the enthesis, the ligament may be loaded with greater forces than a ligament without a fibrocartilaginous enthesis. Furthermore, excessive loading of the ligament may promote development of greater enthesial bone support to aid the transmission of forces through the joint.

Articular surfaces are subject to the greatest forces in a joint (Fulkerson *et al*, 1987; Sayers *et al*, 1987). Most of these forces are absorbed by articular cartilage (Forster, 1984), as suggested by the relative area of subchondral bone being lower than enthesial bone (figure 2.22). The higher degree of force absorption provided by the articular cartilage suggests that the subchondral bone has a secondary role of transmitting any force that is not absorbed by the cartilage. As the sample population is older (79.63±19.5 years) on average than the total population, it may be suggested that these data exhibit a mean area of subchondral bone greater than the mean of the total population. This may be due to age-related degradation of articular cartilage (Adams and Horton, 1998; Armstrong and Mow, 1982; Bank *et al*, 1998), and hence reduced force absorption by the cartilage. Reduction in cartilage function results in increased transmission of force to the subchondral bone. Such increased force transmission would induce thickening of the subchondral bone (Benjamin *et al*, 2002; Francois *et al*, 2001). A younger sample population may be expected to have a lower mean relative area of subchondral bone as the protective layer of cartilage is more likely to be functioning normally (Armstrong and Mow, 1982; Meachim *et al*, 1977; Weiss, 1979).

The capsular bone had the lowest relative area (figure 2.22), indicative of the limited role in force transmission played by the joint capsule (Staszyk and Gasse, 2001). Joint capsule is composed of an irregular array of fibrous tissues (Buckwalter and Cooper, 1987; Flint, 1983). As the fibrous tissue lacks uniform orientation, forces are unlikely to be absorbed or transmitted efficiently, or for larger forces, atraumatically. These data reinforce the suggestion that capsular tissue is not designed for force transmission. When a thickening of the joint capsule is not accompanied by a change in histological structure (irregular to regular tissue) the thickening cannot be assumed to provide specific mechanical resistance in a particular direction (cf. ligament). This is supported by these data (figure 2.22), as there is no significant difference in bone area at various regions of capsular attachment.

2.5.2 Scaphoid Data

The scaphoid is equally articular and a base for ligamentous attachments. In relation to the area of bone devoted to articular cartilage and ligamentous attachments, very little of the scaphoid provides area primarily for capsular attachment (figure 2.18). This suggests that the scaphoid, already established as a highly mobile component of the carpus (Moojen *et al*, 2003), requires the support of much more force bearing structures than previously thought. These data suggest that the majority of tissues attached to the scaphoid are significant transmitters of force, contradicting the common theory that the scaphoid provides a large area for capsular, non-force transmitting tissue (Berger, 1996; Bogumill, 1988; Dobyns and Linscheid, 1997; Garcia-Elias, 2001; Kauer and de Lange, 1987). The suggestion of greater force transmission is clearly portrayed clinically with the high impact force necessary for scaphoid fracture (Berdia and Wolfe, 2001; Berna *et al*, 1998; Compson, 1998; Cooney *et al*, 1984; Garcia-Mata, 2002; Hambidge *et al*, 1999; Kulkarni *et al*, 1999; Polsky *et al*, 2002). This typically occurs in a backwards fall on an outstretched hand (Amadio, 1992; Hooper *et al*, 1992). When no injury occurs the force of impact is transferred through the hand and wrist to the radius (figure 2.23b), which then passes the force to the ulna via the interosseous membrane (Gupta *et al*, 2002). When the injury does occur (figure 2.23c) the transfer of force from hand to radius (via the carpus) is not successful. The result is the full force of the impact being taken by the scaphoid, and hence, its fracture (Gupta *et al*, 2002). This severe example is suggestive of the degree of force transmission through the scaphoid in non-traumatic activity, given that there is only a slight difference in angle between a force that fractures the scaphoid and one that is completely asymptomatic. It therefore may be suggested that the scaphoid, as one of the key force transmitting elements of the carpus, requires significant force absorbing and spreading structures, such as ligaments and cartilage, and not joint capsule (Hoogbergen *et al*, 2002; Schuind *et al*, 1995).

The scaphoid data suggest that the majority of non-articular surfaces of the scaphoid are for ligamentous attachments (figure 2.24). In addition to the necessary avenues for transmission of forces from the hand to the radius (discussed above), the predominance of ligamentous attachments over capsular attachments attests to the importance of the scaphoid to force transmission and movement of the wrist (Moojen *et al*, 2002; Moritomo *et al*, 2000). With a greater range of movements comes a greater need for limitation of those movements, consequently, multiple ligaments are required in multiple directions to stabilise the scaphoid (Short *et al*, 2002a). This is further exacerbated by the radial position of the scaphoid within the carpus (Kauer, 1996). Ulnar skeletal support is

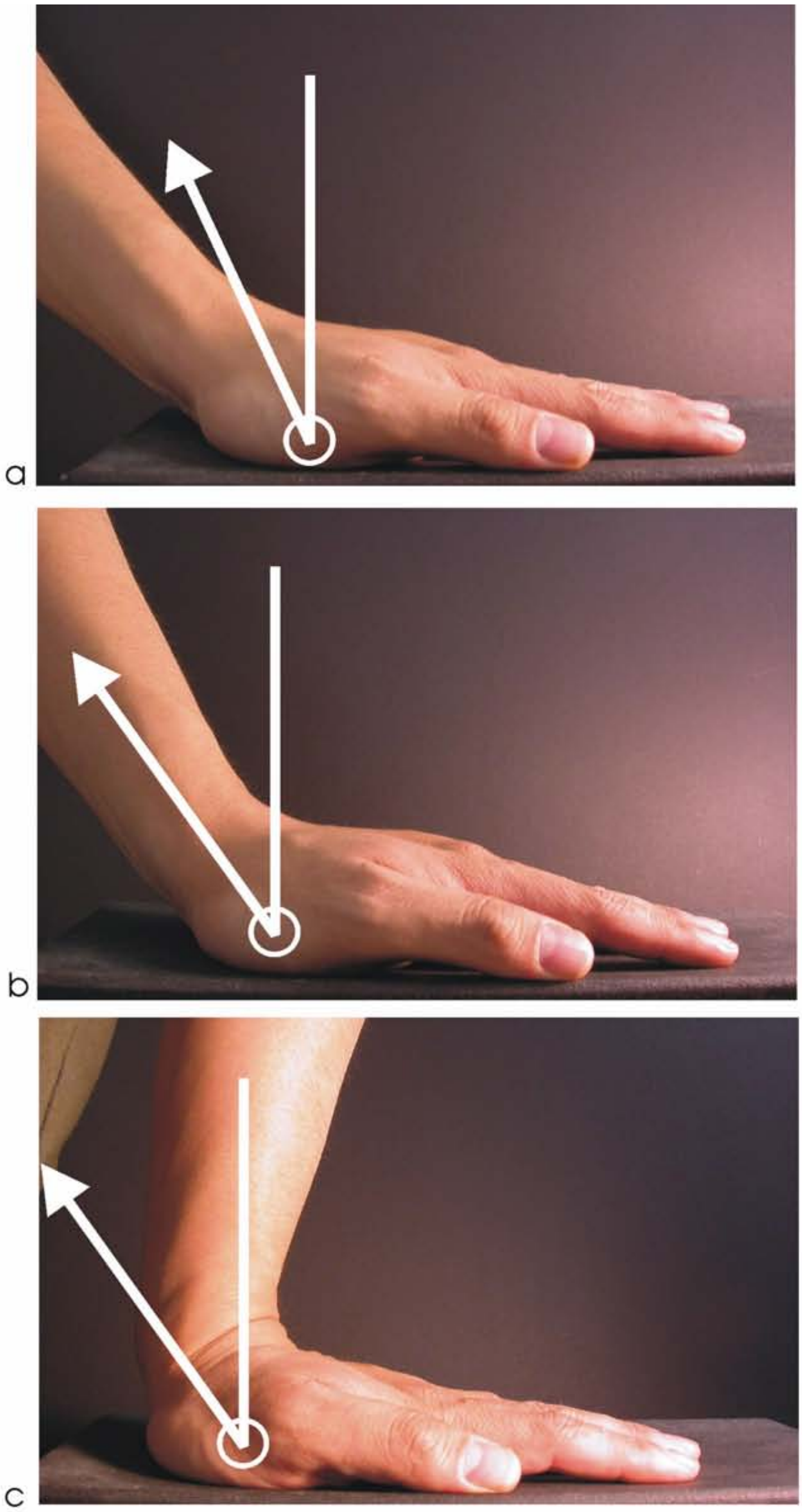

Figure 2.23 Force transmission through the wrist. a - high impact forces upon an outstretched hand (typically in front of the person) where the angle between hand (metacarpals) and forearm is more obtuse (approaching 180^0) is likely to result in a Colles fracture. Force directed distally through the wrist is transmitted to the radius, but the angle is insufficient for metaphyseal-diaphyseal transmission, and the distal third of the radius absorbs the full load; b - with the angle between hand and forearm closer to 45^0 skeletal damage is unlikely unless the force is excessive; c - with the angle between hand and forearm closer to 90^0, the impact force is directed distally through the wrist, but misses the radius. This heavily loads the scaphoid, increasing the possibility of scaphoid fracture.

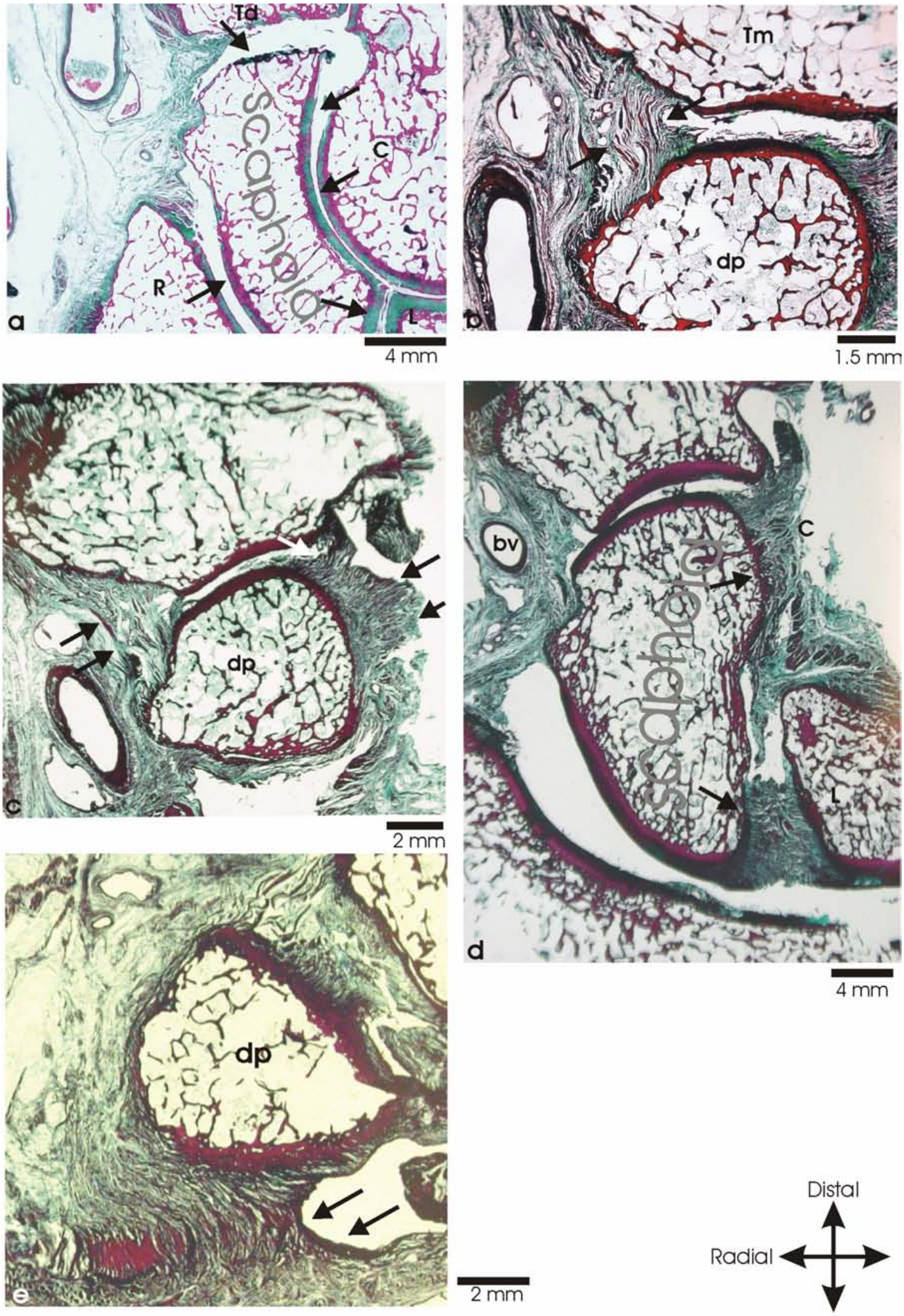

Figure 2.24 The Scaphoid. a - large articular surfaces (arrows) for radius (R), capitate (C), and trapezoid (Td); b - ligaments (arrows) attached to the trapezium (Tm) and the distal pole of scaphoid (dp) ; c - radial and ulnar ligamentous support (arrows) for the distal pole of the scaphoid (dp); d - ulnar ligamentous attachment (arrows) to lunate (L) and capitate (C), radial supporting tissue and blood vessels (bv); e - ligamentous support (arrows) for the proximal pole of the scaphoid attached to the distal pole of the scaphoid (dp); all photos Modified Masson's Trichrome.

provided by the presence of the capitate and lunate, proximal support by the radius, and distal support by the trapezium and trapezoid. However, the scaphoid is dependent on soft tissue support radially*, hence the importance of ligamentous limitation of scaphoid movements (Nuttal *et al*, 1998).

The high relative area of enthesial bone for each non-articular region of the scaphoid suggests that ligaments attached to the scaphoid surgically will have suitable skeletal support. When attached to bone already designed for ligamentous attachment, these data suggest that there will be a suitable degree of skeletal support for the replacement ligament. Post-operatively, the enthesial bone to which the new ligament is attached will be able to bear the loads transferred through the new ligament. However, if the ligament was attached to a capsular area an attempt to load the capsular bone with similar forces would increase the amount of force relative to the amount of bone, increasing the likelihood of fracture. These data suggest that there is limited chance of this happening when re-attaching ligaments to the scaphoid. The precise location of the weakened, or capsular, areas is still to be determined. Accurate clinical identification of the capsular attachment areas may provide a means of avoiding such weak areas, and hence may improve post-operative outcomes.

2.5.3 Trapezium Data

The area of bone observed on trapezium specimens suggested that ligamentous attachments and cartilaginous surfaces predominated (figure 2.19). Very little capsular tissue was attached to the measured bone. The high proportion of the trapezium devoted to ligamentous and cartilaginous attachments supports the perceived function of the

* With the wrist in neutral position, the radial styloid process gives some radial support to the scaphoid, and a great deal when the wrist is radially deviated but this is reduced when the wrist is moved into ulnar deviation.

trapezium (Bettinger *et al*, 1999; North and Eaton, 1983) (figure 2.25). Proximal to the trapezium is the scaphoid, with which the trapezium is articulated. The ulnar aspect of the trapezium is largely articulated with the trapezoid, whilst the distal aspect incorporates the large “saddle” joint at which the trapezium is articulated with the base of the first metacarpal (Momose *et al*, 1999). Hence a large proportion of the trapezium is articular (figure 2.19). As a consequence of being largely articular, the relatively (when compared to the scaphoid and first metacarpal) immobile trapezium (Moojen *et al*, 2003; Moritomo *et al*, 2000) may act as a stable base upon which the articulated bones are moved. This then suggests that the trapezium may be a suitable point at which to attach ligaments that will restore stability of an unstable joint. This suggestion is supported by the data reported and gross morphological observations of the trapezium.The data suggest that the area of cortices to which cartilage is attached is similar to the area to which ligamentous tissue is attached.The articular role of the trapezium is therefore supported by a large amount of ligamentous attachments.Gross morphological observation also suggests that the trapezium provides attachment sites for many of the ligaments supporting the surrounding joints (Bettinger *et al*, 1999; Drewniany *et al*, 1985).The morphology of the trapezium exhibits several tubercles and crests that increase the surface area for such attachments, and may optimise the angles at which the attached ligaments are taut (Bettinger *et al*, 1999; Short *et al*, 2002a).A stable base with increased area for ligament attachment, such as the trapezium in relation to the scaphoid and first metacarpal, may therefore contribute enormously to the stability of either joint. The integral position of the scaphoid in most carpal motion theories (Kobayashi *et al*, 1997; Moojen *et al*, 2002; Youm *et al*, 1979) also suggests that failure of the support provided by the trapezium, or surgical removal of such support, may greatly influence the biomechanics of the entire carpus. Similarly, interruption of this support may influence the stability and range of movements able to be performed with the thumb (North and Eaton, 1983; Swanson, 1972). Both scenarios would greatly limit the functional use of

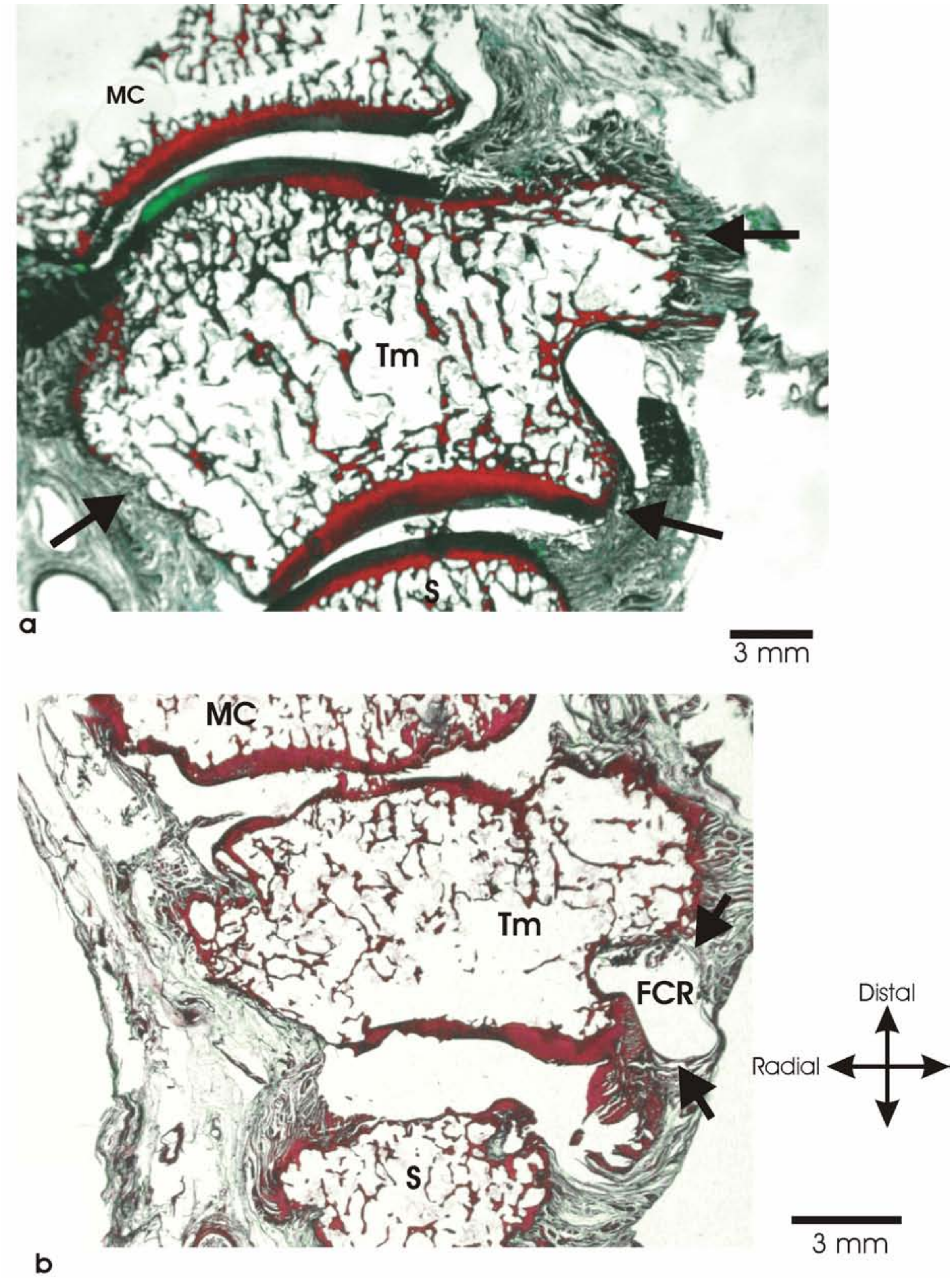

Figure 2.25 The trapezium; a - the trapezium (Tm) with radial and ulnar ligamentous support (arrows), proximal articulation with the scaphoid (S) and distally with the first metacarpal (MC); b - sheath for the tendon of flexor carpi radialis muscle (FCR) and articulation with the scaphoid (S) and first metacarpal (MC). The tendon is enstheathed in a fibrous tube (arrows) which is attached the trapezium; all photos Modified Masson's Trichrome.

the hand as a whole, and therefore reduce the quality of life for an individual and those upon whom they may become dependent (Pellegrini, 1992).

The area of bone relative to the length of bone differs from the original areas measured. Whilst the area of trapezial bone to which ligament was attached was similar to the area of subchondral bone (figure 2.19), the relative areas (area per length) were significantly greater for the ligamentous attachment sites (figure 2.22). The area of bone at an enthesis may be considered as indicative of the strength of the ligament, where more bone suggests more force transmitted, which suggests stronger ligaments (Benjamin *et al*, 2002; Palesy, 1997). The greater relative area of enthesial bone to subchondral bone suggests that the ligaments attached to the trapezium are capable of transmitting greater forces than inferred from the area data alone. In comparison with the previously discussed scaphoid data, it may also be suggested that the trapezial attachments of the ligaments transmit more force than the scaphoid attachments. The difference, despite similar anatomical position, may be due to several factors:

1. the forces upon the first carpometacarpal joint may be greater than those upon the scapho-trapezial-trapezoidal joint
2. forces transmitted through the carpus may place greater loads upon distal attachments (such as those to the trapezium); load transfer throughout the hand and wrist may disperse greater forces amongst more structures at the scaphoid level than the trapezial level, thus reducing the load upon the scaphoid attachments.
3. the scaphoid may transmit more load through its articular surfaces than through its supporting ligaments (hence the prevalence of scaphoid fractures (Amadio, 1992; Hooper *et al*, 1992)) whilst the ligaments supporting the trapezium may transmit more of the force.

4. across all three bones measured, there was no significant difference in relative area of subchondral bone, suggesting that similar strength forces are being transmitted to subchondral bone; variation in relative enthesial bone area for ligamentous attachments therefore represents a difference in force transmission through ligaments.

The suggested strength of the trapezial ligament entheses may be used intra-operatively. Natural ligamentous entheses capable of transmitting greater forces than neighbouring capsular bone may be of greater importance to post-operative function than relying on bone less capable of force transmission. It may therefore be important to retain trapezial enthesial bone in order to maintain adequate post-operative force transmission through the wrist. This may be particularly evident in restoring the thumb to full function (Nylen *et al*, 1993; Renfree and Dell, 2002; Swanson, 1972; Tomaino *et al*, 1999).

2.5.4 Lunate data

The lunate differed from the measured scaphoids and trapezia as the area of enthesial bone measured was much greater than that of subchondral and capsular bone (figure 2.20). This trend was unaltered by the calculation of areas relative to length of bone measured, as enthesial bone had a far greater relative area than both subchondral and capsular bone. These data suggest that the lunate is predominately a site for ligamentous attachment (figure 2.26). This is further supported by reports of fibrous interosseous connections between the lunate and scaphoid (Abe *et al*, 2003; Coe *et al*, 1995; Gupta and Al-Moosawi, 2002; Short *et al*, 2002a), and between the lunate and triquetrum (Gupta and Al-Moosawi, 2002; Harrington and Quinlan, 1999; Nakamura *et al*, 2001; Taleisnik, 1984; Viegas *et al*, 1990), both of which were considered ligamentous structures despite being intra-articular. The histological appearance of these structures supports this consideration

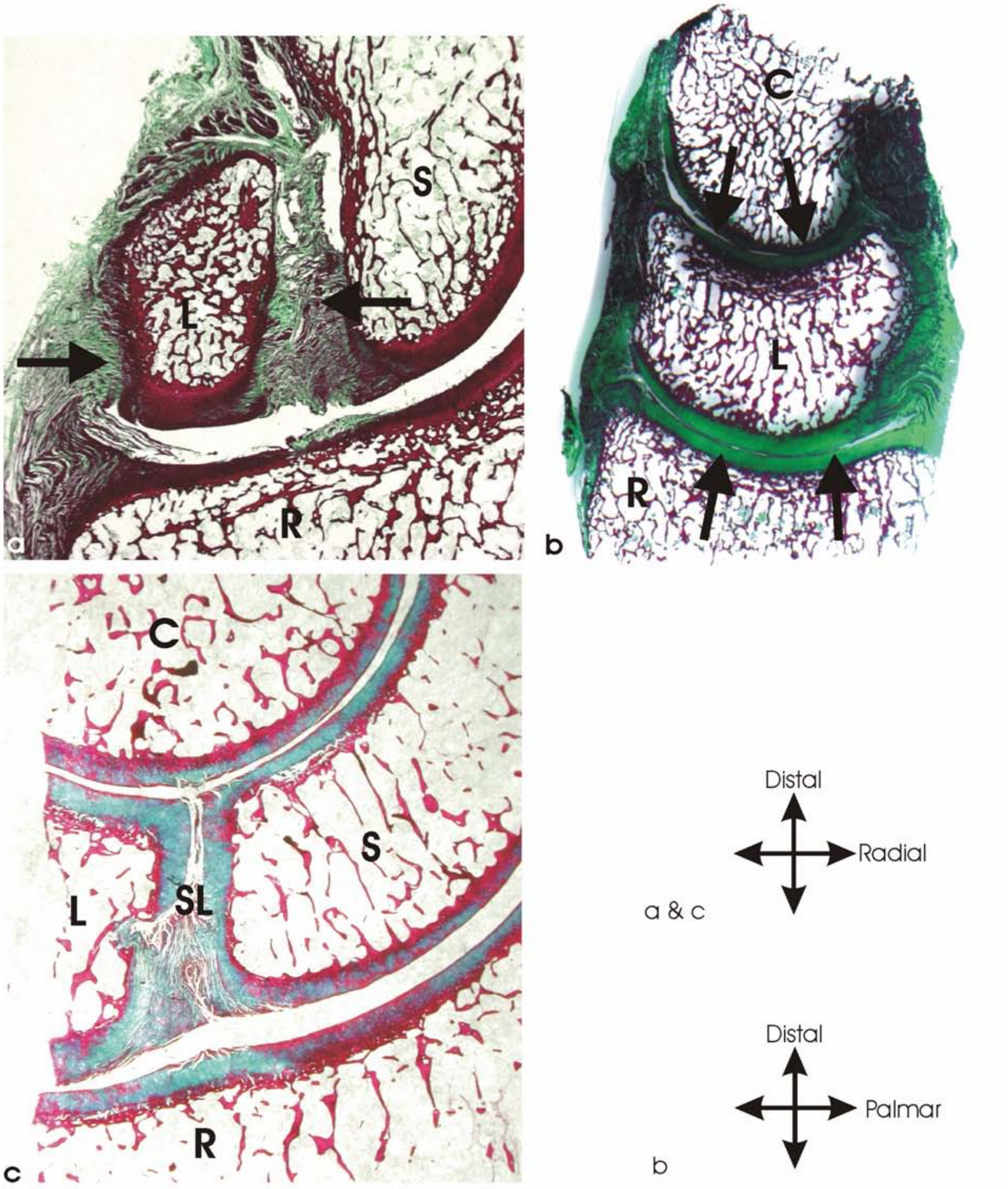

Figure 2.26 The Lunate. a - ligaments (arrows) support the lunate (L) from the scaphoid (S) and the radius (R); b - the proximal and distal aspects are predominately articular (arrows) for the radius (R) and capitate (C) respectively; c - the scapholunate joint (SL) is shown to be partly synovial and partly fibrous; all photos Modified Masson's Trichrome.

(figure 2.26). These data, in addition to numerous reports of severe wrist dysfunction following disruption of lunate ligamentous support (Black *et al*, 1987; Harrington and Quinlan, 1999; Herzberg and Forissier, 2002; Taleisnik, 1984; Tang *et al*, 2002; Watson and Ballet, 1984), suggest that ligamentous support of the lunate is important to wrist function. The area of enthesial bone observed relative to the length of enthesial bone measured was significantly greater than the relative areas observed on the scaphoid and trapezial specimens. This suggests that the lunate entheses are designed to transmit more force than the trapezial entheses discussed earlier. As the lunate is centrally orientated within the proximal row of the carpus, it may be suggested that the lunate, and its entheses, may have to transmit a significant percentage of force between the hand, distal carpus and forearm (Hoogbergen *et al*, 2002; Linscheid and Dobyns, 2002; Schuind *et al*, 1995). It may also be suggested that ulnar contribution to the net force transmitted through the lunate may be greater due to the proximal position of the head of the ulna, and hence the necessity for forces to be directed to the radius (Af Ekenstam, 1992; Linscheid and Dobyns, 2002; Nakamura *et al*, 1999). Some of the ulnar load may be absorbed by the triangular fibrocartilage complex (Nakamura *et al*, 1999).

2.6 Conclusions

The tissue types observed (ligament, capsule and cartilage) may be differentiated by their histological structure. The functional difference between the tissue types may be quantified by measurement of the bone to which they are attached. The quantification of specialised bone area provides a significant means of differentiating tissue types based on function.

The bone to which various tissues are attached may indicate the ability of the structural complexes (tissue and the bone to which it is attached) to absorb and transmit force. Enthesial bone appears well suited to heavy loading, whist capsular bone does not seem likely to maintain its integrity with any significant increase in loading. Subchondral bone thickness may be determined by the functional state of the articular cartilage it supports, so thickening of subchondral bone may be indicative of cartilage dysfunction.

The carpal bones observed demonstrated variable association with each tissue type. Lunates were primarily enthesial, whilst subchondral and enthesial bone dominated the scaphoids and trapezia.

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Chapter 3

Ligamentous Support of the Scaphoid

3.1 Introduction

Understanding the morphology of the carpal bones is insufficient for a detailed comprehension of carpal mechanics. The movements of the carpal bones and the maintenance of the carpal articulations is reliant on ligamentous support (Berger, 1996; Kauer and de Lange, 1987; Lewis *et al*, 1970). A detailed understanding of the ligaments of the wrist and their variation is therefore required. The complex arrangement of fibrous tissues in the wrist has made clear descriptions of the ligamentous array of the wrist difficult. Variation and the difficulty in differentiating between ligament and joint capsule may have influenced the results published to date.

3.1.1 The Distal Radioulnar and Radiocarpal Joints

The distal radioulnar joint (DRUJ) is the articulation of the radial surface of the ulna with the sigmoid notch on the ulnar aspect of the radius (Bond and Berquist, 1991). The joint is enclosed by a loose capsule that permits rotation of the radius around the ulna (Bogumill, 1988). Dorsal and palmar fibres of transverse orientation reinforce the joint capsule, but joint stability is predominately maintained by the interosseous membrane lying proximal to the joint, and the triangular fibrocartilage complex (Bogumill, 1988).

The radiocarpal joint complex is formed by the articulation of the proximal row of carpal bones with the distal articular surface of the radius and its ulnar continuation as the triangular fibrocartilage complex (TFCC) (Bogumill, 1988) (figure 3.1). The proximal articular surface of the joint complex is formed by the radius and the TFCC, and is roughly congruent with the distal articular surface of the complex. The distal surface of the

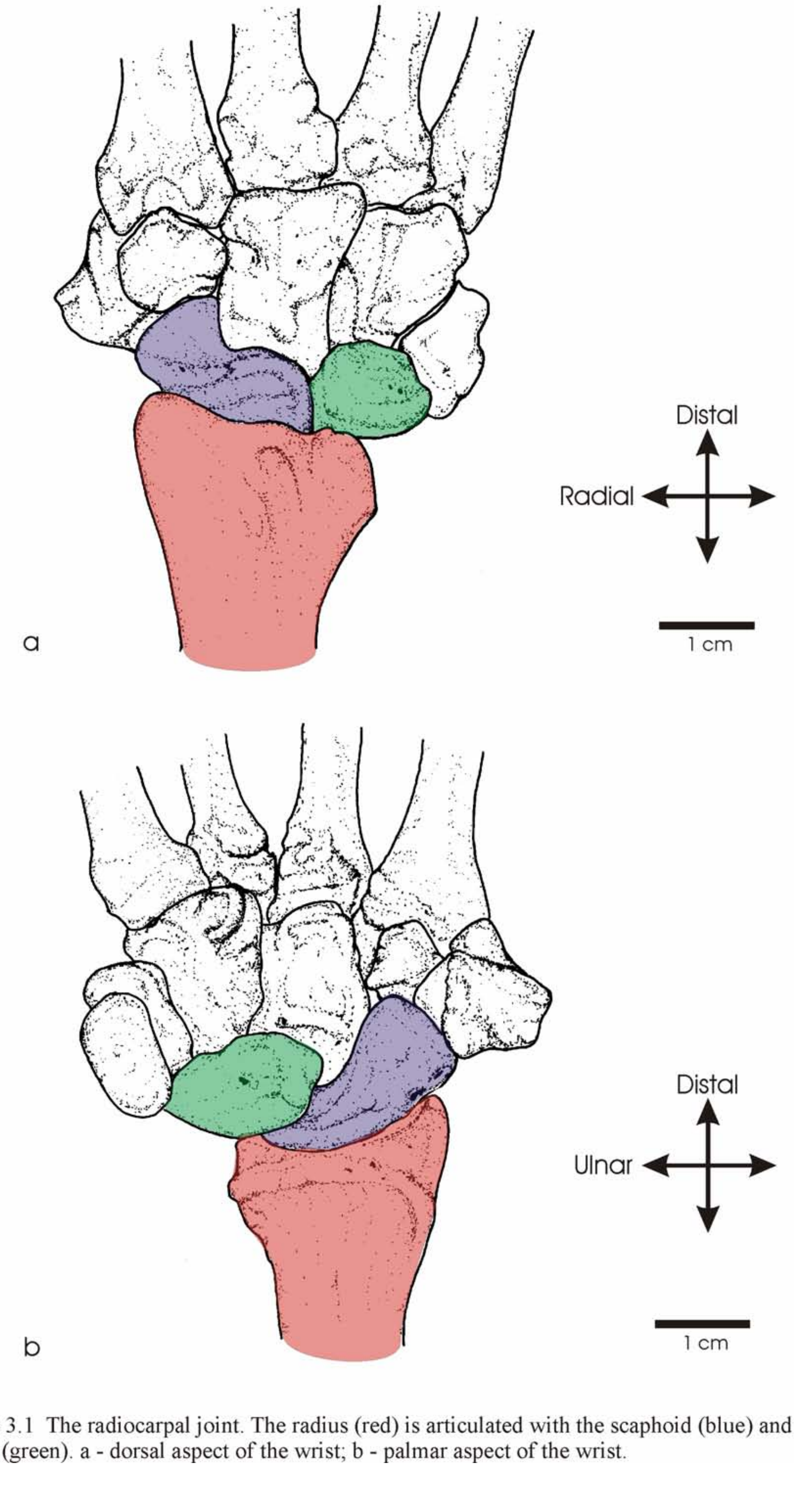


Figure 3.1 The radiocarpal joint. The radius (red) is articulated with the scaphoid (blue) and the lunate (green). a - dorsal aspect of the wrist; b - palmar aspect of the wrist.

radiocarpal joint complex is formed by the proximal surfaces of the scaphoid, lunate and triquetrum, and the interosseous ligaments that connect them; thus the distal articular surface of the radiocarpal joint is a smooth biconcave surface, despite being composed of variable elements along its length (Bogumill, 1988).

Motion at the radiocarpal joint complex is determined by the degree of movement permitted by the skeletal structures and the ligamentous reinforcements of the capsule, the radiocarpal ligaments (Bogumill, 1988). The radiocarpal ligaments are obliquely orientated, proximal-radial to distal-ulnar, such that the hand will passively rotate with the radius as the forearm is pronated or supinated. The radiocarpal joint does not communicate with any other joint as the capsule is attached to the proximal row of carpal bones, sealing it off from neighbouring intercarpal joints (Bogumill, 1988).

Bond and Berquist (1991) describe two ligamentous arcs crossed over the radiocarpal joint. The proximal arc is simply the radiolunotriquetral ligament, whilst the distal arc is composed of the radiocapitate and triquetrocapitate ligaments. Both arcs are completed and stabilised ulnarly by the ulnotriquetral ligament (Bond and Berquist, 1991). Between the ligamentous arcs lies an unsupported region of the carpus, often referred to as the “Space of Poirier” (Taleisnik, 1976). The radiocapitate ligament, along with the radioscapholunate ligament, immobilises the proximal pole of the scaphoid (Bond and Berquist, 1991). Bogumill (1988) describes a palmar radiocapitate ligament. The palmar radiocapitate ligament is attached to the palmar and radial aspects of the radial styloid process. It is then transversely crossed over the waist of the scaphoid before its distal attachment to the palmar aspect of the capitate. In some individuals the ligament may be attached to the waist of the scaphoid. *In lieu* of these attachments, Bogumill (1988) also suggests that the ligament could be termed the radioscaphocapitate ligament.

The palmar radiocapitate ligament is one of a three ligament complex proposed by Bogumill (1988) (figure 3.2). This radiocarpal complex may add ligamentous support to the radiocarpal joint and stabilise the proximal row of carpal bones in relation to the radius. The palmar radiocapitate ligament is the most radial of the three ligaments. Ulnar to the palmar radiocapitate ligament is the radiotriquetral ligament, which may also be termed the radiolunotriquetral ligament (Bogumill, 1988). The radiotriquetral ligament is attached to the styloid process and palmar lip of the radius and is obliquely traversed across the lunate. The degree of attachment to the lunate may vary between individuals. The radiotriquetral ligament is then attached to the palmar aspect of the triquetrum (Bogumill, 1988). The space of Poirier may lie between the radiocapitate and radiotriquetral ligaments (Bogumill, 1988). The most ulnar of the radiocarpal ligaments is the palmar radioscapholunate ligament. It is attached ulnar and deep to the radiotriquetral ligament on the palmar margin of the distal articular surface of the radius, and is then attached to the palmar surface of the scapholunate joint. Bogumill (1988) suggests that this large ligament may be the principle support for the scapholunate joint and must be disrupted when scapholunate dislocation is suspected.

Alternatively, the palmar surface of the wrist may be characterised by four radiocarpal ligaments (Berger, 1996) (figure 3.3). The most radial of the proximal attachments of these ligaments is that for the radioscaphocapitate ligament. It is attached to the styloid process of the radius and is extended distally to the scaphoid and capitate. Berger (2001) adds further detail to this description, stating that only about ten percent of

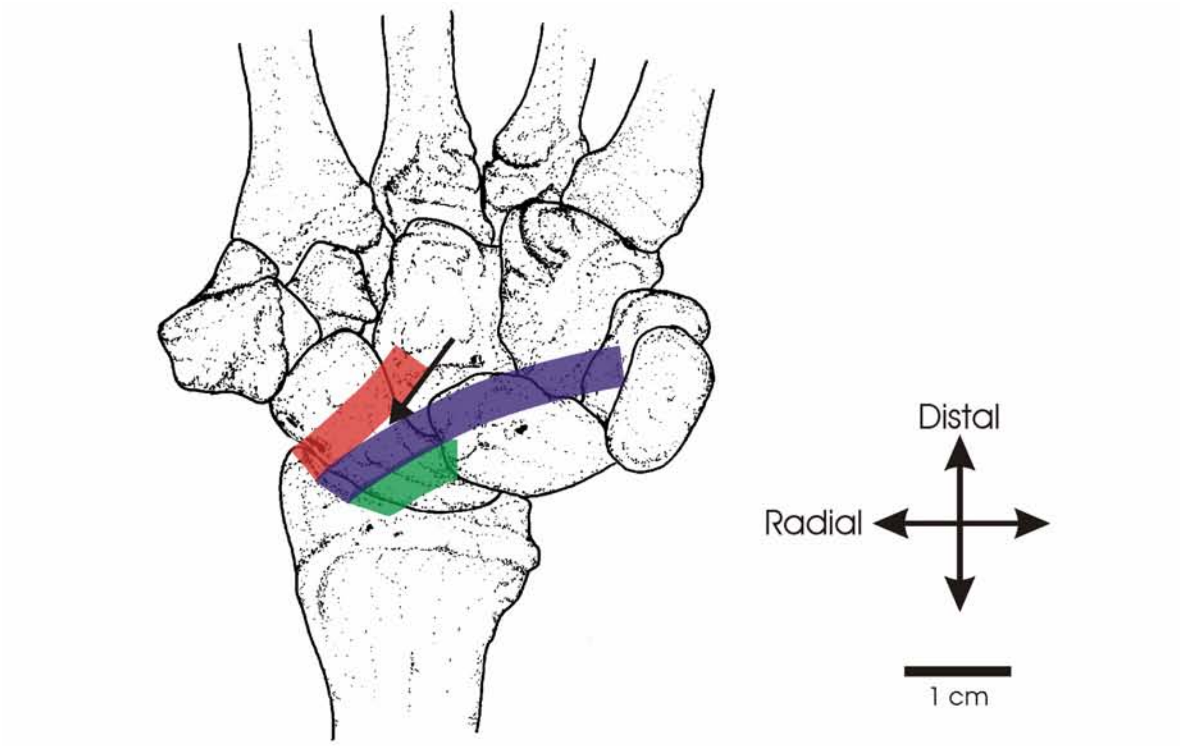


Figure 3.2 The radiocarpal ligaments of Bogumill (1988). The most radial radiocarpal ligament is the radiocapitate ligament (red). Ulnar to this is the radiotriquetral ligament (blue). These two ligaments are divided by the interligamentous groove (space of Poirier, arrow). The most ulnar of the radiocarpal ligaments is the radioscapholunate ligament (green).

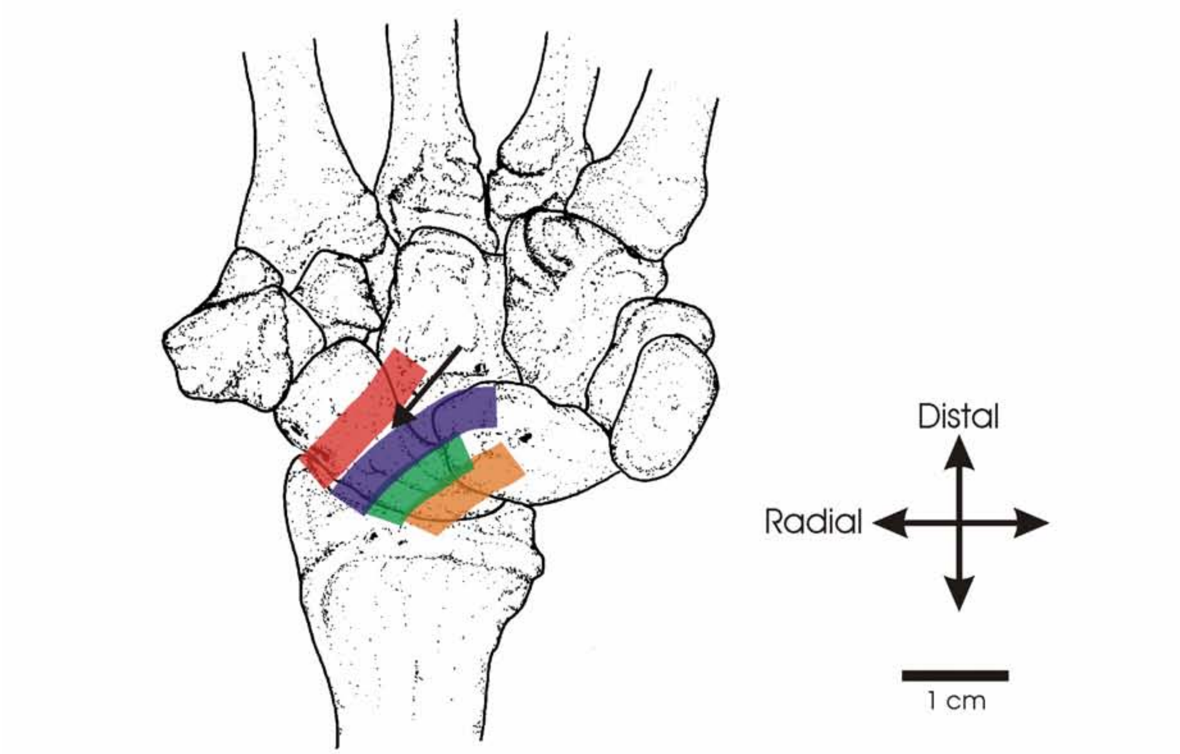


Figure 3.3 The radiocarpal ligaments of Berger (1996;2001). From radial to ulnar the ligaments are the radioscaphocapitate (red), the long radiolunate (blue), the radioscapholunate (green) and the short radiolunate (orange). The interligamentous groove (arrow) separates the radioscaphocapitate and long radiolunate ligaments.

fibres from this ligament are attached to the capitate. The arcuate ligaments are formed by the interdigitating fibres of the remaining radioscaphocapitate and ulnocapitate ligaments (Berger, 2001a). The arcuate ligaments support the capitate without being attached to it (Berger, 2001a), acting like a labrum to guide the seemingly unconstrained capitate head whilst providing support for the radial and ulnar sides of the carpus. The arcuate ligaments may therefore be considered a functional derivation of the ligamentous arrangement of the carpus, rather than distinct structures. The scaphoid attachment of the radioscaphocapitate ligament is on the radial aspect of the waist of the scaphoid and the proximal half of the scaphoid tubercle. It forms the radial segment of the radiocarpal capsule and contributes to the palmar segment of the capsule (Berger, 2001a). A triangular depression may be observed on the palmar surface of the ligament that demarcates the hemi-circumferential attachment to the proximal margins of the distal pole of the scaphoid (Berger, 2001a). Ulnar to this, the long radiolunate ligament is attached to the palmar margin of the radius and separated from the radioscaphocapitate ligament by an interligamentous groove[*] (Berger, 2001a). Moving in a proximal-ulnar direction along the palmar margin of the radius, the long radiolunate, the radioscapholunate and the short radiolunate ligaments are consecutively attached (Berger, 1996). The long radiolunate ligament is attached to the radial margin of the palmar "horn" of the lunate, as is the short radiolunate ligament. Together they form a thick band that is only separated by the radioscapholunate ligament (Berger, 2001a), which is not considered to be a true ligament (Berger, 2001a; Berger and Kauer, 1991; Feipel and Rooze, 1999).

[*] termed "interligamentous sulcus" and "Space of Poirier" in the reviewed literature. Terminologia Anatomica (1999) requires the use of "groove" instead of "sulcus" when describing structures using the common English nomenclature. "Sulcus" may only be used if all descriptions are in latin.

The radioscapholunate ligament is a neurovascular mesocapsule that is attached between the proximal attachments of the short and long radiolunate ligaments on the radius (Berger and Kauer, 1991). Interdigitated with the proximal region of the scapholunate interosseous ligament, the radioscapholunate ligament primarily transmits vascular and nervous tissue to the lunate, and therefore has greatly reduced collagen content (Berger, 1996). The fascicular organisation is less ordered than a true ligament and transmits a high concentration of small vessels (Berger, 2001a; Berger and Blair, 1984). The ligament contains the terminal branches of the anterior interosseous nerve and blood vessels that are anastomosed with the distal radial arch (Berger, 2001a). The blood vessels within the ligament do not supply the scaphoid or the lunate, but appear to supply the scapholunate ligament (Berger and Kauer, 1991). The ligament pierces the palmar radiocarpal capsule. A distinct epiligamentous sheath was found to envelope the radioscapholunate ligament, and was continuous with the local capsular tissue (Berger and Blair, 1984). The radioscapholunate ligament may serve some minor mechanical purpose, stabilising the proximal pole of the scaphoid in relation to the radius, but its major function seems to be to provide support for the vessels which it conveys (Berger and Blair, 1984).

The dorsal radiocarpal ligament is attached to the dorsal margin of the distal aspect of the radius (figure 3.4). The site of attachment is continuous from the sigmoid notch of the radius to an area distal to Lister’s tubercle (Berger, 2001a). The dorsal radiocarpal ligament may also be attached jointly to the dorsal margin of the distal aspect of the radius and the scaphoid waist (Bogumill, 1988). It is then passed in an oblique and ulnar fashion to the dorsal apsects of the lunate and triquetrum, where the most extensive attachment is to the dorsal aspect of the triquetrum (Berger, 2001a). The dorsal radiocarpal ligament

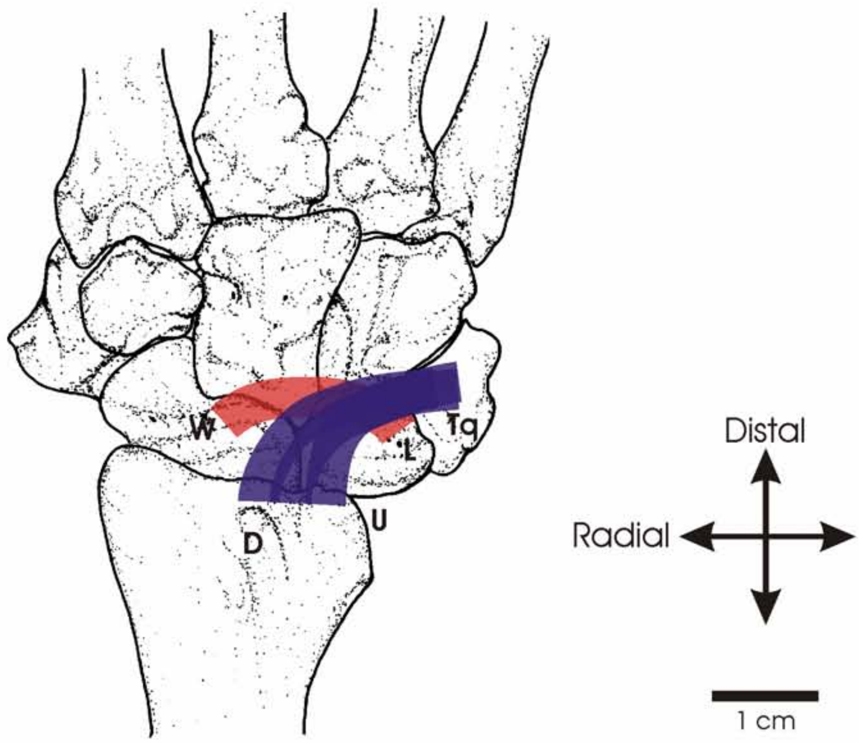


Figure 3.4 The dorsal radiocarpal ligament. The main fibres (blue) of the dorsal radiocarpal ligament are attached proximally to the radius between the ulnar notch (U) and the dorsal tubercle (D), and distally to the triquetrum (Tq). Accessory fibres (red) are attached to the dorsal aspect of the waist of the scaphoid (W) and the lunate (L).

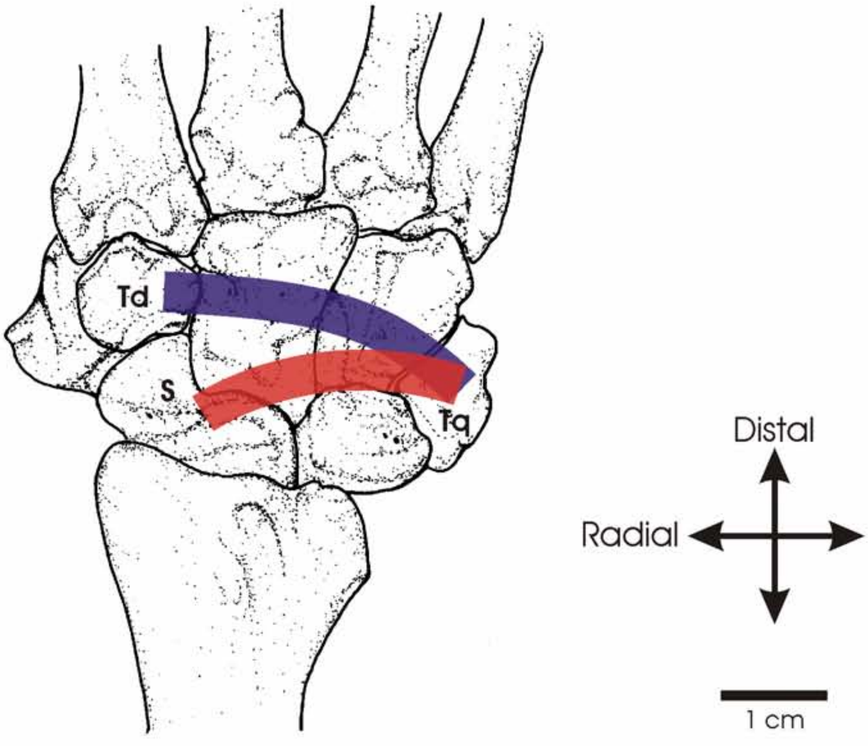


Figure 3.5 The dorsal intercarpal ligament. The ulnar attachment of the dorsal intercarpal ligament is to the dorsal tubercle of the triquetrum (Tq). A proximal band (red) is attached radially to the crest of the scaphoid (S) and a distal band is attached to the trapezoid (Td).

ensures that the carpus and hand are passively pronated when the radius is actively pronated by the pronator quadratus and/or pronator teres muscles (Bogumill, 1988).

The dorsal intercarpal ligament is attached to the dorsal tubercle of the triquetrum (Berger, 2001a). The dorsal intercarpal ligament is passed radially across the carpus as two distinct bands (figure 3.5). The proximal band is attached to the crest of the scaphoid, whilst the distal band is attached to the trapezoid (Berger, 2001a). The relationship between the bands is important in maintaining wrist stability through flexion and extension (Berger, 2001b). The angle between the two bands at their common site of attachment on the triquetrum is acute during extension. In full extension the dorsal structures of the wrist have no influence over the stability of the wrist. When the wrist is moved into flexion, the angle between the attachments becomes almost orthogonal, indirectly stabilising the scaphoid against the radius (Berger, 2001a).

The dorsal scaphotriquetral ligament is extended from the dorsal part of the scapholunate interosseous ligament and attached to large area of the dorsal aspect of the triquetrum (Berger, 2001a). The dorsal scaphotriquetral ligament is also attached to the dorsal part of the triquetrolunate interosseous ligament, and is suggested to act as a labrum for the midcarpal joint (Berger, 2001a). The radial attachment of the dorsal scaphotriquetral ligament is to the dorsal surface of the waist of the scaphoid (Berger, 2001a).

3.1.2 The Scaphotrapeziotrapezoidal Joint

The articulation formed between the scaphoid, trapezium and trapezoid is termed the scaphotrapeziotrapezoidal (STT), or triscaphe joint (figure 3.6). As per the majority of carpal structures, ligamentous support is greatest on the palmar aspect of the joint. In fact, several authors report little or no dorsal support for the STT joint (Brown *et al*, 1998; Mizuseki and Ikuta, 1989; Viegas *et al*, 1999). Surprisingly, other authors have failed to report palmar ligaments supporting this joint, besides a radial collateral ligament (Brown *et al*, 1998; Feipel and Rooze, 1999; Johnstone *et al*, 1995; Mayfield, 1984; Mayfield *et al*, 1976; Timins *et al*, 1995). Conversely, other authors (Berger, 1997; Boabighi *et al*, 1993; Drewniany *et al*, 1985; Sicre *et al*, 1997; Taleisnik, 1976) report some dorsal support for the STT joint, and extensive palmar support. The palmar ligamentous support for the STT joint was even reported as multi-ligament complexes (Boabighi *et al*, 1993; Drewniany *et al*, 1985). Black *et al* (1987) reported no ligamentous support for the distal pole of the scaphoid, reasoning that the lack of support is responsible for high incidences of STT arthritis with prolonged scaphoid non-union. Similarly, Bogumill (1988) reports no ligamentous attachments on the scaphoid tubercle, but suggests that the dorsal radiocarpal ligament and "radial collateral ligaments" are attached to the scaphoid waist.

Boabighi *et al* (1993) reported two ligamentous components, forming a fan-like projection from the distal pole of the scaphoid (figure 3.7a). The radial component of the fan consisted of the radial scaphotrapezial ligament, while the ulnar component contained three ligaments: the ulnar scaphotrapezial, the scaphotrapezoid and the scaphocapitate ligaments. The authors alluded to the exemption of this complex from other reports, stating that it was hidden by the flexor carpi radialis tendon, and therefore likely to go

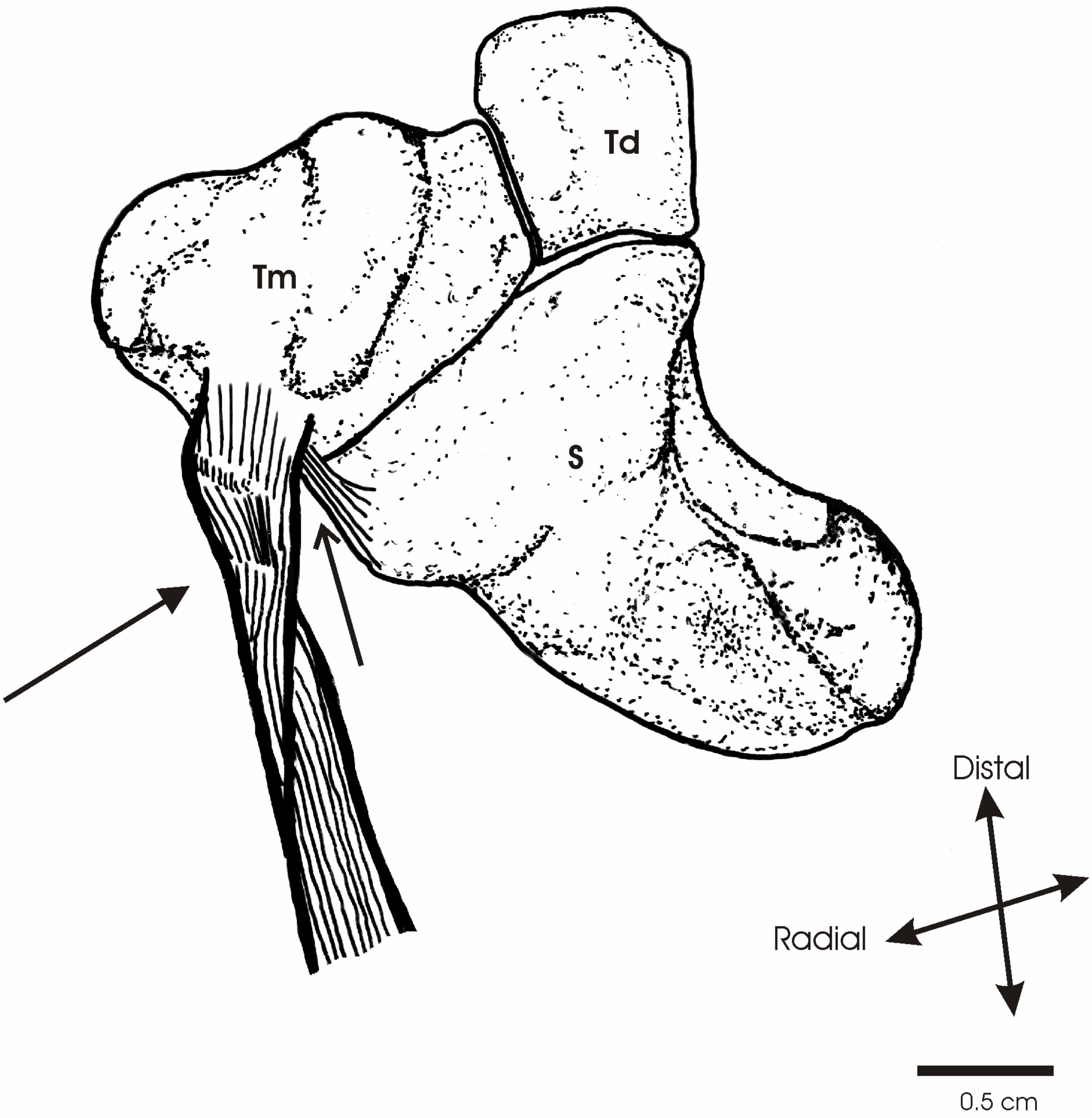


Figure 3.6 The scaphotrapeziotrapezoid joint. The STT joint is the three-way articulation between the scaphoid (S), trapezium (Tm) and trapezoid (Td). It is the most radial joint of the wrist and may also be called the triscaphe joint. Tendons (closed arrow) and ligaments (open arrow) support and move the joint, primarily on the radial margin of the joint.

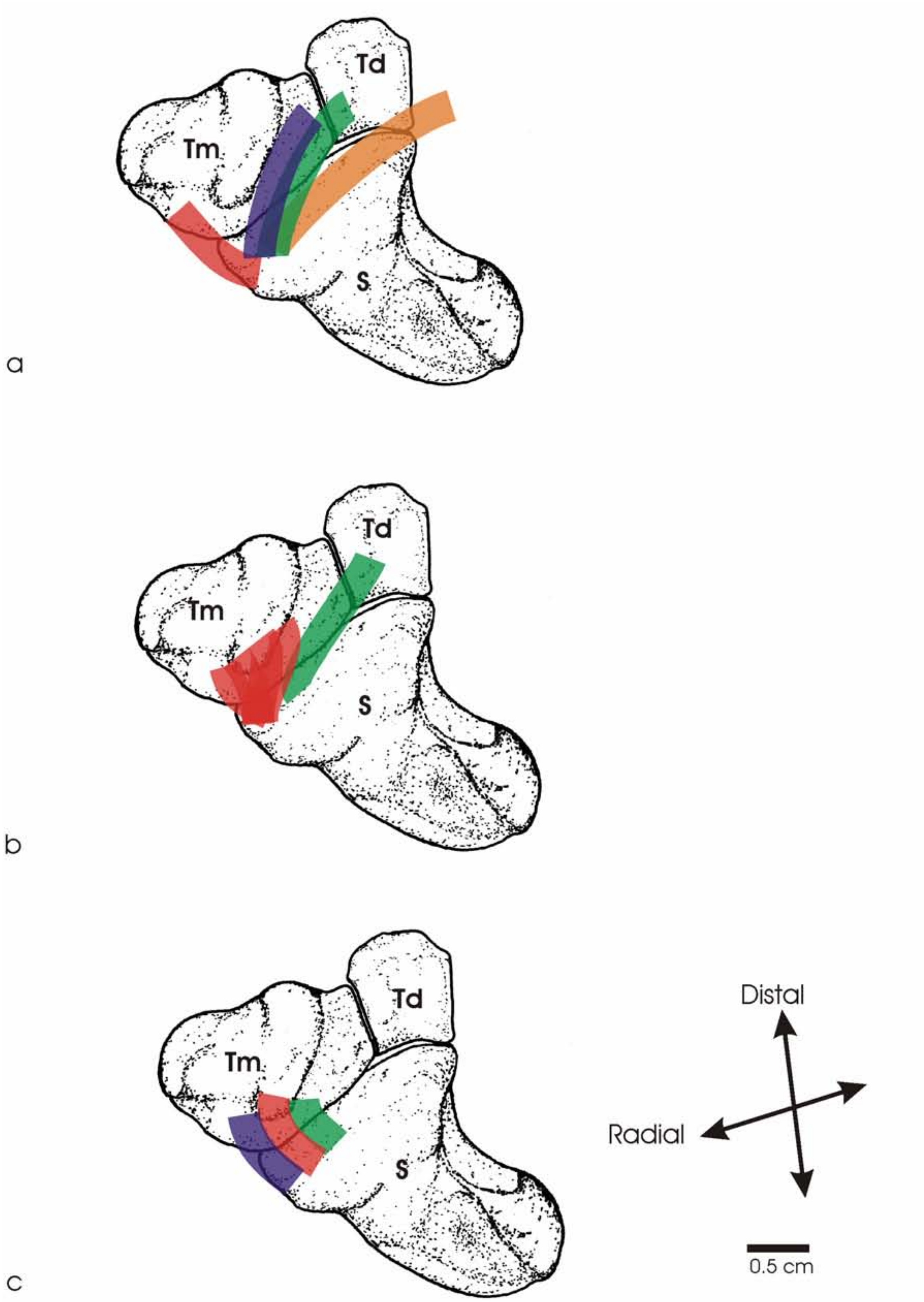


Figure 3.7 Varied descriptions of scaphotrapeziotrapezoidal ligaments. a - Boabighi et al (1993) report radial scaphotrapezial (red), ulnar scaphotrapezial (blue), scaphotrapezoid (green) and scaphocapitate (orange) ligaments; b - Berger (1996; 2001) reports a single scaphotrapeziotrapezoid ligament with a trapezial (red) and trapezoidal (green) band; c - Bettinger et al (1999) report a palmar scaphotrapezial ligament (green) and a radial scaphotrapezial ligament with trapezial (blue) and trapezial crest (red) distal attachments; S- scaphoid, Tm - trapezium, Td - trapezoid.

unrecognised. All of these ligaments were attached proximally to the scaphoid tubercle. Ligamentous structures were classified by the arrangement of collagen fibres and interstitial connective tissue. Two classes were described; wavy and parallel collagen fibres, and collagen fibres intermingled with interstitial tissue (Boabighi *et al*, 1993). The distal ligamentous complex of the scaphoid is described as being composed of wavy, parallel collagen fibres.

Biomechanical analysis suggests that the ‘distal scaphoid complex’ is twice as strong as the scapholunate ligament, and hence is the primary supporter of the scaphoid (Boabighi *et al*, 1993). Failure of the ‘distal scaphoid complex’ allows the scaphoid to lie transversely within the carpus, thus force is transmitted directly to the scapholunate ligament, rather than being dispersed through the scaphoid to the radius (Boabighi *et al*, 1993). Scapholunate ligament failure is therefore secondary to disruption of the ‘distal scaphoid complex’.

Berger (1996; 2001) reports only of a single ligamentous structure at the STT joint (figure 3.7b). The scaphotrapeziotrapezoid ligament encapsulates the distal pole of the scaphoid and is attached to the radial and ulnar aspects of the distal pole of the scaphoid from whence it is divided into trapezial and trapezoidal bands (Berger, 2001a). The trapezial band is triangular in structure, with the attachments to the palmar and radial aspects of the trapezium being likened to the arms of the triangle, whilst the scaphoid attachment provides a proximal apex to the simile (Berger, 2001a). The trapezoidal band of the scaphotrapeziotrapezoid ligament is attached to the palmar aspect of the trapezoid (Berger, 2001a). The dimensions of the trapezial band dominate over the thin, straight trapezoidal band as more support may be required for the radially positioned trapezium.

The palmar scaphotrapezial ligament is attached to the proximal fourth of the palmar aspect of the trapezium and the scaphoid tuberosity (Bettinger *et al*, 1999) (figure 3.7c). The fibres of this ligament are orientated longitudinally in the same direction as the first metacarpal. The trapezial attachment contributes to the floor of the flexor carpi radialis tendon tunnel. The radial scaphotrapezial ligament is attached to the radial aspects of the trapezial crest, the trapezium and the scaphoid tuberosity (Bettinger *et al*, 1999). The fibres are longitudinally orientated.

The scaphocapitate ligament is attached to the distal pole of the scaphoid and to the palmar aspect of the capitate body (Berger, 2001a). Boabighi *et al* (1993) considered it part of the ulnar band of the scaphotrapeziotrapezoid ligament complex, and stated that the radial attachment of the scaphocapitate ligament was to the scaphoid tubercle. The scaphocapitate ligament has been observed in coexistence with a scaphocapitate interosseous ligament, and has been replaced by it in other observations. Some studies report no scaphocapitate ligament at all.

3.1.3 The Radial Collateral Ligament

Bogumill (1988) reports that the dorsal radiocarpal ligament and "radial collateral ligaments" are attached to the scaphoid waist. The radial collateral ligament is attached to the styloid process of the radius and is then attached to the radial aspect of the scaphoid waist. The ligament is then continued to the trapezium, where the fibres are interdigitated with those of the transverse carpal ligament and dorsal capsular ligament (Bogumill, 1988).

The radial artery is crossed over the radial collateral ligament at the radial margin of the wrist.

3.1.4 The Trapeziotrapezoidal and Trapezocapitate Joints

The trapeziotrapezoidal joint is formed by the articulation between the ulnar aspect of the trapezium and the radial aspect of the trapezoid (Berger, 1996) (figure 3.8). The stability of the joint is maintained by the trapeziotrapezoidal interosseous ligament. This ligament may be separated into dorsal and palmar parts, each of which is attached to the entire length of the respective joint margin (Berger, 2001a). Both parts are composed of transverse fibres that are extended into the cortices of each bone (Berger, 2001a).

Contrary to the report of Berger (1996), dorsal and palmar trapeziotrapezoid ligaments were observed (Berger, 1996; Bettinger *et al*, 1999). The dorsal trapeziotrapezoidal ligament is attached to the proximal half of the dorso-radial aspect of the trapezoid (Bettinger *et al*, 1999). The palmar trapeziotrapezoidal ligament is attached to the palmar-ulnar tubercle of the trapezium, and is separated from the trapeziocapitate ligament that lies superficial to it by a layer of fatty connective tissue. The trapezoidal attachment of the ligament is to the palmar-radial corner of the trapezoid (Bettinger *et al*, 1999).

The trapezocapitate joint is similar in composition to the trapeziotrapezoidal joint (Berger, 2001a; Bogumill, 1988) (figure 3.9). Dorsal and palmar parts of the interosseous ligament are composed of transverse fibres, but they are not attached along the entire joint margin. The trapezocapitate interosseous ligament is only attached to the body of the

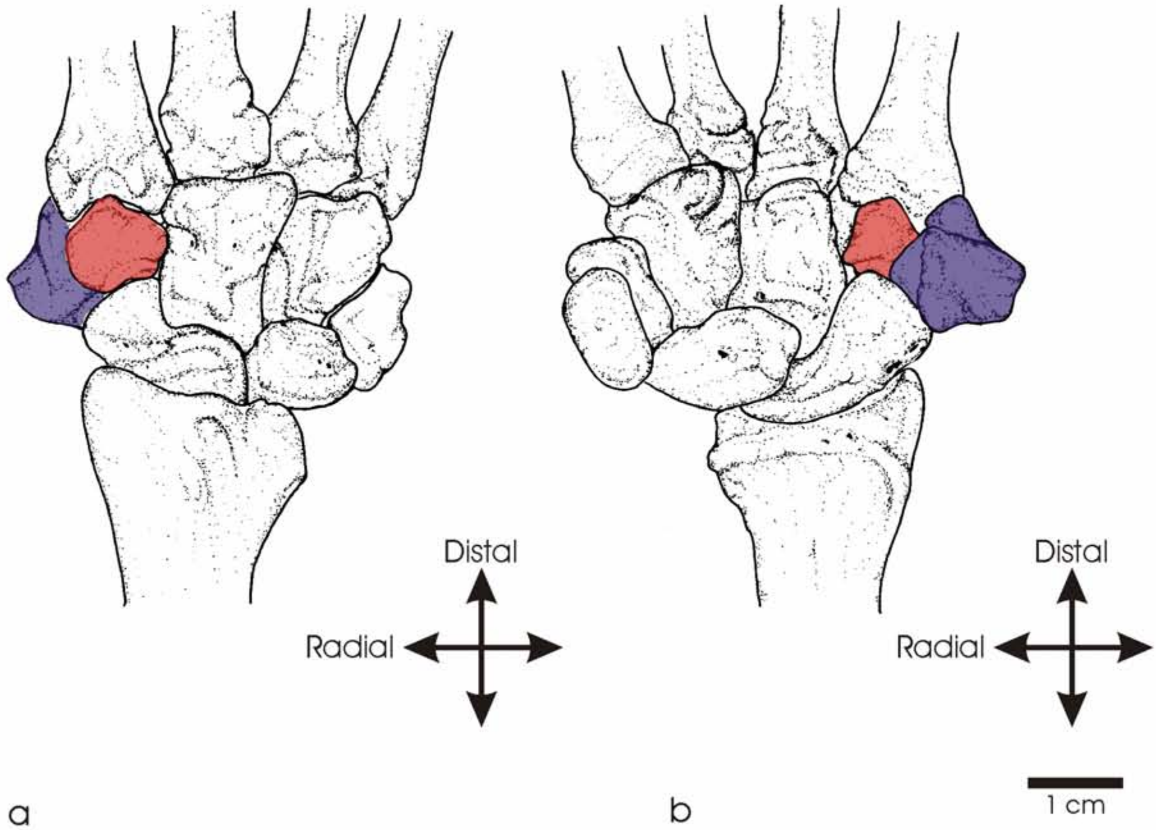


Figure 3.8 The trapeziotrapezoid joint. a - dorsal aspect of the wrist; b - palmar aspect of the wrist; red - trapezoid, blue - trapezium.

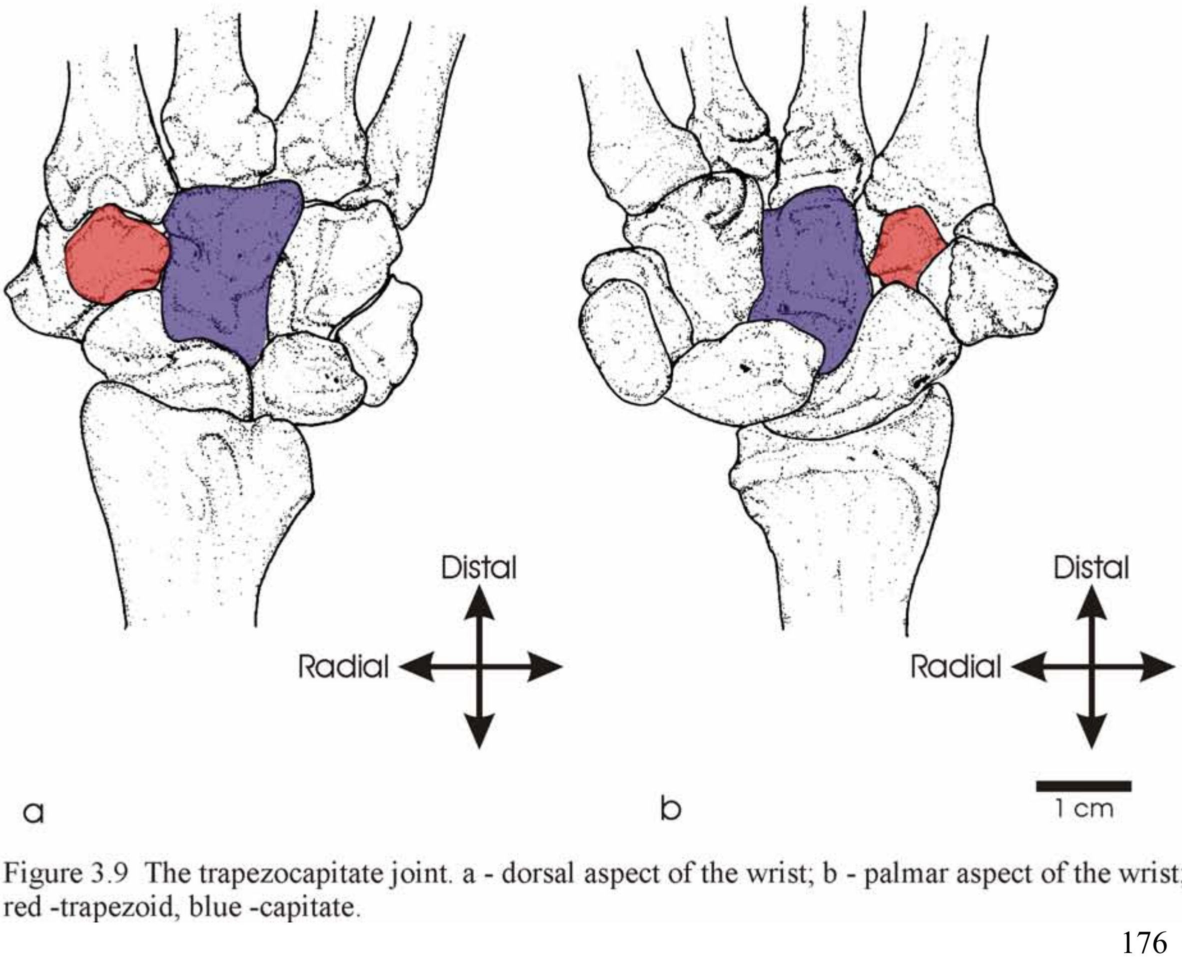


Figure 3.9 The trapezocapitate joint. a - dorsal aspect of the wrist; b - palmar aspect of the wrist; red -trapezoid, blue -capitate.

capitate and a corresponding length along the trapezoidal margin of the joint. These two bands are joined by a third, deeper band, which may be considered singularly as a deep trapezocapitate ligament (Berger, 1996), or the three may be collectively termed a trapezocapitate interosseous ligament (Berger, 2001a). The trapezoid has a notch marking the attachment of the deep band (Berger, 2001a).

The trapeziocapitate ligament is attached to the palmar-ulnar corner of the proximal half of the trapezium (Bettinger *et al*, 1999). The fibres are then passed transversely to the distal half of the palmar-radial aspect of the capitate (Bettinger *et al*, 1999). The ligament forms the floor of the flexor carpi radialis tendon tunnel and lies superficial to the palmar trapeziotrapezoidal ligament (Bettinger *et al*, 1999). The trapeziocapitate ligament is superficial to a fatty layer of connective tissue and the palmar trapeziotrapezoid ligament.

3.1.5 The Scapholunate Joint

The articulation between the scaphoid and lunate is essential to wrist function (Belsole *et al*, 1986; Kauer, 1986; Kobayashi *et al*, 1997). During dorsal-palmar movement of the wrist the scaphoid and lunate are dissociated from each other (Short *et al*, 2002; Tang *et al*, 2002; Wolfe *et al*, 2000; Youm *et al*, 1978). This motion is promoted by the differences in curvature of the articulating surfaces involved and is regulated by soft tissue support (Belsole *et al*, 1986). An arthroscopic probe should not be able to enter the scapholunate joint unless the integrity of the joint has been compromised (Bettinger *et al*, 1995).

The scapholunate interosseous ligament is a "C-shaped" ligament with three distinct regions (Abe *et al*, 2003; Berger and Blair, 1984; Sokolow and Saffar, 2001). The ligament is attached to the proximal, dorsal and palmar aspect of the scapholunate joint articular surfaces. The dorsal and palmar parts of the ligament are structurally similar to capsular ligaments, whilst the proximal part is a fibrocartilaginous membrane (Berger, 1996). The proximal fibrocartilaginous region is merged with the radioscapholunate ligament at the distal attachment of the latter. There may be a distal meniscal projection into the joint space from this part of the ligament (Berger, 2001a). The dorsal part of the ligament is the thickest, with collagen fibres orientated transversely across the joint. The palmar part of the ligament is much thinner and is passed obliquely (palmar to dorsal from scaphoid to lunate) across the joint. The radial (scaphoid) attachment of the palmar part of the ligament is more palmar than the ulnar (lunate) attachment, which is more dorsal. The palmar part of the scapholunate interosseous ligament lies deep to the long radiolunate ligament, but the two ligaments are not structurally linked (Berger, 2001a).

The scapholunate ligament is described as a "horse shoe" between the articulating surfaces (Boabighi *et al*, 1993). The palmar region of the scapholunate ligament is described as collagen fibres intermingled with interstitial tissue. It is suggested that this fibre orientation gives only weak support to the scapholunate joint (Sokolow and Saffar, 2001). Biomechanical studies suggest that the weak proximal area of the scapholunate ligament was the first to rupture under simulated loading (Busse *et al*, 2002; Short *et al*, 2002; Tang *et al*, 2002; Thienpont *et al*, 2003). Whilst some contend that the scapholunate ligament integrity is essential to stability of the wrist (Berger, 2001a; Bond and Berquist, 1991), others suggest that its importance is only realised once the distal ligamentous support of the scaphoid has been disrupted (Boabighi *et al*, 1993). Those in favour of a predominant role for the scapholunate ligament also suggest poor ligamentous support for the distal pole of the scaphoid (Bond and Berquist, 1991; Brown *et al*, 1998).

3.1.6 Aims

The aims of this component of the study are to clarify the ligamentous anatomy of the radial side of the carpus. The many detailed descriptions of various ligaments by various authors often contradict each other. It is unclear whether variation between reports is due to anatomical variation between sample populations or variation between observers. Furthermore, the functional significance of these results is often unclear .To facilitate clear descriptions and reduce the subjectivity of the investigation a combination of detailed dissection and histological sectioning will be used to describe the ligaments. The ligament descriptions will be used to discuss the potential influence of the observed ligaments on carpal mechanics. It is hoped that reduction in subjectivity and a focus on functional anatomy will clarify conflicting results in the reviewed literature and allow the results to be applied to the long-standing issue of carpal movement.

3.2 Materials

Cadaveric specimens were arbitrarily selected from the Ray Last Anatomy Laboratory, Department of Anatomical Sciences, The University of Adelaide. Permission for their use, as granted by the Head of the Department of Anatomical Sciences, was covered by the Anatomy Act of South Australia (1983). All specimens were previously embalmed through the normal procedures of the Ray Last Anatomy Laboratory (see Appendix I).

From the sample population 15 pairs (right and left hands from an individual) were included. The left hand of each pair was used dissected, whilst the right hand was processed for histological assessment. The remaining, unpaired hands (n = 40) were dissected, resulting in a total dissection sample number of 55 hands.

3.3 Methods

Specimens were dissected using standard surgical equipment and with the aid of three-times magnification surgical loupes. High intensity lighting was used to ensure optimal visualisation of the specimen at all times. A standard dorsal approach to the midcarpal joint capsule was used, as described previously (Mizuseki and Ikuta, 1989), but was later amended to include only dissection of the radial half of the wrist, thus preserving the ulnar half of each specimen for future studies. Once the dorsal capsular surface was exposed the dissection was continued radially to expose the palmar structures. Each subsequent tissue layer (from superficial to deep) was removed and the specimen digitally photographed (see Appendix V). This unveiling procedure was continued until the dissection reached the midcarpal joint capsule. Close examination was then required to discern the orientation of fibrous tissues. Larger ligaments were clearly defined as ensheathed or encapsulated groupings of parallel fibres identifiable from an attachment on one bone to an attachment on another (Benjamin and Ralphs, 1997). Smaller ligaments were difficult to determine so identification was reliant upon fibre orientation. Classification as a ligament required fibres to be identified from one attachment to another. Once identified, capsular and adipose tissue was dissected away from the individual ligaments to clarify the outline of the ligaments for photography. The ligament attachment sites were also cleared of surrounding tissues to clarify the recorded images and facilitate measurement of the ligament.

The occurrences of ligamentous attachment to various osseous landmarks throughout the sample population were tabulated. Specimens with similar combinations of attachments were grouped together. In order to precisely describe the individual ligaments observed, a distinctive nomenclature was designed. This nomenclature closely followed the guidelines presented in Terminologia Anatomica (Terminology, 1999), and those proposed by the International Wrist Investigator's Workshop (Gilula *et al*, 2002).

The ligaments were measured individually. The initial cohort of specimens (n = 10) was measured manually (DialMax, Swiss Precision) on three separate occasions, and three subsequent times digitally. These results were then compared to assess their reliability. There were no statistically significant ($p>0.05$) differences between each round of measurements. All remaining specimens were then subject to three rounds of digital measurement. Three measures of length and width, and one measure of angulation were taken for each ligament. More detail of the measurements is reported in Appendix VIII. The ligaments observed within a single group of specimens were re-grouped according to their individual attachment sites. Statistical analyses were run to assess the significance of any difference in angulation and dimensions within each of these subgroups.

Histological sections (as described in Chapter 2.2) were used to objectively differentiate between ligament and joint capsule. The histological data were used to create generalised maps of ligamentous and capsular attachment to the carpal bones investigated. The specimens prepared for histological investigation (n = 15) were paired with hands from the gross component of the study. The hands of thirty individuals were therefore studied macroscopically and microscopically. The histological sections were also used in specific circumstances to eliminate uncertainty over dubious structures.

3.4 Results

3.4.1 Distal Pole of the Scaphoid

The gross specimens (n = 55) could be divided into two groups based on their ligamentous arrangements. In all specimens, a band of ligamentous tissue was attached to the distal pole of the scaphoid and some part of the trapeziotrapezoid complex. Specimens were noted to have either a trapeziotrapezoid attachment width greater than the scaphoid attachment width (n = 32; 58.2%; figure 3.10a), or a scaphoid attachment width greater than the trapeziotrapezoid width (n = 23; 41.8%; figure 3.10b). When the distal attachment width was greatest (type one), the average greatest trapeziotrapezoid attachment width for these specimens (3.95±1.25mm) was significantly greater than the average greatest proximal (scaphoid) attachment width for the same specimens (2.364±0.695mm; $p < 0.05$; figure 3.11). When the proximal (scaphoid) attachment was greatest (type two), the average greatest scaphoid attachment width for these specimens (5.443±1.627mm) was significantly greater than the average greatest trapeziotrapezoid (distal) attachment width for the same specimens (2.68±0.785mm; $p < 0.01$). The average greatest distal attachment widths for the two types were significantly different from each other ($p < 0.05$), as were the average greatest proximal attachment widths for the two types ($p < 0.01$). The specimens were divided into two groups based on the arrangement of the scaphotrapeziotrapezoidal ligaments. Type one wrists had greater distal ligament attachment widths, whilst type two wrists had greater proximal ligament attachment widths at the scaphotrapeziotrapezoidal joint.

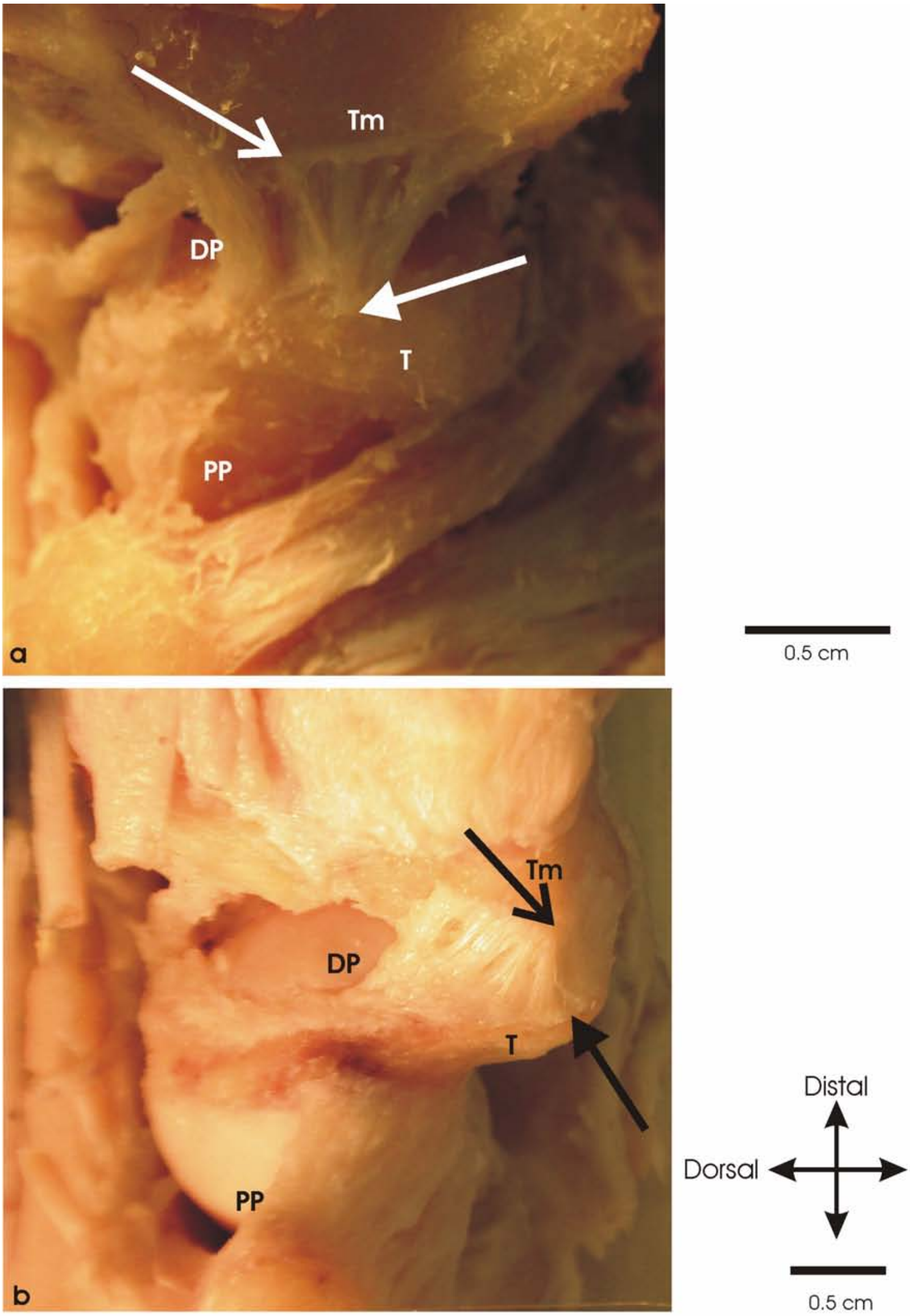


Figure 3.10 Radial view of the two types of scaphotrapeziotrapezoid ligaments. a - v-shaped band of ligamentous tissue with the width of the distal attachment (open arrow) to the trapezium (Tm) greater than the width of the proximal attachment (closed arrow). Specimens with this arrangement were categorised as type one wrists; b - inverted v-shaped band with width of the proximal attachment (closed arrow) to the scaphoid tubercle (T) greater than the width of the distal attachment (open arrow). Specimens with this arrangement were categorised as type two wrists; DP - distal articular surface of the scaphoid, PP - proximal articular surface of the scaphoid.

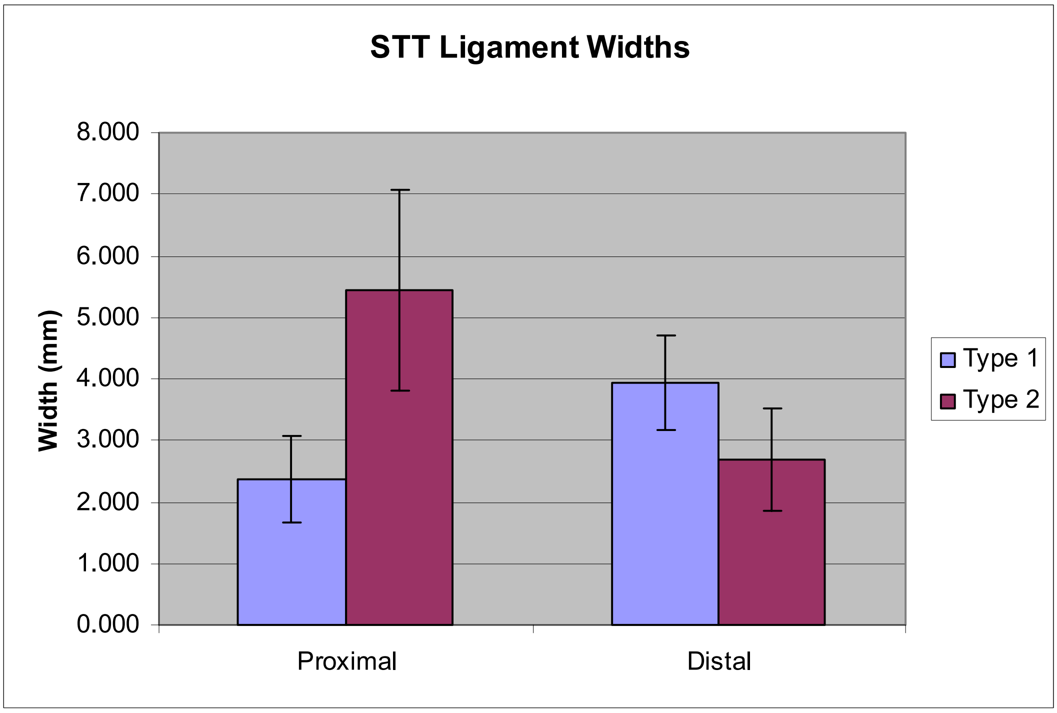


Figure 3.11 Mean Scaphotrapeziotrapezoidal (STT) joint ligament attachment widths. The width of the proximal (scaphoid) and distal (trapeziotrapezoid) attachment sites were measured.

Scaphotrapeziotrapezoid joint ligament indices were calculated by dividing the distal attachment width of each specimen by the proximal attachment width. The resulting scaphoid indices were compared for each type of wrist. The mean scaphotrapeziotrapezoid ligament index of the type one wrists (1.783±0.659mm/mm) was significantly greater than the index of the type two wrists (0.543±0.260mm/mm; $p < 0.05$).

Despite statistically significant differences in the attachment widths, the position of the ligamentous attachments was similar in all specimens. The mid-point of the proximal attachments, regardless of width, was near the most radial point of the scaphoid tubercle, whilst the mid-point of the distal attachments was the palmar-radial tubercle. The distal attachments were primarily to the radial proximal-palmar eminence of the palmar margin of the scaphoid articular facet of the trapezium and the palmar-radial tubercle (figure

3.12a). Wide distal attachments were also attached to the dorsal-radial tubercle of the trapezium. When the distal attachment width was greatest 7.3% (n = 4) of specimens had fibres attached to the trapezoid. These attachments were generally limited to the dorsal aspect of the trapezoid (figure 3.12b). When the proximal attachment width was greatest, there were no fibres attached to the trapezoid.

Only one case of significant variation of the trapeziotrapezoid complex was observed (figure 3.13). The variant specimen had an elongated dorsal-ulnar margin of the trapezoid that continued to be articulated with the third metacarpal. The ligamentous array of the scaphotrapeziotrapezoidal joint of this specimen was not distinct from that of other specimens of the same type.

The histological comparisons confirmed the results of the gross investigation (figure 3.14). Type one wrists had greater trapezial ligamentous attachments than type two wrists. Type two wrists had greater distal scaphoid ligamentous attachments that type one wrists. The enthesial bone to which the ligaments were attached had a significantly greater mean relative area in type one trapezia (0.642±0.1 mm^2/mm) than that of type two trapezia (0.352±0.105 mm^2/mm; $p < 0.05$; figure 3.15). The mean relative enthesial bone area of the distal pole of the scaphoid for type two (0.496±0.088 mm^2/mm) wrists was significantly greater than that of type one wrists (0.305±0.085 mm^2/mm; $p < 0.05$; figure 3.15).

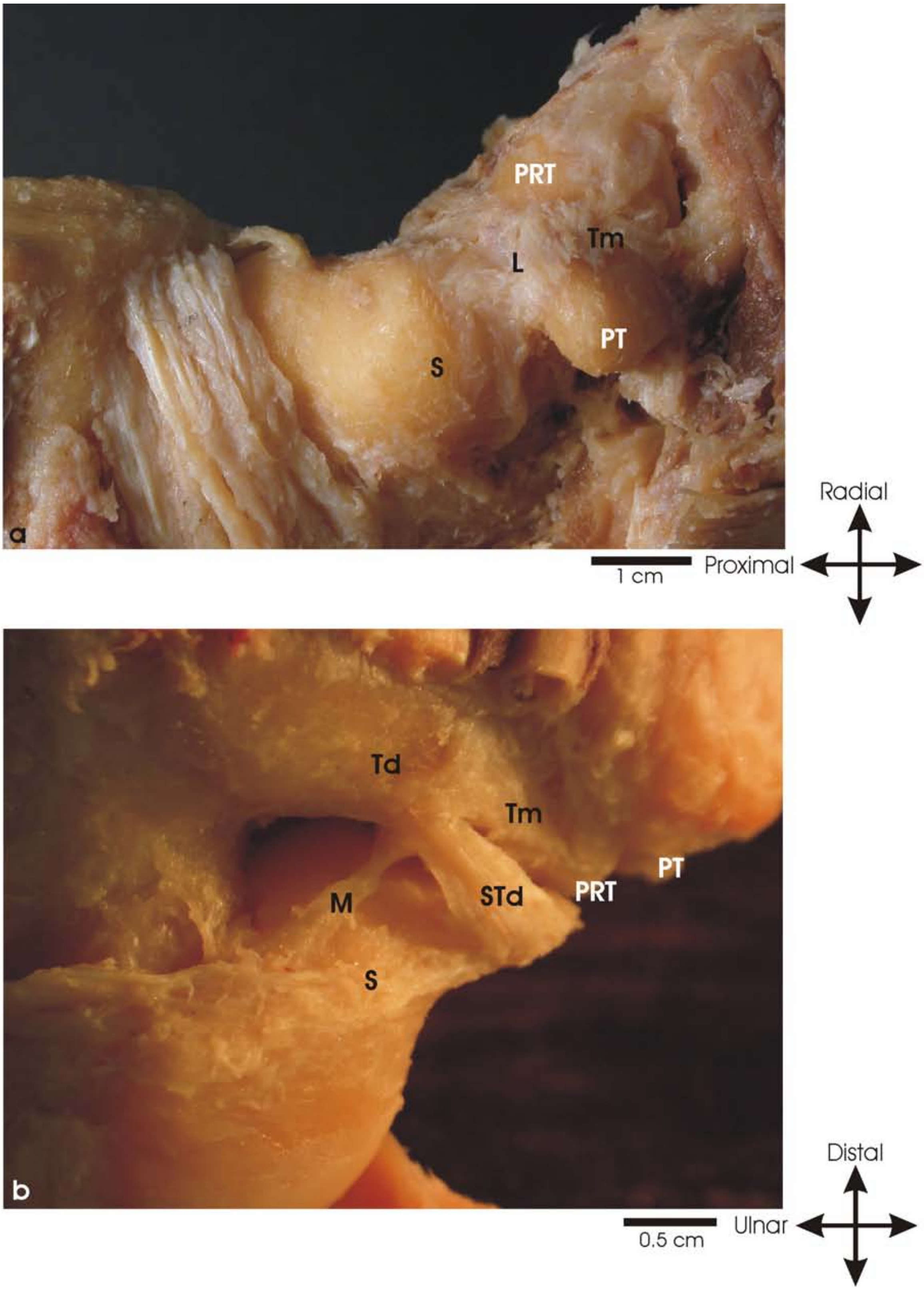


Figure 3.12 Distal attachments of scaphotrapeziotrapezoidal joint ligaments. a - the type one wrists had a ligamentous band with a wide distal attachment to the trapezium (Tm) and a narrow proximal attachment to the scaphoid (S). The distal attachment was predominately to the palmar tubercle (PT) and the palmar-radial tubercle (PR) of the trapezium. The narrow distal attachment of the type two wrists was predominately to the palmar-radial tubercle (PRT) or to the radial proximal-palmar eminence (not shown); b - the only trapezoidal attachments of the STT joint ligaments observed were to the dorsal aspect of the trapezoid (Td). These attachments were only observed on the type one wrists; STd -scaphotrapezoid ligament, M - membranous band.

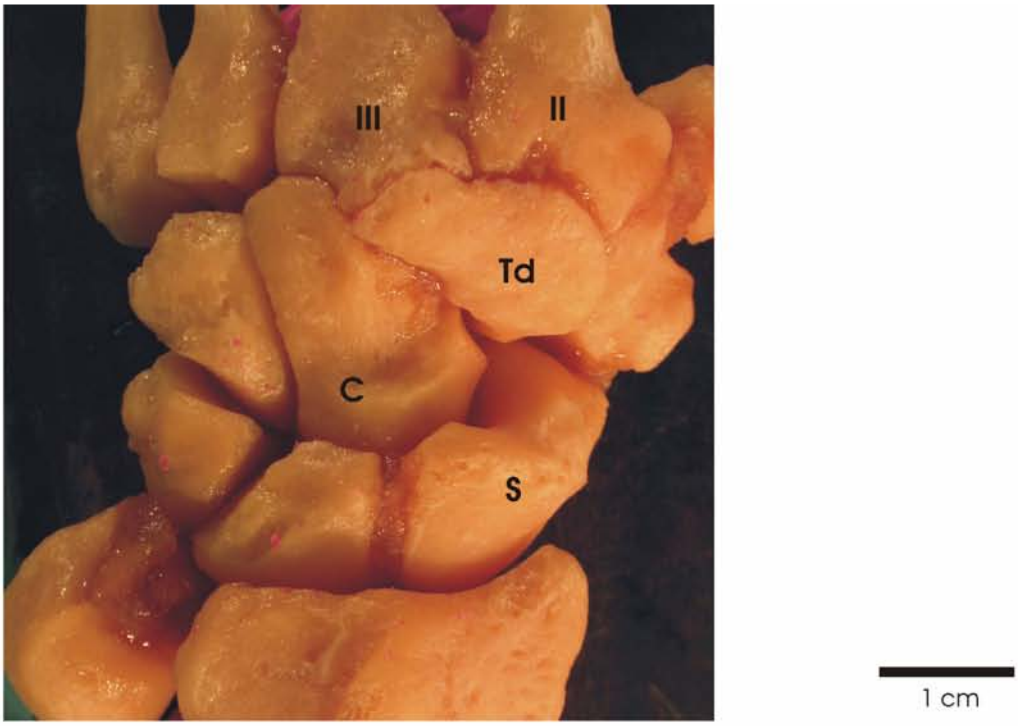


Figure 3.13 Variation of trapezoid. One specimen was observed with a variant of the trapezoid (Td) which involved an articulation with the third metacarpal (III) in addition to capitate (C) and second metacarpal (II) articulations. The ligaments observed were similar to other specimens in the group.

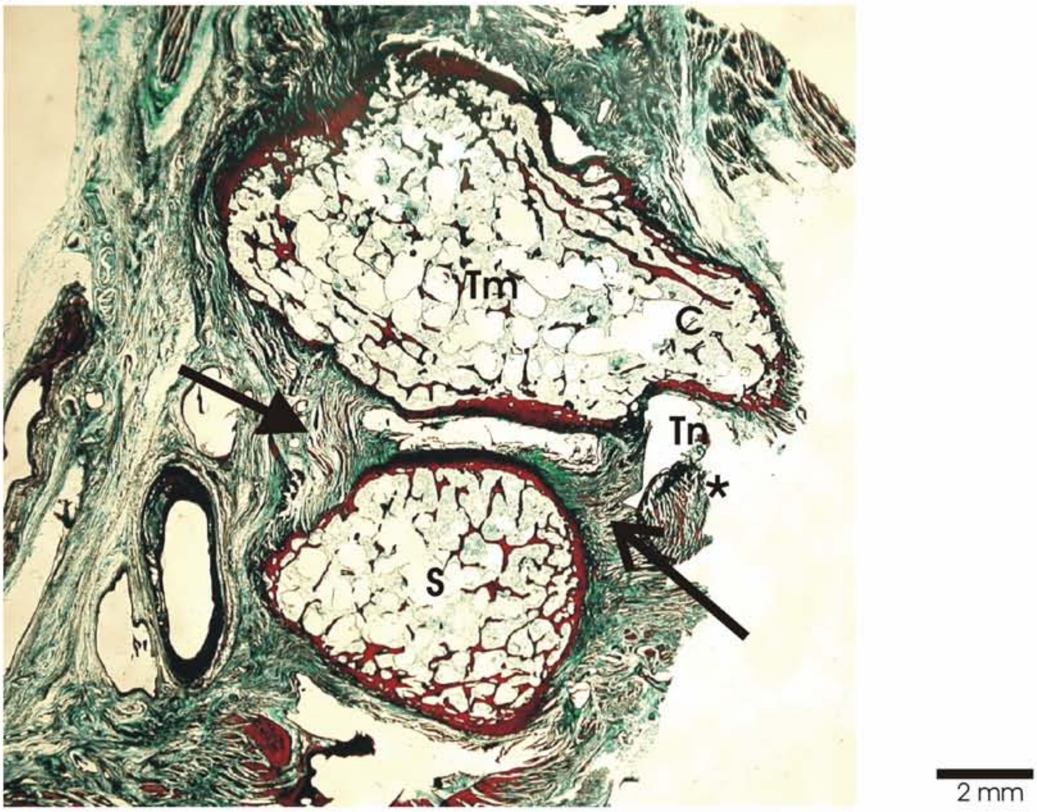


Figure 3.14 Histology of the scaphotrapezial joint. The articulation between the scaphoid (S) and the trapezium (Tm) is supported at its dorsal (closed arrow) and palmar (open arow) margins by ligaments (stained red). The dorsal trapezial attachment is to the concave dorsal aspect of the trapezium, whilst the palmar trapezial attachment is to one of the proximal-palmar eminences of the palmar margin of the scaphoid articular facet of the trapezium; * - artefactual tear may have destroyed ligamentous attachmentto the trapezial crest (C). These fibres may have contributed to the palmar roof of the sheath for the flexor carpi radialis tendon (Tn, removed).

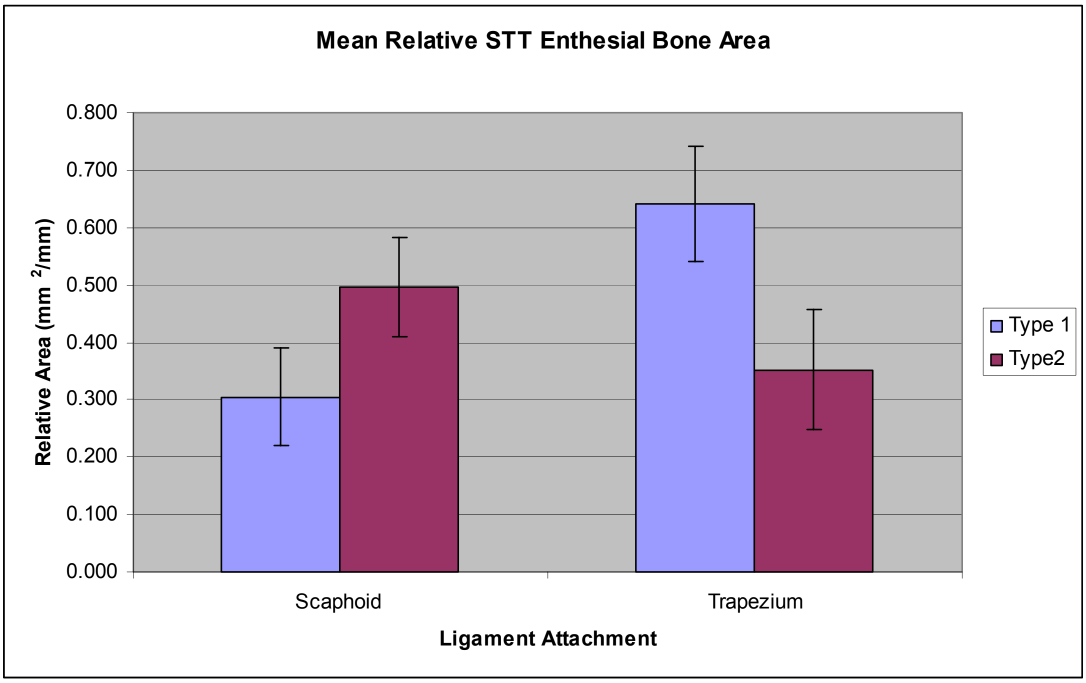


Figure 3.15 Mean relative STT enthesial areas. The mean area of enthesial bone relative to the length of enthesial bone for the STT ligament attachments in each type of wrist observed.

3.4.2 Dorsal Aspect of the Scaphoid

The dorsal intercarpal ligament was variable between type one and type two wrists. The dorsal intercarpal ligament of the type one wrists was attached to the proximal margin of the dorsal aspect of the trapeziotrapezoid complex and was not directly attached to the scaphoid (figure 3.16a). In some type one wrists (n = 19; 34.5% sample, 60% type one) the dorsal intercarpal ligament received fibres from the dorsal aspect of the scaphoid. These accessory fibres were perpendicular to the fibres of the dorsal intercarpal ligament (figure 3.16b). The dorsal intercarpal ligament of type two wrists was attached to the proximal crest of the dorsal aspect of the scaphoid, and was not attached to the trapeziotrapezoid complex (figure 3.16c). The average fibre angle of the dorsal intercarpal ligaments relative

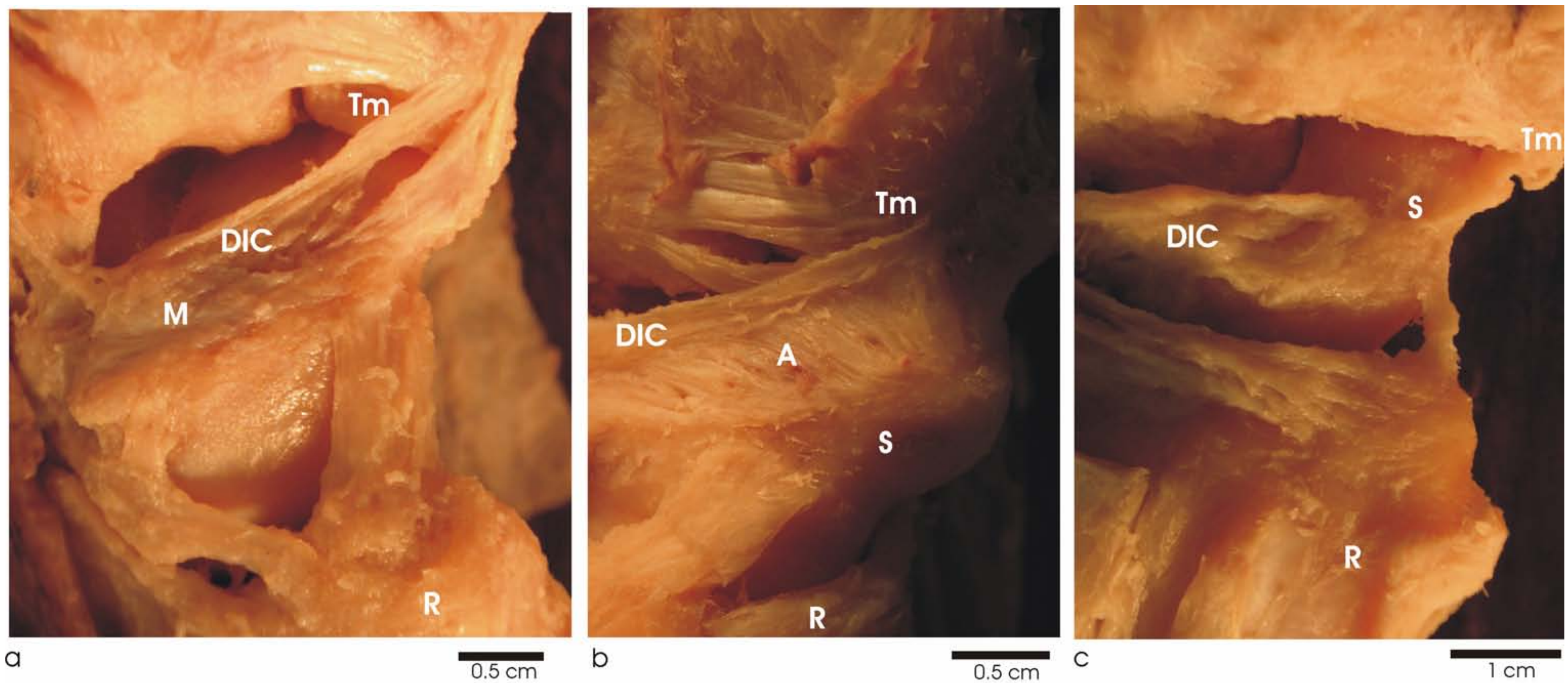


Figure 3.16 The dorsal intercarpal ligament in the two types of wrist. a - some type one wrists (n = 13) had the dorsal intercarpal ligament (DIC) attached to the trapezium (Tm) with only a membranous (M) attachment to the scaphoid; b - the remaining type one wrists (n = 19) had the dorsal intercapal ligament (DIC) attached to the trapezium (Tm) and accessory fibres (A) attached to the scaphoid (S) perpendicular to the dorsal intercarpal ligament fibres; c - type two wrists (n = 23) had the dorsal intercarpal ligament (DIC) attached to the scaphoid (S), but not to the trapezium (Tm); R - radius.

to the transverse plane of the carpus was measured (figure 3.17). The average angle of the dorsal intercarpal ligaments with trapeziotrapezoid attachments (31.6 ± 6.32^0) was significantly greater than the average angle of the dorsal intercarpal ligaments with scaphoid attachments (14.72 ± 2.11^0; $p < 0.05$).

The histological comparisons confirmed the results of the gross investigation (figure 3.18). Type one wrists had no distinct ligamentous attachments to the dorsal aspect of the scaphoid, with the exception of accessory attachments of the dorsal intercarpal ligament in the corresponding specimens. Type two wrists had a small area of enthesial bone on the dorsal aspect of the scaphoid corresponding to the attachment site of the dorsal intercarpal ligament observed macroscopically.

3.4.3 The Scaphocapitate Ligament

The length of the scaphocapitate ligament was variable between the two types of wrists (figure 3.19). The mean proximal fibre length (11.879±0.593mm) and mean median length (9.507±1.23mm) for type one wrists were significantly greater than the mean proximal (7.381±0.781mm; $p < 0.05$) and mean median (7.109±1.782mm; $p < 0.05$) lengths of the type two specimens (figure 3.20). The mean distal fibre length was not statistically different ($p > 0.05$) between the type one wrists (8.224±0.363mm) and the type two wrists (7.307±1.123mm; figure 3.20). There was no difference in ligament angle between the two types. The mean ulnar width of the scaphocapitate ligament in the type one wrists (5.45±1.935mm) was not significantly different from that of the type two wrists (5.957±0.904mm; $p > 0.05$; figure 3.21). However, the mean radial width of the scaphocapitate ligament in type two wrists (8.076±1.656mm) was significantly greater than

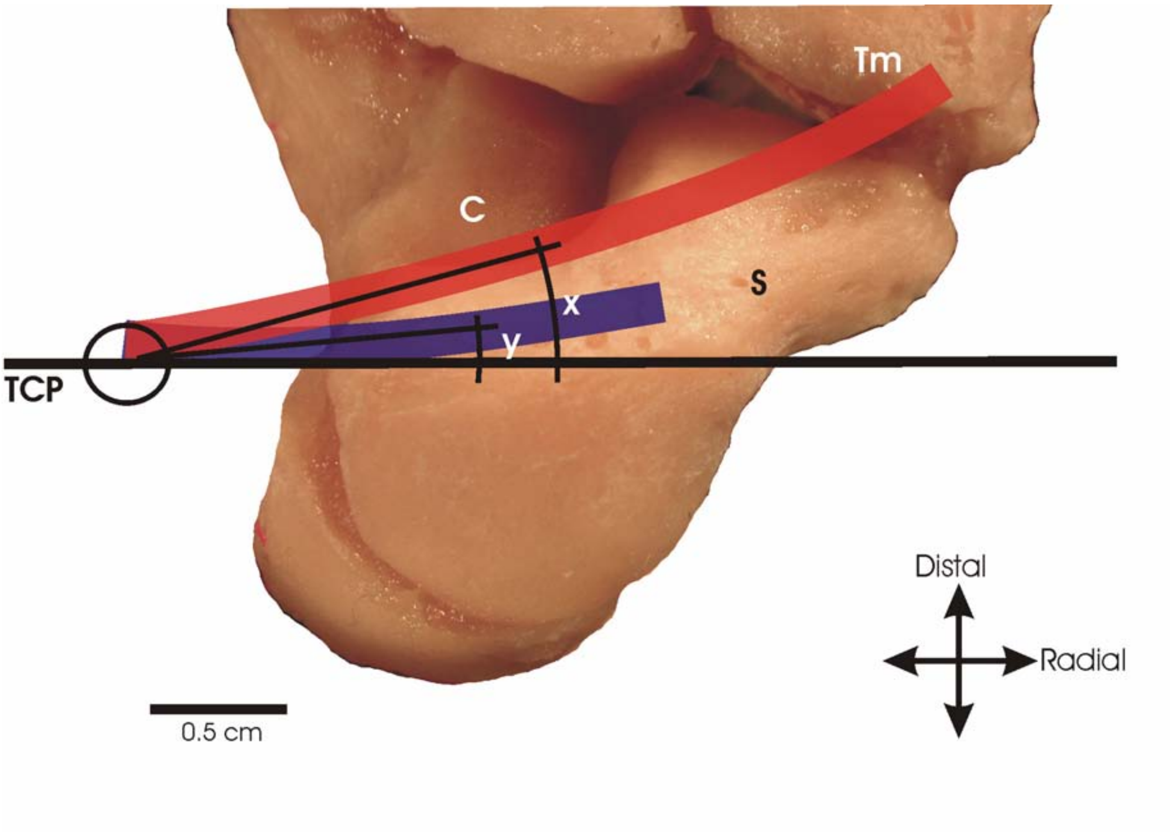


Figure 3.17 The angle of the dorsal intercarpal ligament. The dorsal intercarpal ligament of the type one wrists (red) was radially attached to the trapezium (Tm). The dorsal intercarpal ligament of the type two wrists (blue) was radially attached to the scaphoid (S). The angle of the ligament from the transverse carpal plane (TCP) was greater in the type one wrists (X) than the type two wrists (Y); C - capitate.

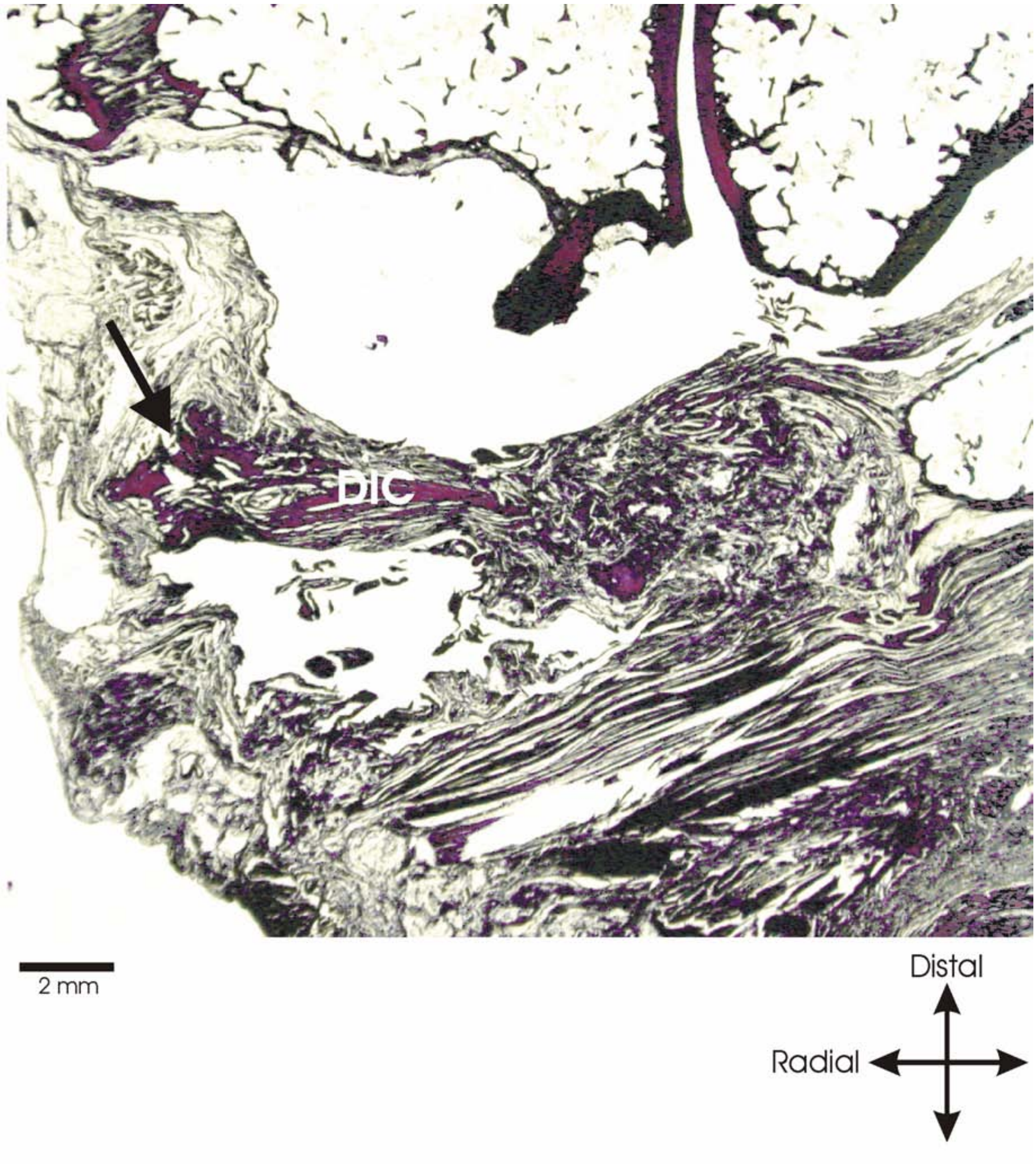


Figure 3.18 Histology of the dorsal intercarpal ligament. The dorsal intercarpal (DIC) ligament of a type two wrist is attached to the dorsal aspect of the scaphoid (arrow); Masson's Trichrome.

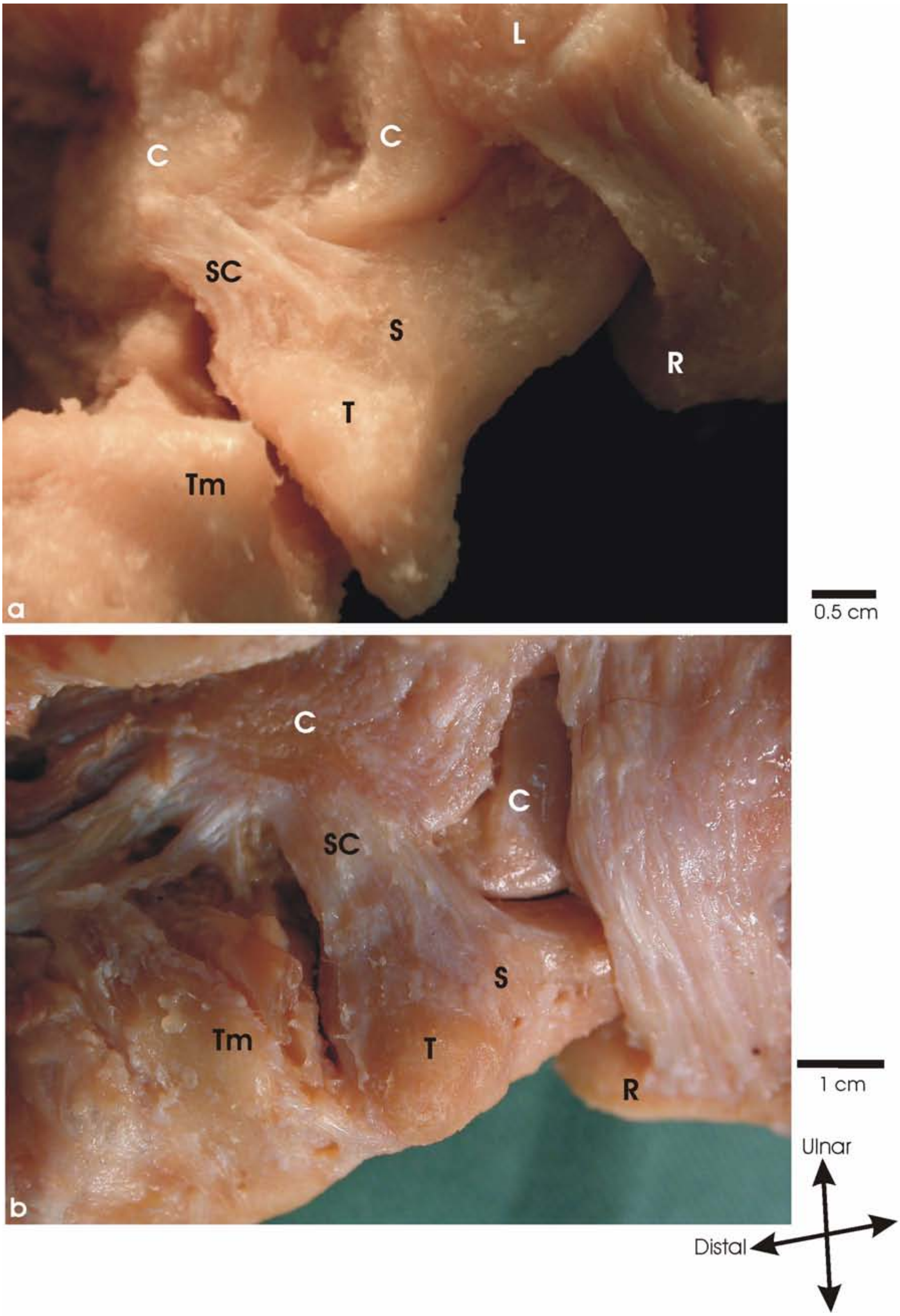


Figure 3.19 The scaphocapitate ligament. a - The scaphocapitate ligament (SC) of the type one wrists was attached to the radial margin of the palmar aspect of the capitate (C) and to the palmar aspect of the scaphoid (S) where it encircled the proximal and ulnar margins of the scaphoid tubercle (T); b - the scaphocapitate ligament (SC) of the type two wrists was attached to the radial margin of the palmar aspect of the capitate (C) and to the ulnar margin of the palmar aspect of the scaphoid (S). The radial attachment did not involve the scaphoid tubercle (T); Tm - trapezium, R - radius, L - lunate.

that of the type one wrists (4.908±1.716mm; $p < 0.05$; figure 3.21). The type one scaphocapitate ligaments had consistently parallel fibres with little divergence at their radial attachment (figure 3.22a). The type two scaphocapitate ligaments had proximal and distal "splaying" of the fibres near the radial attachment of the ligament (figure 3.22b).

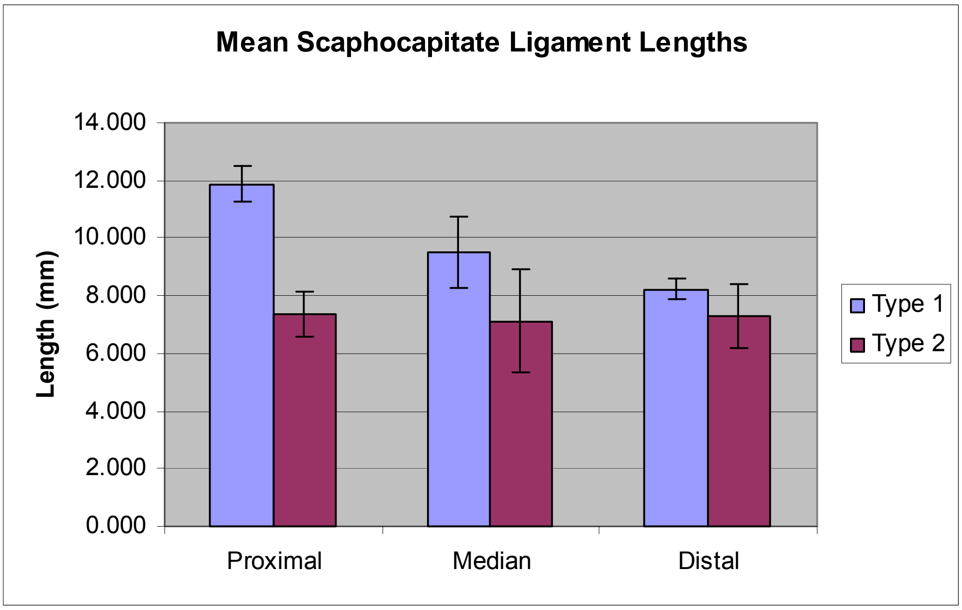


Figure 3.20 Mean Scaphocapitate ligament lengths.

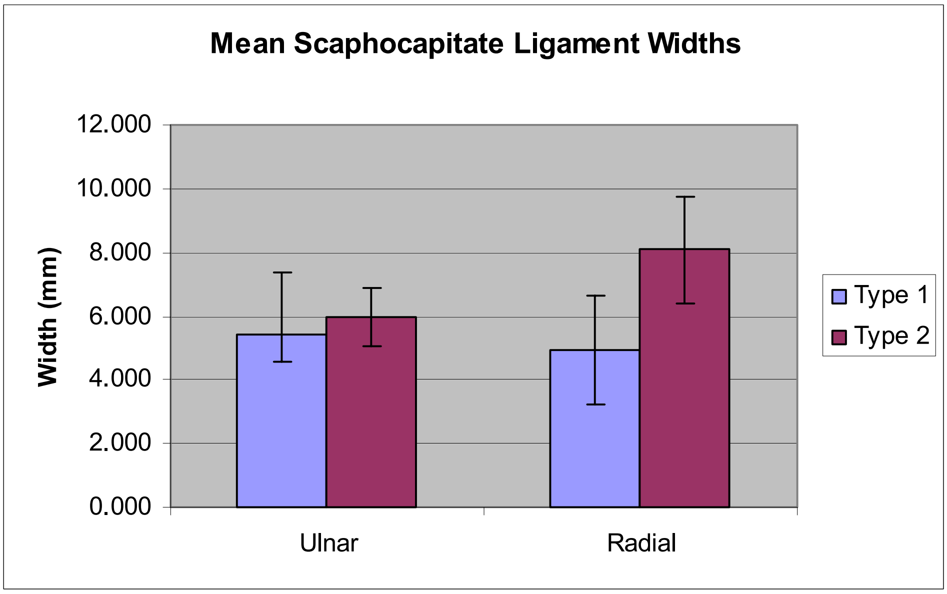


Figure 3.21 Mean scaphocapitate ligament widths.

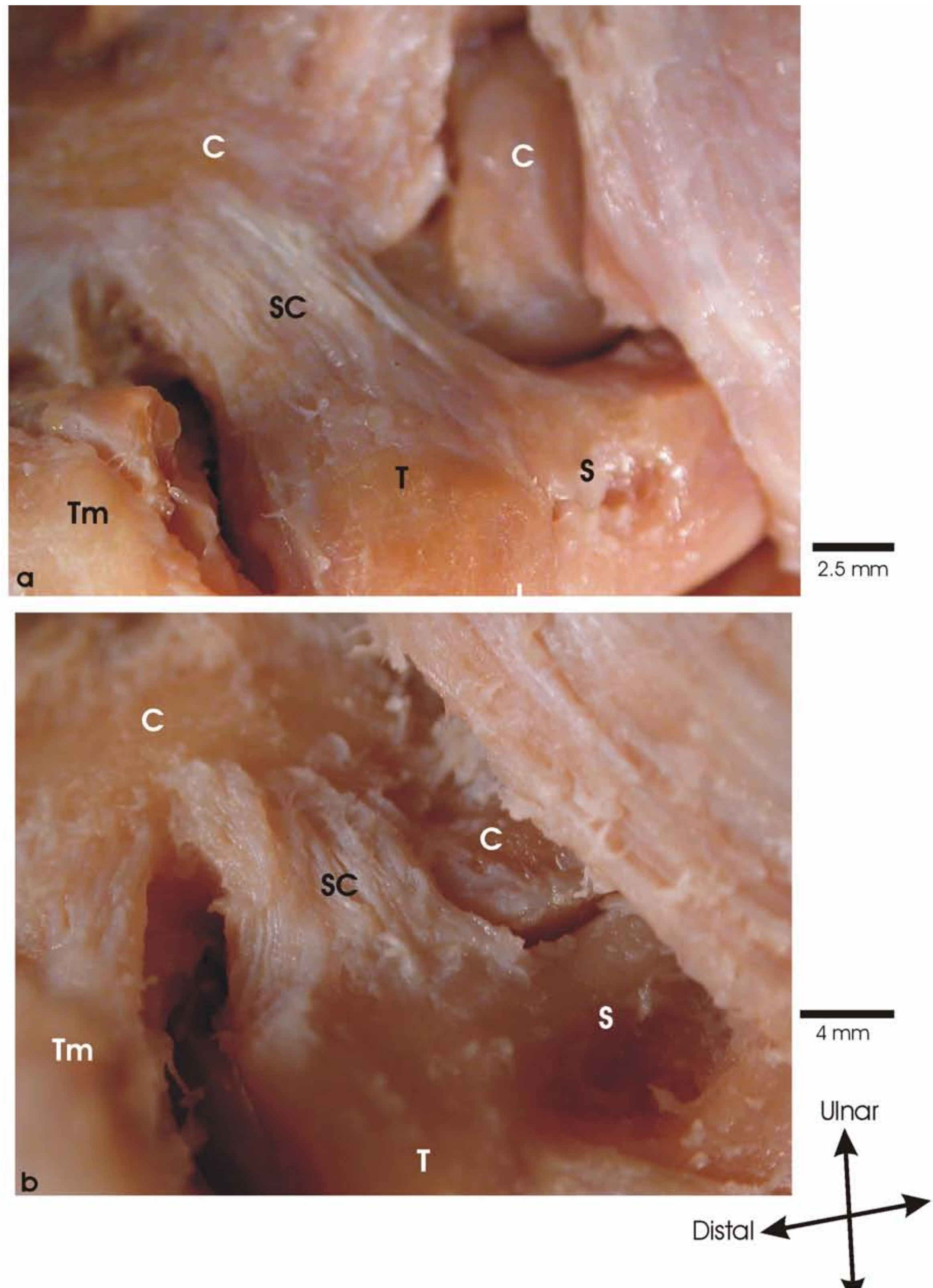
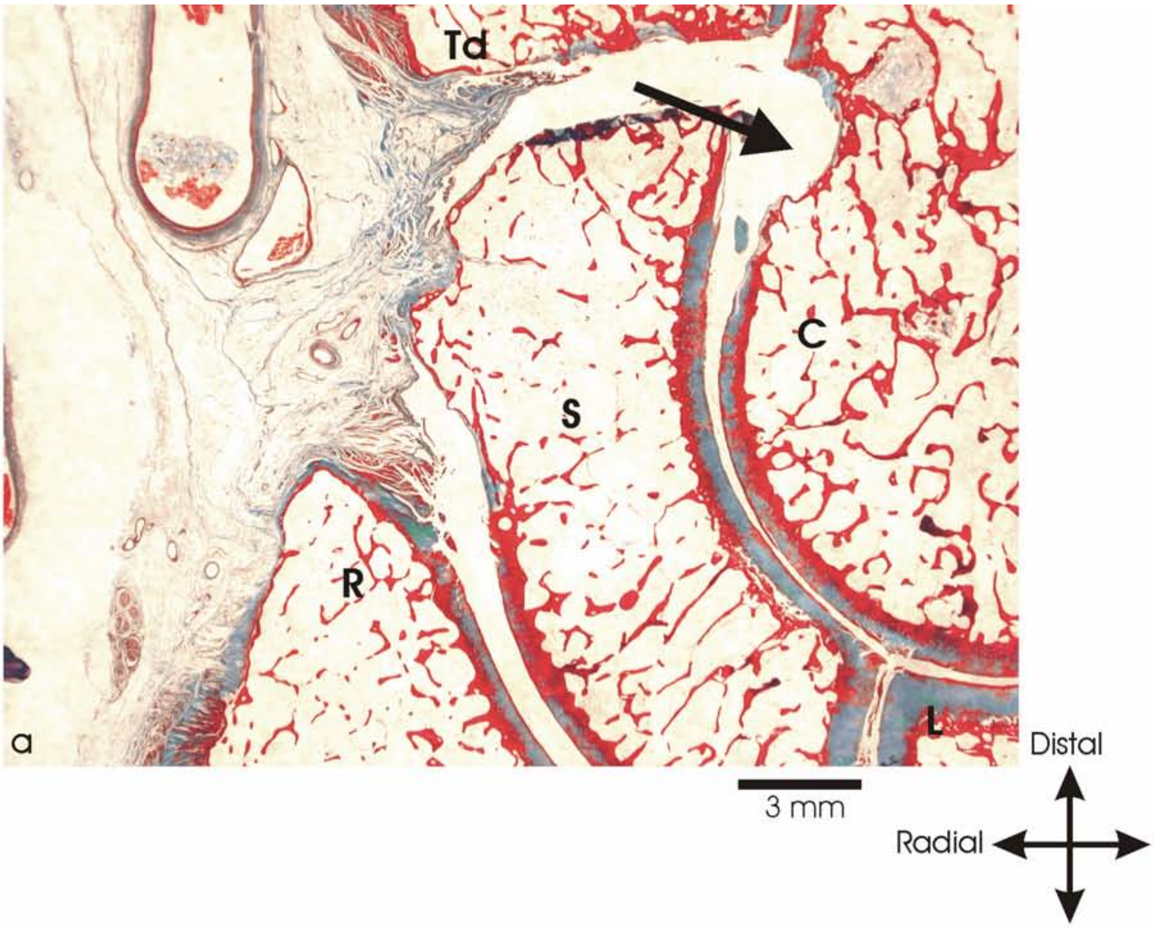


Figure 3.22 The radial attachment of the scaphocapitate ligament. a - the scaphocapitate ligament (SC) of the type one wrists was attached to the scaphoid (S). The fibres of the ligament encircle the scaphoid tubercle (T) as the longest fibres are attached to the radial margin of the palmar aspect of the scaphoid; b - the scaphocapitate ligament (SC) of the type two wrists was attached to the ulnar margin of the palmar aspect of the scaphoid (S). The longest fibres did not reach the scaphoid tubercle (T); Tm - trapezium, C - capitate.

The histological comparisons were comparable to the results of the gross investigation. Whilst the scaphocapitate ligament was difficult to identify histologically (due to technical difficulties) in the planes sectioned, the scaphocapitate joint was readily identified (figure 3.23). The histological investigation revealed variable scaphocapitate articulations between the two types of wrist. Type one wrists had a cartilaginous articulation between the scaphoid and the capitate (figure 3.24a). The cartilaginous articulation of the type two wrists was interrupted by a fibrous connection between the scaphoid and the capitate at the distal end of the scaphocapitate joint (figure 3.24b).

3.4.4 The Radiocarpal Ligaments

Ligamentous attachments between the radius, scaphoid and capitate were not consistent in all specimens. A true radioscaphocapitate ligament was observed on all type two wrists. Each of these specimens had a ligament attached to the radius, scaphoid, and capitate (figure 3.25a). The corresponding ligament on the type one wrists was attached to the radius and capitate, but was not attached to the scaphoid, despite being passed palmar to the scaphoid (figure 3.25b). In the majority of the type one specimens (n = 19; 34.6%) an isolated radioscaphoid band was observed, but in the remaining type one wrists (n = 13; 23.64%) only a membranous band could be identified figure 3.26a). The proximal attachment of this accessory band was dorsal to the most radial point of the radial styloid process. The radioscaphoid ligament and the membranous band were attached to the dorsal aspect of the scaphoid. In all specimens the radioscaphocapitate ligament had a radiolunate band originating from an adjacent proximal attachment (figure 3.26b). This band continued



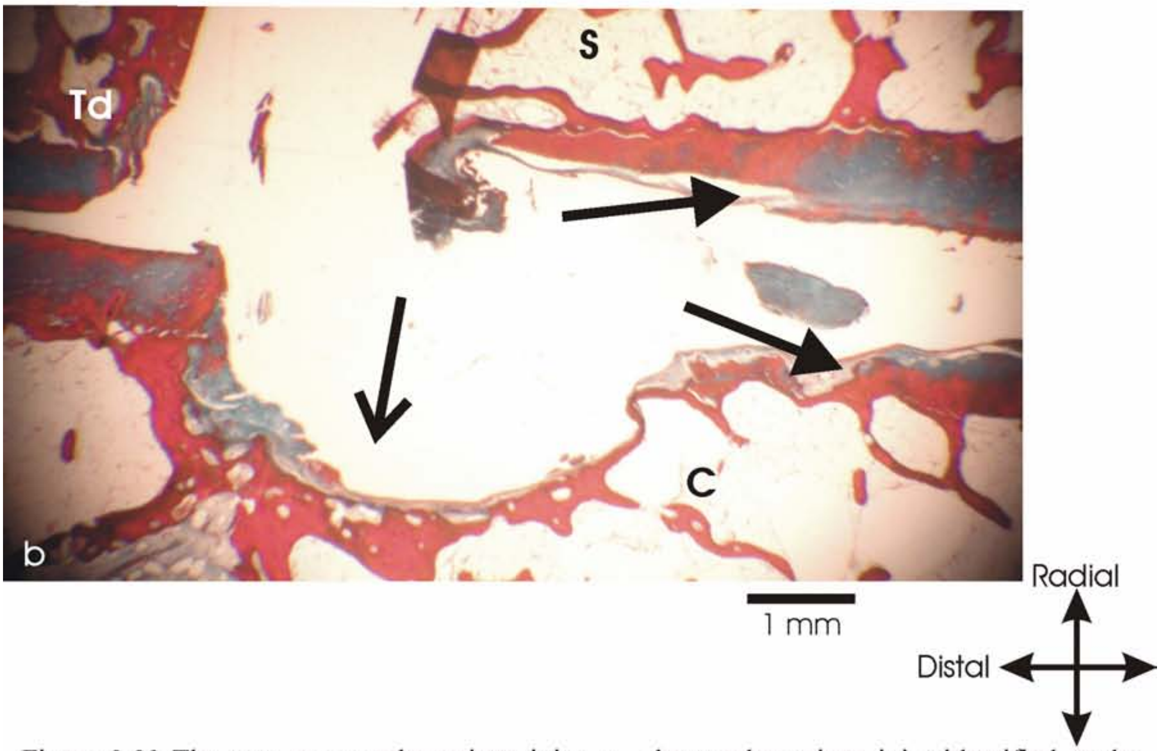


Figure 3.23 The type two scaphocapitate joint. a - the scaphocapitate joint identified as the articulation between the scaphoid (S) and the capitate (C) and modified at the distal margin of the joint (arrow); detail of the distal margin illustrates the termination of the articular cartilage (closed arrows) of the scaphoid (S) and the capitate (C), and the invagination of the capitate (open arrow) to accomodate the scaphoid; Td - trapezoid, R - radius, L - lunate.

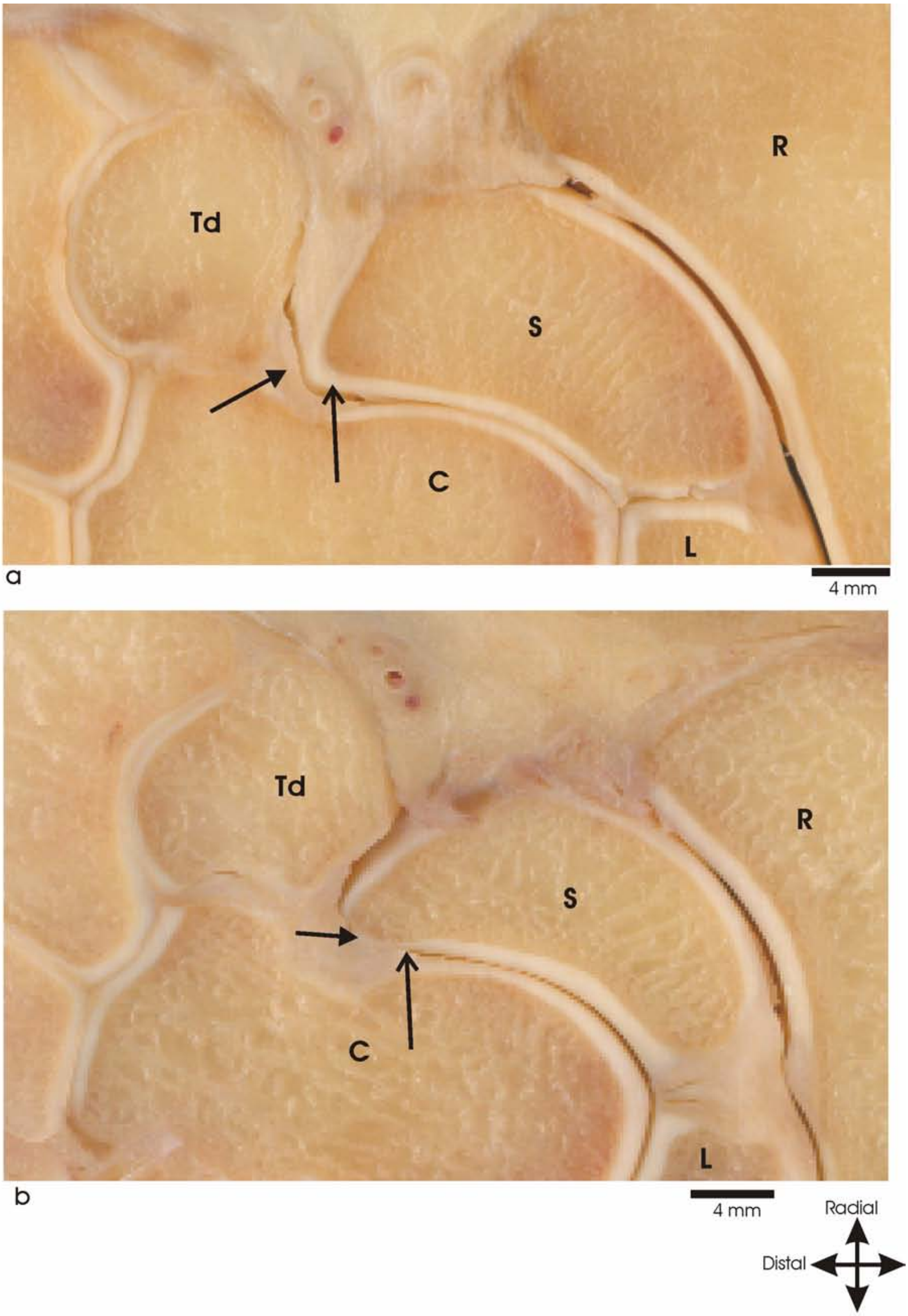


Figure 3.24 Variations of the scaphocapitate joint. a - the type one wrists had no fibrous connections (closed arrow) between the capitate (C) and the scaphoid (S), but rather between the capitate (C) and the trapezoid (Td). The cartilage (open arrow) of the capitate articular facet of the scaphoid was continuous through the scaphocapitate joint; b - the type two wrists had a fibrous connection (closed arrow) between the capitate (C) and the scaphoid (S). The cartilage of the capitate articular facet of the scaphoid was not continous (open arrow) through the scaphocapitate joint; L - lunate, R- radius.

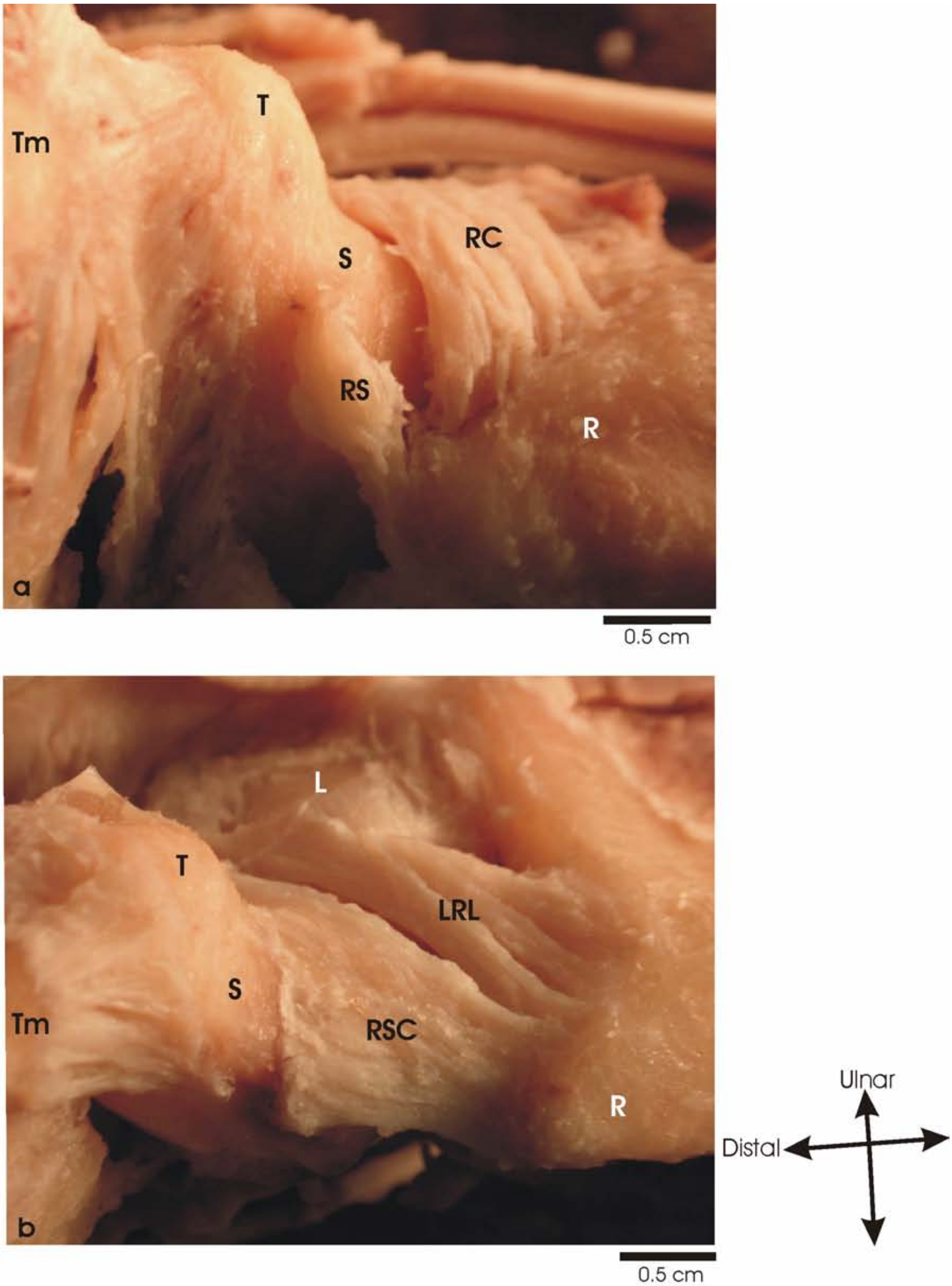


Figure 3.25 The radioscaphocapitate ligament and the radiocapitate ligament. a - type one wrists had a radiocapitate ligament (RC) attached to the radius (R) and the capitate (not shown), but that was not attached to the scaphoid (S). An additional ligament, the radioscaphoid ligament (RS) was attached to the proximal crest of the dorsal aspect of the scaphoid. It was separated from the radiocapitate ligament by membranous capsule (dissected); b - type two wrists had a radioscaphocapitate ligament (RSC) that was attached to the radius (R) proximally. The ligament had a short component attached to the scaphoid (S) and a long component attached to the capitate (not shown). The two components were continuous with each other; Tm - trapezium, T - tubercle of scaphoid, LRL - long radiolunate ligament.

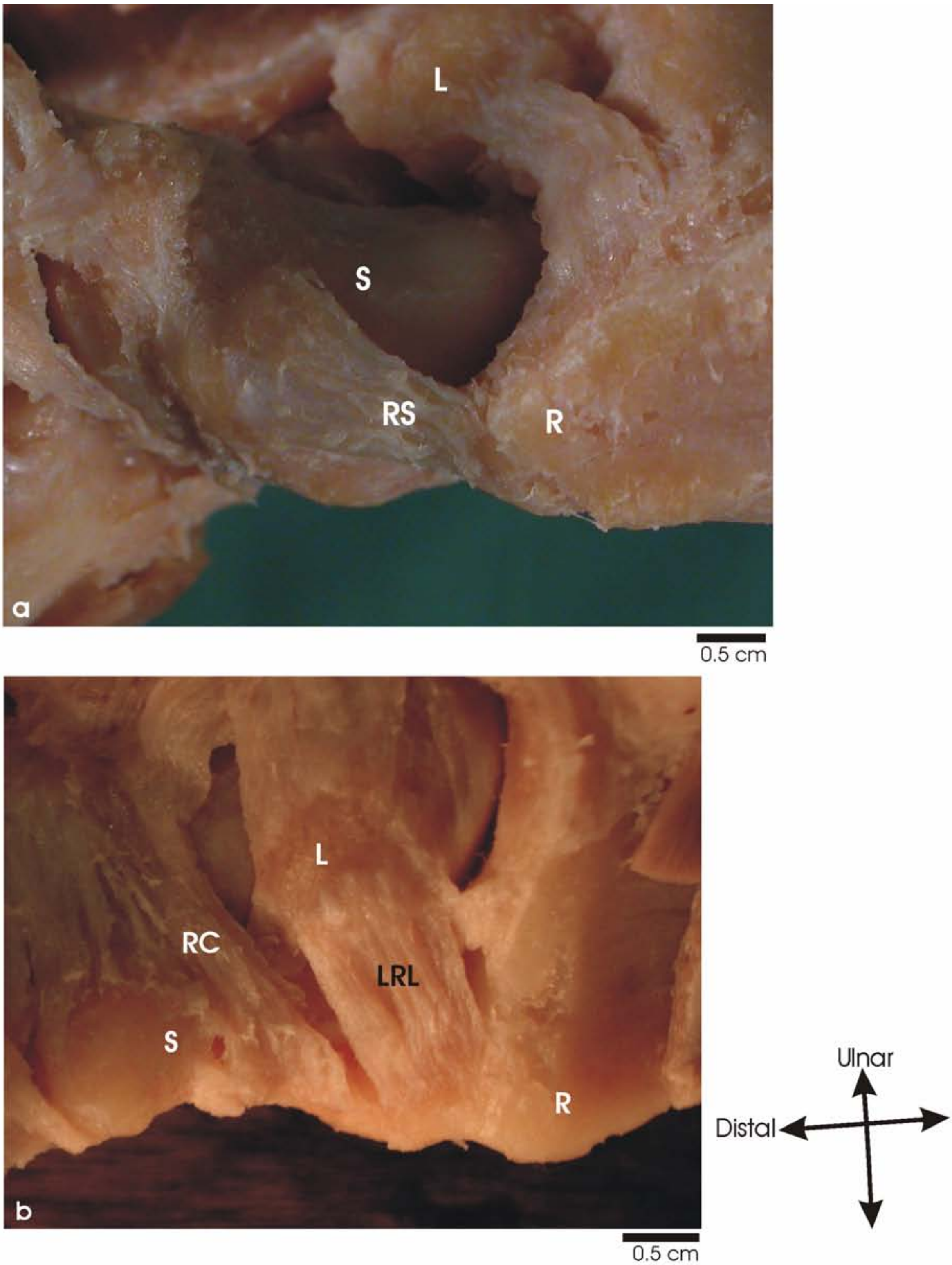


Figure 3.26 Radiocarpal ligaments. a - the majority of type one wrists had an radioscaphoid (RS) ligament separate from the radiocapitate ligament (dissected). The proximal attachment was on the dorsal aspect of the radial styloid process (R) and the distal attachment was to the proximal crest of the dorsal aspect of the scaphoid (S); b - all wrists observed had a long radiolunate ligament (LRL). The proximal attachment was in radial juxtaposition with that of the radioscaphocapitate (not on this type specimen) or radiocapitate ligament (RC). The distal attachment was to the lunate (L) where some fibres were attached to the triquetrum (not shown).

in an ulnar direction to the lunate, where it may or may not have been continuous with a band to the triquetrum.

The histological comparisons confirmed the results of the gross investigation (figure 3.27). The histological investigation also confirmed the presence of the interligamentous groove ulnar to the radioscaphocapitate ligament (figure 3.28). The scaphoid attachment of the radioscaphocapitate ligament in the type two wrists was observed (figure 3.29a), but could not be identified in the type one wrists (figure 3.29b). Instead of a scaphoid attach on the type one wrists, the radiocapitate ligament had a fibrocartilaginous component where it was congruent with the palmar aspect of the scaphoid (figure 3.29b).

3.4.5 Ligamentous Patterns

The ligaments observed constituted two basic patterns, with only occasional variations from either of the patterns. Most of the variations may be deemed enhancements of the pattern from which they are derived, and may have developed due to extreme patterns of carpal movement. The patterns may be summarised in table 3.1.

Figure 3.27 The radioscaphocapitate and radiocapitate ligaments. a - the type one wrists had a radiocapitate ligament (RC) that was not attached (arrows) to the scaphoid (S); b - the type two wrists had a radioscaphocapitate ligament (RSC) that was attached (arrows) to the scaphoid (S); R -radius, Tm - trapezium, IG - interligamentous groove, LRL - long radiolunate ligament.

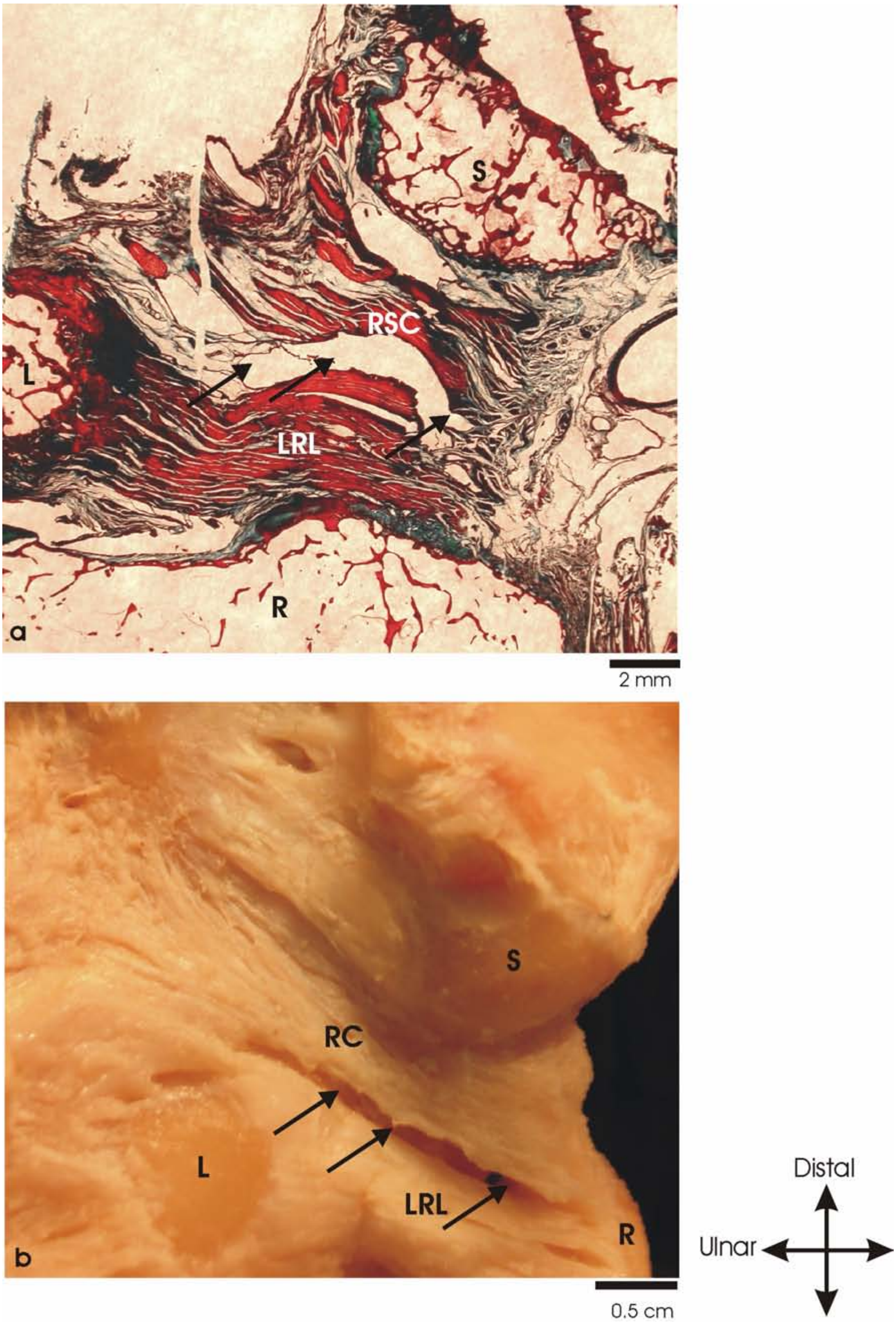


Figure 3.28 The interligamentous groove. a - coronal section stained with Masson's Trichrome and indicating the interligamentous groove (arrows) in type two wrists between the radioscaphocapitate ligament (RSC) and the long radiolunate ligament (LRL); gross specimen indicating the interligamentous groove in type one wrists between the radiocapitate ligament (RC) and the long radiolunate ligament (LRL). The interligamentous groove was observed in both wrist types despite the difference in ligament pattern.

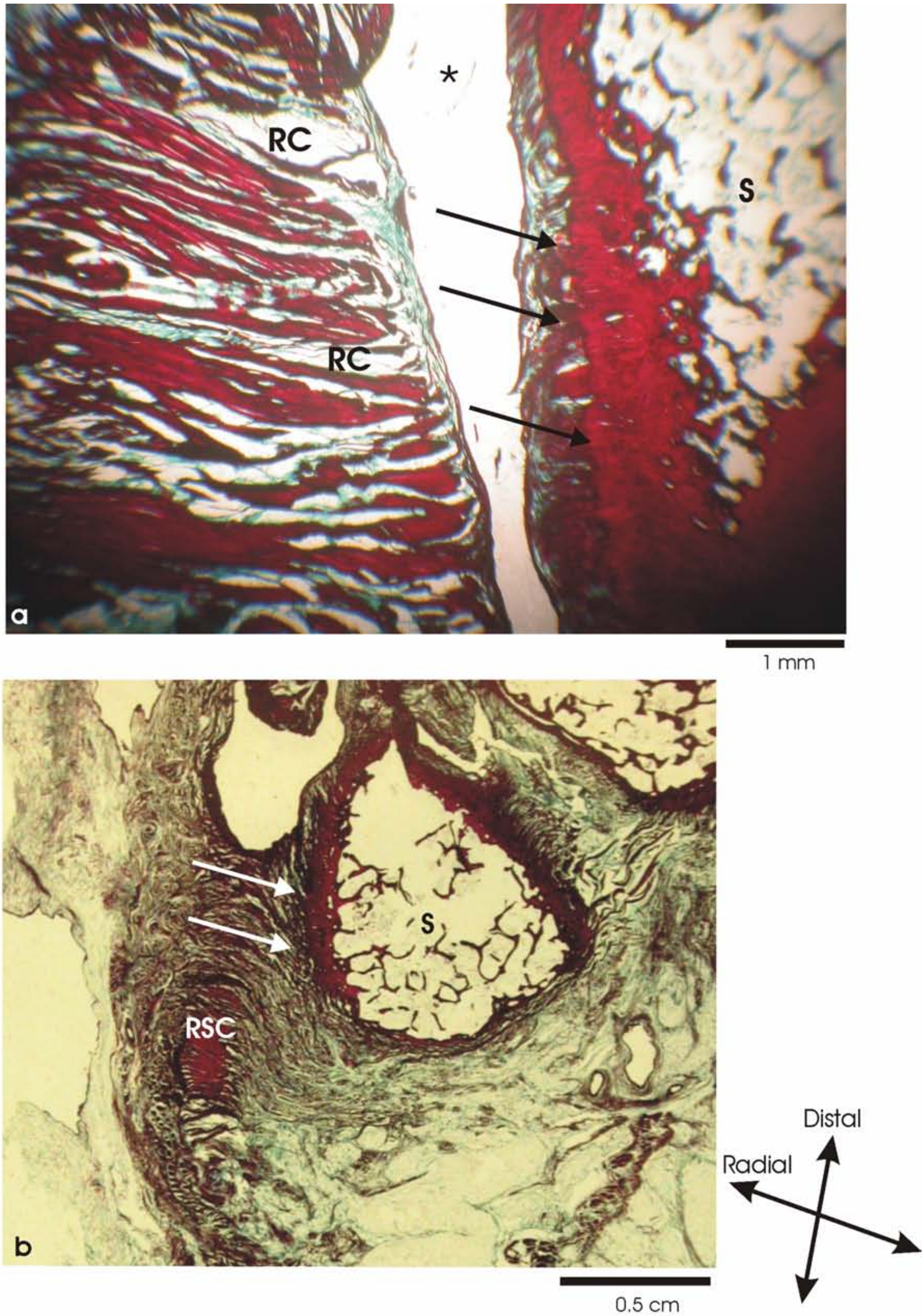


Figure 3.29 Radiocarpal ligaments and the scaphoid. a - the type one wrists had a radiocapitate ligament (RC) that was not attached to the scaphoid (S). The scaphoid was lined with fibrocartilage (arrows) were the radiocapitate ligament might be rubbed; b - the type two wrists had a radioscaphocapitate ligament (RSC) that was attached (arrows) to the scaphoid (S). Specialisations of the scaphoid, such as fibrocartilage, were therefore not required; * this space may have been enlarged during the dehydrating and staining procedures (Appendix IV) but the separation of these tissues was observed on the cutting surface of the specimen block.

Table 3.1

Wrist Type	STT Ligament	Scaphocapitate Ligament	Dorsal Intercarpal Ligament	Radiocarpal Ligaments
1	V-shape with proximal apex	Long and thin; radial scaphoid attachment	Trapeziotrapezoid radial attachment	No scaphoid attachment (radiocapitate ligament); May have separate radioscaphoid
2	V-shape with distal apex	Short and wide; ulnar scaphoid attachment	Scaphoid radial attachment	Scaphoid attachment (radioscaphocapitate ligament)

Table 3.1 Summary of ligamentous patterns observed. Specimens were divided into types based on the attachment widths of the STT joint ligaments. Each type of wrist exhibited a distinct pattern of ligamentous support.

3.5 Discussion

The arrangement of the observed ligaments into two distinct patterns suggests that two patterns of scaphoid motion are supported within the sample population. Consideration of the functional role of these ligaments may enable suggestion of the different types of scaphoid motion. The ligamentous support for the scaphotrapeziotrapezoid joint is either in the form of a ligamentous V-shape with a proximal (scaphoid) apex, or a ligamentous V-shape with a distal (trapeziotrapezoid) apex. No other significant ligamentous complexes could be identified macroscopically or microscopically. In both patterns the base (widest part) of the V-shape is curved around the bone/s to which it is attached, whilst the apex attachment is a much thinner point upon which all of the fibres are converged. It may be suggested then that pattern one specimens had rotating scaphoids and pattern two specimens had non-rotating scaphoids.

The trapeziotrapezoid complex is articulated with the capitate, which is articulated with the hamate. The four bones together may be considered as a single, inflexible unit about which the remaining carpal bones are moved (Craigen and Stanley, 1995; Kobayashi *et al*, 1997; Moojen *et al*, 2002; Wolfe *et al*, 2000; Youm *et al*, 1978). The trapeziotrapezoid complex may then be considered the immobile component of the scaphotrapeziotrapezoid joint, whilst the scaphoid is the mobile component. Trapeziotrapezoid movements such as the proximal movement of the complex in radial deviation (Berger, 1996; Kauer and de Lange, 1987; Kuhlmann and Tubiana, 1988) may be considered to be movements of the trapeziotrapezoid-capitate-hamate super complex, or rather movements of the surrounding bones relative to the complex. Understanding scaphoid motion is therefore integral to understanding carpal motion and the scaphotrapeziotrapezoid interactions may be significant. With the trapeziotrapezoid complex immobile the ligamentous restraints of the scaphotrapeziotrapezoidal joint may only influence scaphoid motion. The small scaphoid attachment of the type one scaphoids may be permissive of movement about the point of attachment, such as rotation of the scaphoid about its longitudinal axis (figure 3.30a). The large scaphoid attachment of the type two wrists may be less permissive of motion. As the scaphotrapeziotrapezoidal ligament complex of the type two scaphoids had a broad proximal attachment around the radial curvature of the scaphoid tubercle, the ligaments may limit movement to flexion and extension of the scaphoid (figure 3.30b).

The arrangement of the scaphocapitate ligament may lend further support to the suggestion of rotating and non-rotating specimens. The scaphocapitate ligament of type one wrists was long and thin, and was attached to the radial margin of the palmar aspect of the scaphoid (figure 3.31a). This ligament would become taut after a small degree of external rotation, but permit more internal rotation. It may therefore be suggested that internal rotation is the greater of the rotating movements. The scaphocapitate ligament of the type one scaphoids may limit flexion of the scaphoid by acting as sling across the palmar aspect of the scaphoid. In tandem with the radiocapitate ligament, these palmar slings of the scaphoid may tighten if the scaphoid is flexed, limiting the range of scaphoid flexion. This may accommodate the lack of restriction at the scaphotrapeziotrapezoidal joint. The suggestion of scaphoid rotation in type one wrists is further facilitated by the histological observations of the scaphocapitate joint. The cartilaginous articulation between the scaphoid and capitate may offer no restriction to scaphoid motion, enabling rotation

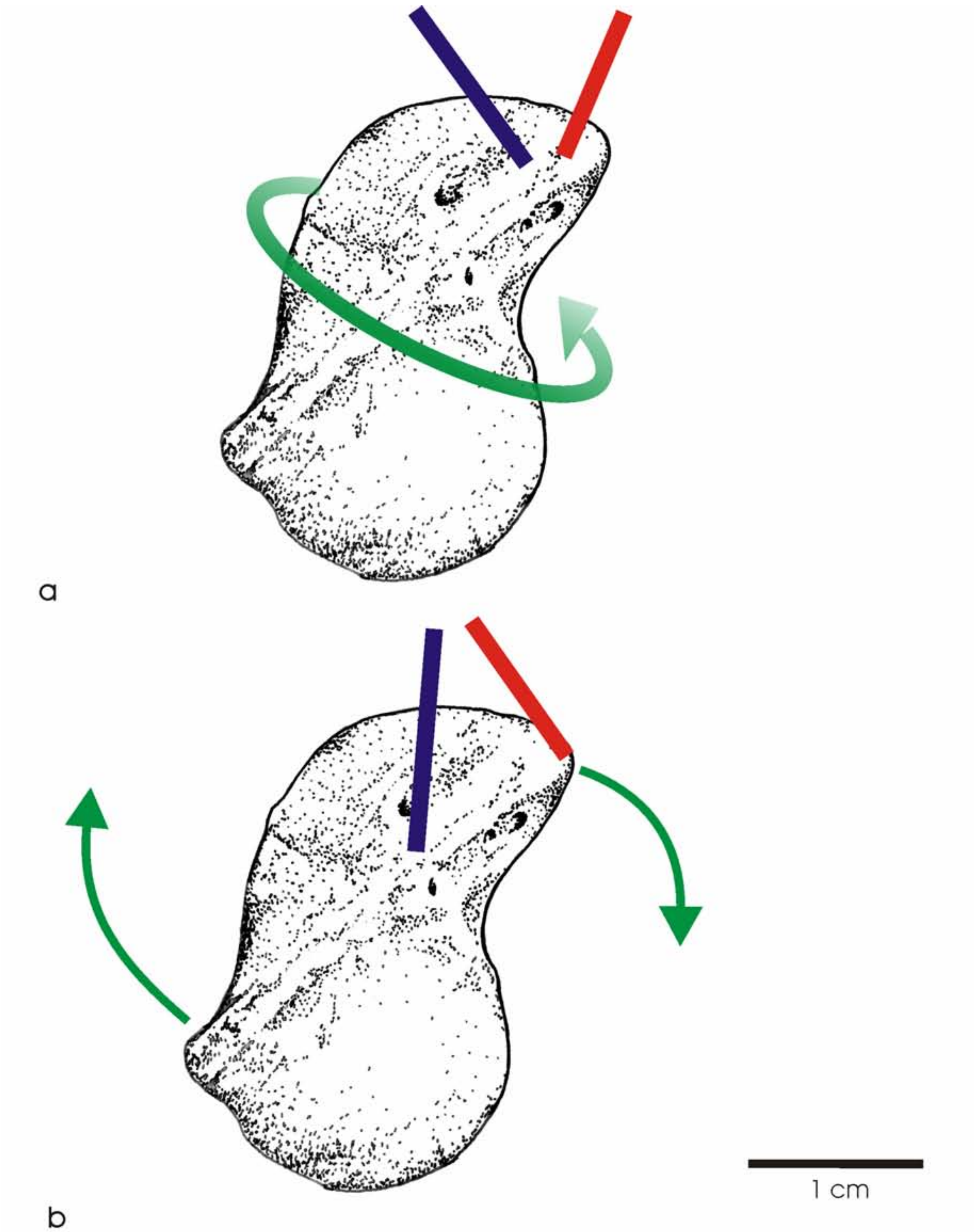


Figure 3.30 Scaphotrapeziotrapezoid joint ligaments and scaphoid movement. a - in the type one wrists the v-shaped STT joint ligaments may influence scaphoid motion. Force transmitted through the most radial (red) or ulnar (blue) fibres of the STT joint ligaments only transmit that force to the narrow proximal attachment site on the scaphoid. The scaphoid is free to rotate (arrow) about the proximal attachment, ie. the longitudinal axis of the scaphoid; b - in the type two wrists the inverted v-shaped STT joint ligaments may influence scaphoid motion differently. Force transmitted through the most radial (red) or ulnar (blue) fibres will transmit that force radially and ulnarly across the distal pole of the scaphoid. In any combination of fibre loading (red and blue loaded, or either separately) the angulation of the proximal ligament attachment may force the scaphoid into a flexed position (arrows). Rotation may be prevented as opposite fibres along the proximal attachment will become taut as rotation is attempted.

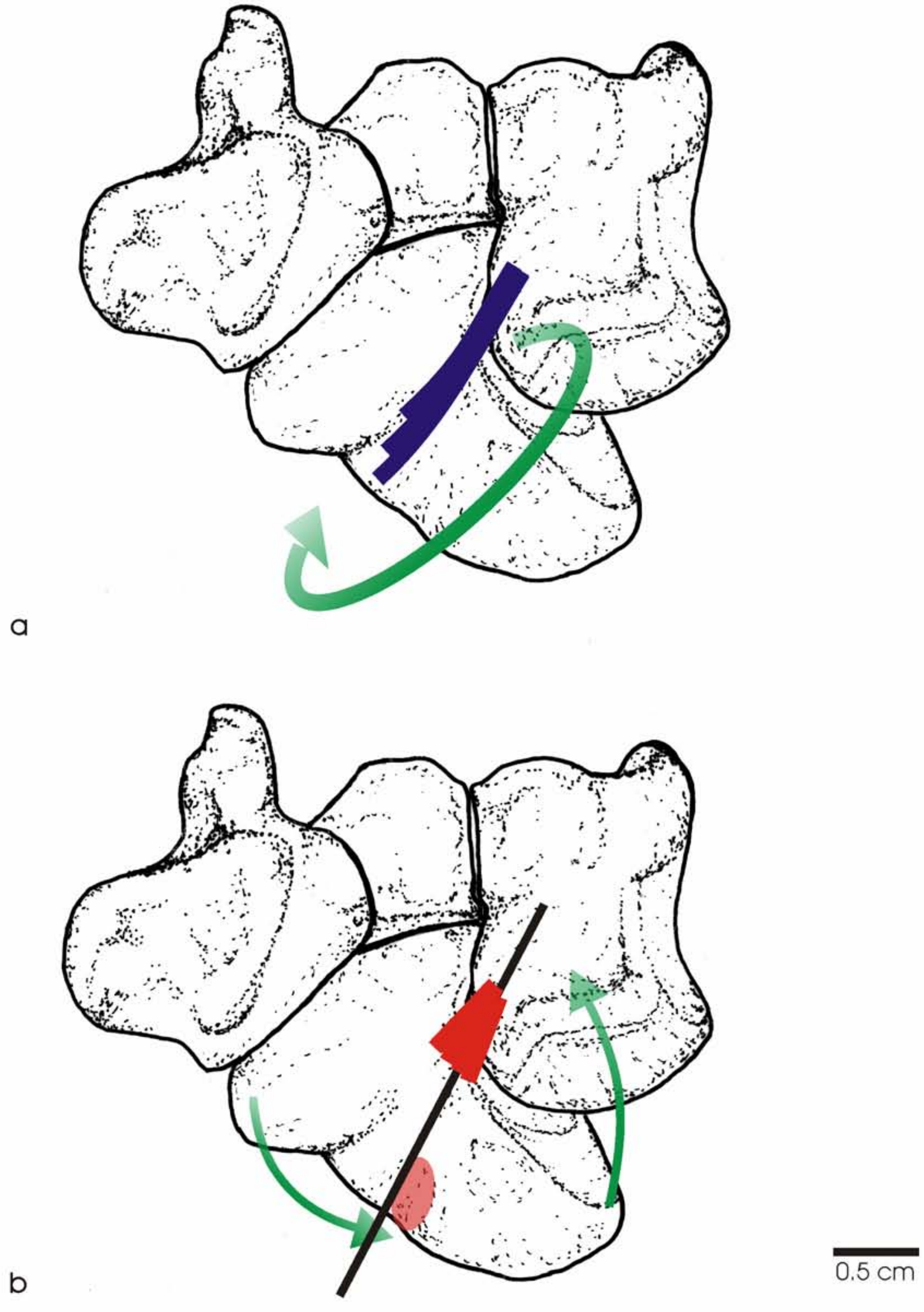


Figure 3.31 The scaphocapitate ligament and scaphoid motion. a - the type one wrists had an elongated scaphocapitate ligament (blue) that may limit external rotation of the scaphoid (arrow) but not internal rotation of the scaphoid. Tension in this ligament may ensure that contact between the articular surfaces of the scaphocapitate joint is maintained as the scaphoid is rotated and translated; b - the type two scaphoids had a short scaphocapitate ligament (red) that may limit rotation and translation of the scaphoid. Together with the dorsal intercarpal ligament (red dot) the scaphocapitate ligaments radial attachment may provide an oblique axis (line) about which the scaphoid can be flexed/extended (arrows).

and translation of the scaphoid. The scaphoid movement in the type one wrists may be predominately mediated by ligamentous supports.

The scaphocapitate ligament of the type two wrists was short and wide, and was attached to the ulnar margin of the palmar aspect of the scaphoid (figure 3.31b). This ligament would become taut after very little external rotation and after only slightly more internal rotation. It may therefore be an effective rotatory restraint. The scaphocapitate ligament may also contribute to maintenance of scaphoid position for flexion/extension. It may prevent dissociation of the scaphoid from the head of the capitate and provided a point (fulcrum) about which the flexion/extension may occur. With the scaphoid attachments of the radioscaphocapitate and dorsal intercarpal ligaments, the scaphocapitate ligament of the type two wrists may create an oblique axis about which the scaphoid is flexed and extended. Disruption of this axis through damage to any of the ligaments may result in instability of the scaphoid. Similar scenarios have been described by others (Feipel and Rooze, 1999; Viegas, 2001; Viegas *et al*, 1999).

The radiocarpal ligaments that influence the scaphoid need not be attached to the scaphoid. The type one wrists had a radiocapitate ligament attached to the palmar margin of the radial styloid process and to the proximal-radial corner of the palmar aspect of the capitate. It was not attached to the scaphoid, despite being passed palmar to the scaphoid, and hence was not termed a radioscaphocapitate ligament (Berger, 2001a). The dorsal surface of the radiocapitate ligament was fibrocartilaginous, facilitating movement of the scaphoid against the ligament. If these scaphoids were to be rotated as the other restraints suggest, this ligament would allow the rotation to occur, acting as a sling or pulley within which the scaphoid is placed. When acting as a sling the ligament may prevent extension of the scaphoid by limiting the palmar movement of the proximal pole of the scaphoid (figure 3.32a). When acting as a pulley the ligament may passively generate some of the scaphoid rotation, as the capitate and radius are moved relative to each other (figure 3.32a).

A radioscaphocapitate ligament was observed in the type two wrists. The ligament had a proximal attachment to the radius and a distal attachment to the capitate similar to those observed in the type one specimens. A radial intermediate band was observed that was attached to the most radial region of the proximal crest of the dorsal aspect of the scaphoid. Much like the STT ligament on these wrists, the radioscaphocapitate ligament may restrict rotation as it has a wide attachment to the mobile component, scaphoid (figure 3.32b). The scaphoid attachment of the radioscaphocapitate ligament may also contain extension of the proximal pole of the scaphoid (flexion of the scaphoid). Tension in the ligament near the full range of extension may prevent dissociation of the scaphoid from the radius and passively flex the proximal pole back towards a neutral position.

The dorsal intercarpal ligament varied between the two types of wrists. The dorsal intercarpal ligament of the type one wrists was attached to the trapeziotrapezoid complex. In a smaller subset of the rotating specimens the dorsal intercarpal ligament was connected to the scaphoid by a series of fibres perpendicular to the fibres of the ligament. In most rotating specimens, however, the dorsal intercarpal ligament was not attached to the scaphoid. In this manner, it may mimic the proposed sling/pulley function of the radiocapitate ligament (figure 3.32a). Whereas the radiocapitate ligament had its proposed effects on the palmar aspect of the proximal pole of the scaphoid, the dorsal intercarpal ligament may provide similar effects on the dorsal aspect of the distal pole of the scaphoid. It may therefore limit extension of the scaphoid and passively assist in generating external

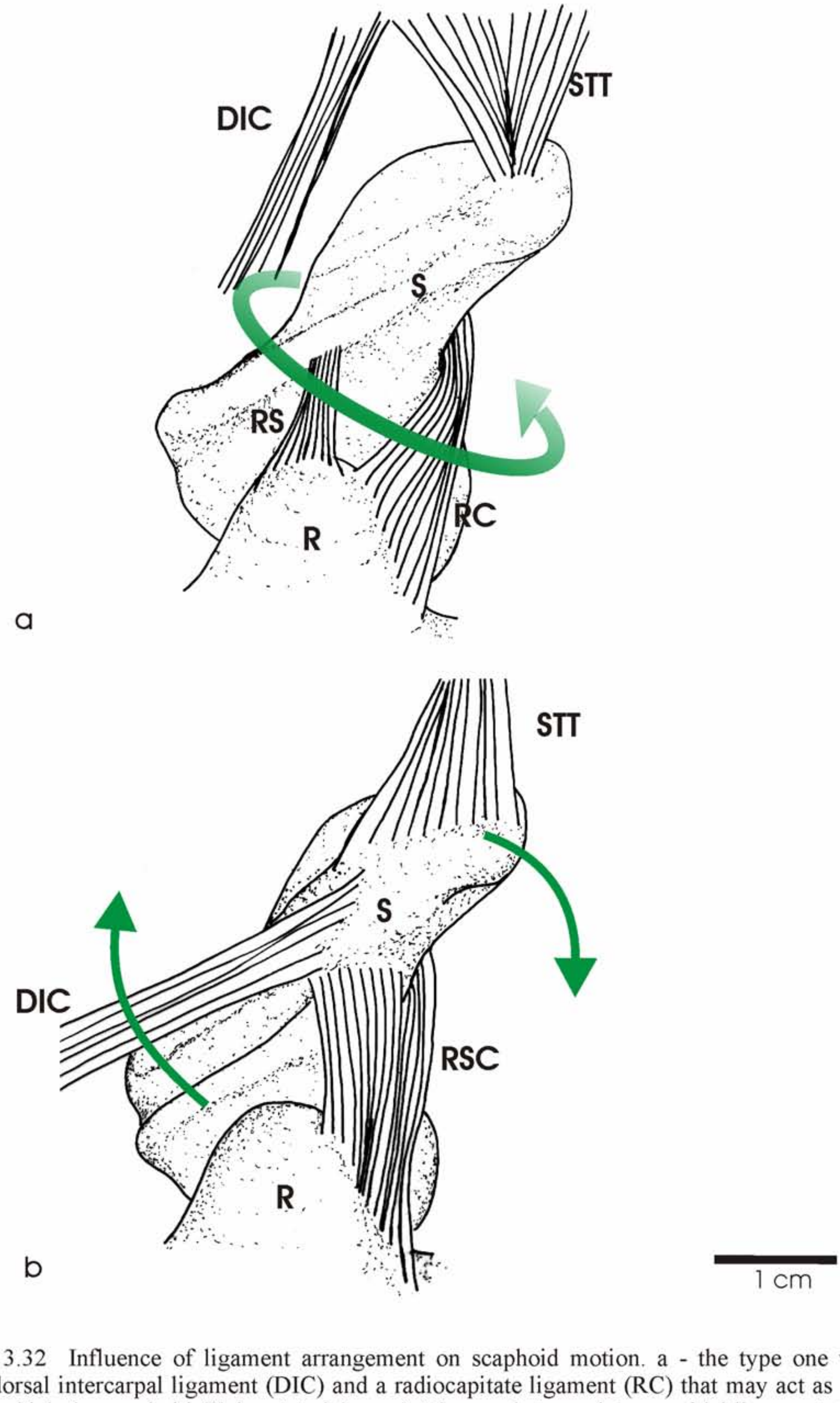


Figure 3.32 Influence of ligament arrangement on scaphoid motion. a - the type one wrists had a dorsal intercarpal ligament (DIC) and a radiocapitate ligament (RC) that may act as slings within which the scaphoid (S) is rotated (arrow). The scaphotrapeziotrapezoidal ligaments (STT) and the radioscaphoid ligament (RS) may determine the axis about which the scaphoid is rotated; b - the type two wrists had a dorsal intercarpal ligament (DIC) and a radioscaphocapitate ligament (RSC), both of which were attached to the scaphoid (S). The radial area of the scaphoid to which both ligaments of the scaphoid are attached may limit the rotation of the scaphoid and contribute to the determination of an axis about which the scaphoid may be flexed/extended (arrows); R - radial styloid process.

rotation of the scaphoid. This passive force generation may be enhanced by the accessory fibres attaching the dorsal intercarpal ligament to the scaphoid (figure 3.32b). In the type two wrists the dorsal intercarpal ligament was not attached to the trapeziotrapezoid complex, but directly to the distal crest of the dorsal aspect of the scaphoid. It may therefore limit the range of scaphoid flexion by becoming taut as the scaphoid is flexed. It may also passively contribute to scaphoid extension, extending the scaphoid as the ulnar carpal bones are moved further away in ulnar deviation (Moojen *et al*, 2003; Nuttal *et al*, 1998; Wolfe *et al*, 2000).

3.6 Conclusions

A combination of gross and histological investigations was used to determine the arrangement of ligaments supporting the radial bones of the carpus. The combination of investigative methods enabled accurate differentiation between macroscopically similar tissues.

Two distinct patterns of ligamentous support were identified. Type one wrists had a ligamentous array that suggested that the scaphoid may be rotated about its longitudinal axis during carpal motion. To facilitate radial deviation the scaphoid of the type one wrists may have to be translated proximal and ulnar to the neutral position. The type two wrists had a ligamentous array which suggested that the scaphoid may be flexed/extended. The ligamentous support and the deep articulation of the scaphoid with the capitate may limit rotation of the scaphoid in the type two wrists. The suggestion of variable scaphoid motion is supported by kinematic studies and may indicate that the clinical approach to treating dysfunction of the wrist should be modified to accommodate these differences.

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Chapter 4
Computed Tomography of Scaphoid Orientation

4.1 Introduction

The *in situ* assessment of the carpus is essential for relaying the significance of anatomical data to a clinical setting. *In situ* assessment enables the carpus to be visualised in much the same manner as the clinician must view the patient. This is most readily done, both in the clinical and laboratory settings, with roentgenographs (x-rays). Convention dictates their initial use in a clinical environment (Martel *et al*, 1991; Robertson *et al*, 2002), as does their relative low cost and availability in the laboratory, but precise detail is associated more commonly with computed tomographs (CTs) and magnetic resonance images (MRIs) (Chung *et al*, 2001; Cone *et al*, 1983; James *et al*, 1992; Patterson *et al*, 1996). Subject to well-documented advantages and limitations of the afore-mentioned media, computed tomographs were chosen to investigate the morphological variation of the scaphoid *in situ*. Inexpensive and accessible in comparison with MRIs during the period of data collection, CTs offered precise detail of the skeletal elements, at the loss of soft tissue detail. Such a compromise suited the study sufficiently, and as such was the limit of the investigation.

4.2 Materials

Cadaveric specimens were arbitrarily selected from the Ray Last Anatomy Laboratory, Department of Anatomical Sciences, the University of Adelaide. Permission for their use, as granted by the Head of the Department of Anatomical Sciences, was covered by the Anatomy Act of South Australia (1983). All specimens were previously embalmed through the normal procedures of the Ray Last Anatomy Laboratory (see Appendix I).

A total of 22 cadaveric hands were selected for this part of the study. Each of these hands were then included in the dissection component of the study (Chapter 3). Therefore it was possible to compare *in situ* and gross results for 22 specimens (Chapter 5).

4.3 Methods

Plain roentgenographs were generated on the Phillips Optimus unit and axial computed tomographs (CTs) were generated on the General Electric HiSpeed Advantage unit and console in the Division of Medical Imaging of the Women's and Children's Hospital, Adelaide.

Standard antero-posterior, lateral and oblique roentgenographs were taken of 22 cadaveric wrists (figure 4.1). Contiguous computed tomographic images were taken at 1mm intervals, such that the angle of the tomograph was approximately perpendicular to the plane of the STT joint (figure 4.2). This was performed using the method described by Bain *et al* (1995), where the scanning plane was orientated along the first metacarpal using the scout image, and hence gave an approximation of the longitudinal axis of the scaphoid. In contrast to the previous technique (Bain *et al*, 1995) the wrist could not be held in radial deviation, so all of the images were taken with the wrist in neutral deviation and flexion. Regardless of this variation, manipulation of the specimen enabled images perpendicular to the STT joint to be taken. Images were selected for two types of analyses; firstly, images with complete longitudinal sections (figure 4.3a) of the scaphoid were used to assess the dimensions of the scaphoid. Secondly, images in which the capitate head was visible between the proximal and distal poles of the scaphoid were used to assess the position on the scaphoid in which the capitate head was articulated (figure 4.3b).

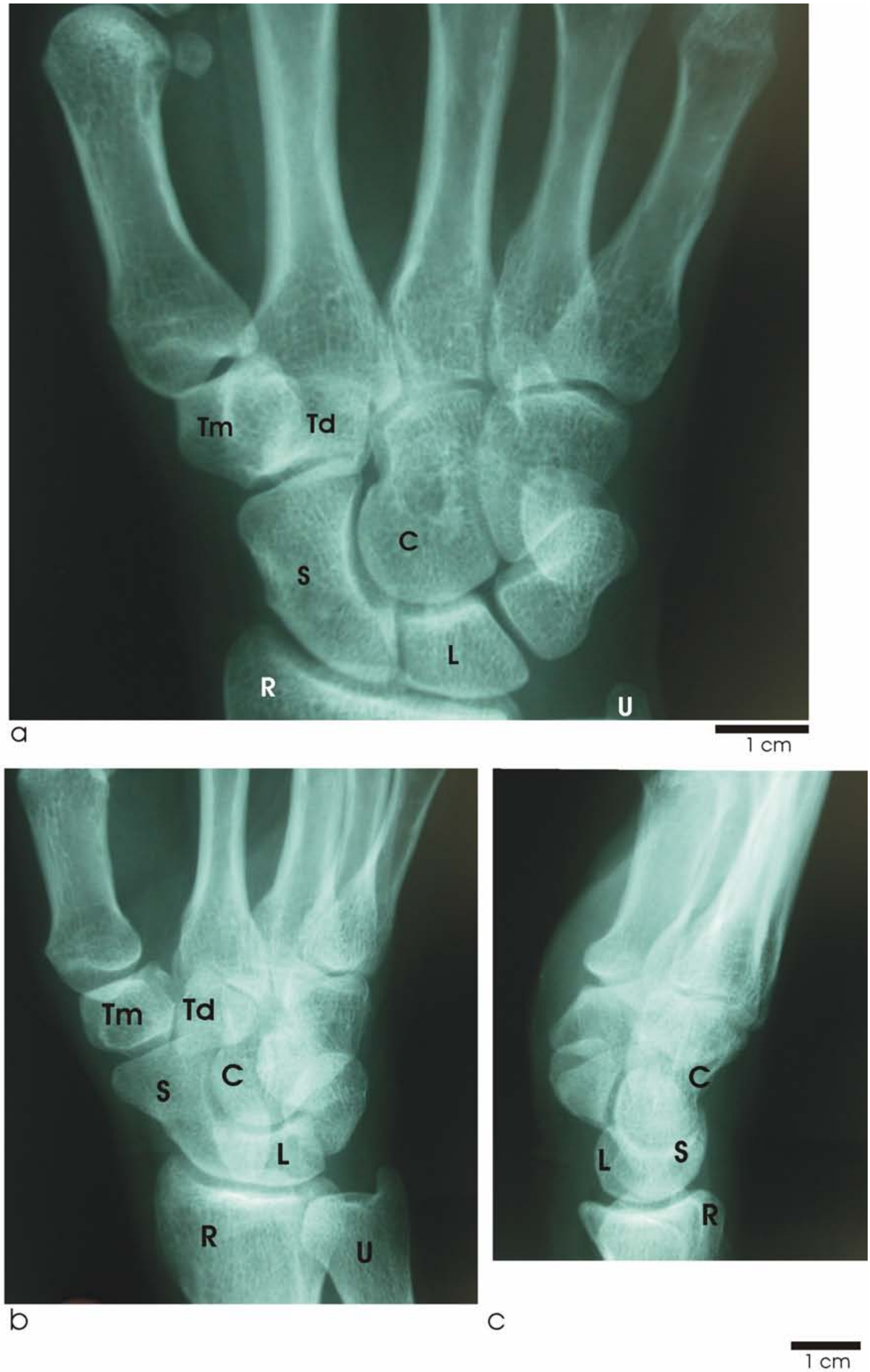

Figure 4.1 Standard x-rays of the wrist. a - antero-posterior; b - oblique; c - lateral; R -radius, U - ulna, S - scaphoid, Td - trapezoid, Tm - trapezium, C - capitate, L - lunate.

Figure 4.2 Scout image for computed tomographs. The orientation of slices (lines) can be observed as perpendicular to the scaphotrapeziotrapezoidal joint (arrow).

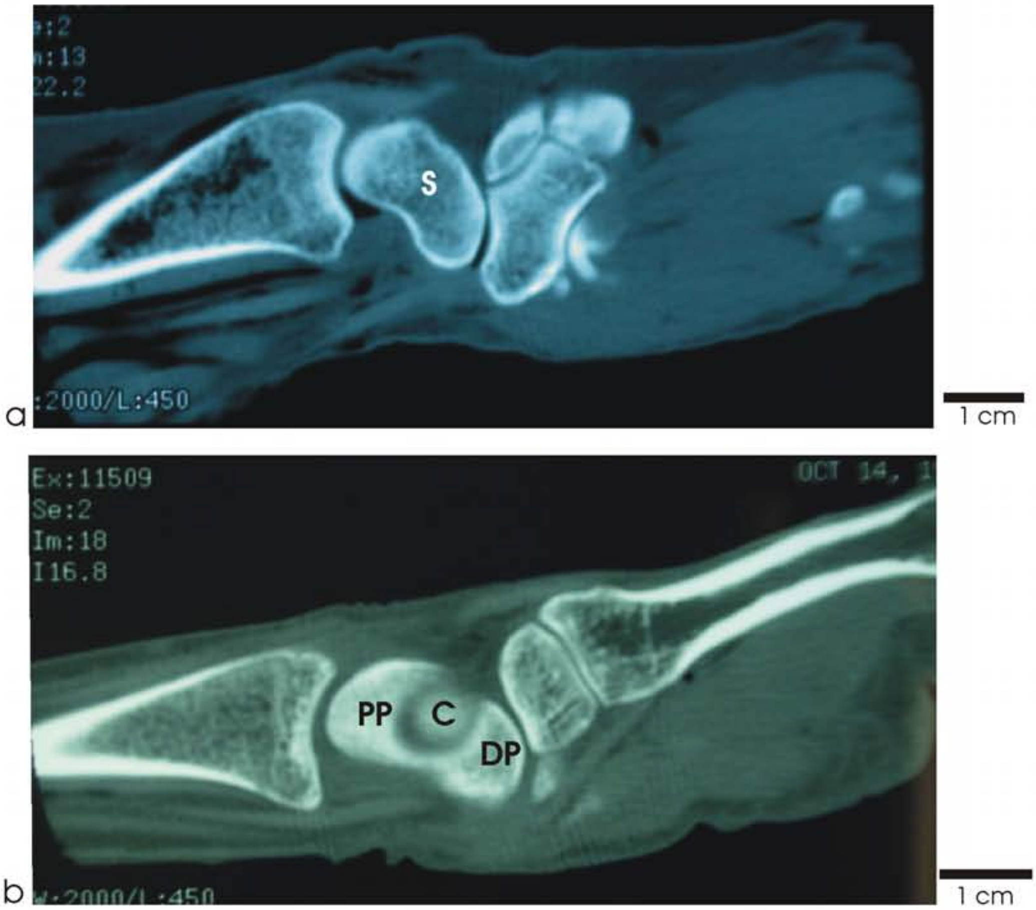

Figure 4.3 Computed tomographs selected for measurement. a - sections with the complete scaphoid (S) were used to measure scaphoid dimensions; b - sections in which the capitate head (C) could be observed between the proximal (PP) and distal (DD) poles of the scaphoid were used to determine the position of the capitate head relative to the scaphoid.

4.3.1 Scaphoid Dimensions

Images with complete longitudinal sections of the scaphoid were selected to measure the dimensions of the scaphoid. The maximum length of the scaphoid was measured in the median three sections in which the complete scaphoid was identified. Incomplete sections of the scaphoid were not measured. The measurements were done digitally using Image J (Rasband, 2002).

4.3.2 Capitate Head Position

Images in which the capitate head was visible between proximal and distal parts of the scaphoid were selected to measure the position of the capitate head against the scaphoid. The position of the capitate head along the ulnar aspect of the scaphoid was determined by measurement of the maximum length of the proximal and distal poles of the scaphoid as seen proximal and distal to the capitate head in each section (figure 4.3b) Measures of the maximum length of the scaphoid and the maximum length of the proximal and distal poles of the scaphoid were taken in each section using Image J (Rasband, 2002). The area of each pole was measured in Image J (Rasband, 2002) by tracing the outline of each pole.

4.4 Results

The length of the scaphoid in the selected slices was measured. The mean maximum length of the type one wrists (19.756±1.605mm) was significantly greater than the mean length of the type two wrists (18.407±1.483mm; $p < 0.05$; figure 4.4).

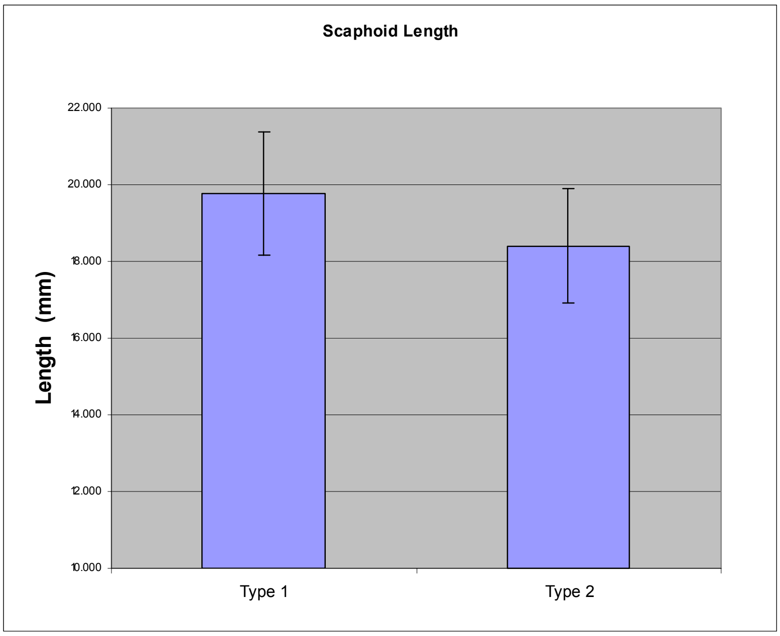

Figure 4.4 Mean maximum scaphoid length of the type one and the type two wrists.

Computed tomographic images were selected that displayed the capitate head between the proximal and distal extremities of the scaphoid (figure 4.3b). The lengths of the proximal and distal poles, separated by the emergence of the capitate head, were measured. These measures were then divided by the total length of the scaphoid (maximal distance between proximal and distal poles) to yield relative lengths of either poles. The mean relative distal pole length of the type two wrists (0.406±0.086 mm/mm) was significantly greater than that of the type one wrists (0.327±0.052 mm/mm; $p < 0.05$;

figure 4.5). The mean relative proximal pole length of the type one wrists (0.316±0.047 mm/mm) was significantly greater than that of the type two wrists (0.192±0.096 mm/mm; $p < 0.05$; figure 4.5). The mean relative proximal and distal pole lengths were not significantly different in the type one wrists ($p > 0.05$; figure 4.5), but the mean relative proximal and distal pole lengths were significantly different in the type two wrists ($p < 0.05$; figure 4.5).

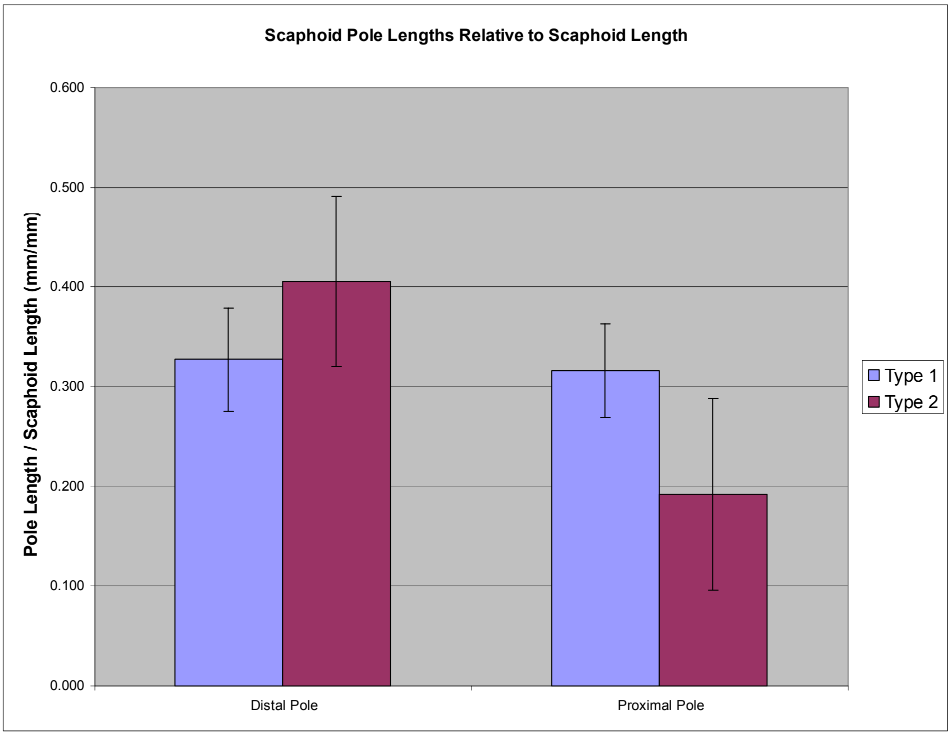

Figure 4.5 Mean relative scaphoid pole lengths. The length of the proximal and distal scaphoid poles were calculated relative to the maximum length of each scaphoid.

The areas of the proximal and distal poles were measured for each type of wrist. The mean area of the proximal pole of the type one wrists (69.953±9.736mm^2) was significantly greater than that of the type two wrists (43.405±14.009 mm^2; $p < 0.05$; figure 4.6). The mean area of the distal pole of the type one wrists (53.161±19.771 mm^2) was not significantly greater than that of the type two wrists (52.656±22.954 mm^2; $p > 0.05$; figure 4.6). The areas of the poles relative to the length of the scaphoid were similarly related. The mean relative proximal pole area of the type one wrists (3.482±0.457 mm^2/mm) was significantly greater than that of the type two wrists (2.364±0.806 mm^2/mm; $p < 0.05$; figure 4.7). The mean relative distal pole area of the type one wrists (1.826±0.183 mm^2/mm) was not significantly greater than that of the type two wrists (1.7±0.233 mm^2/mm; $p < 0.05$; figure 4.7).

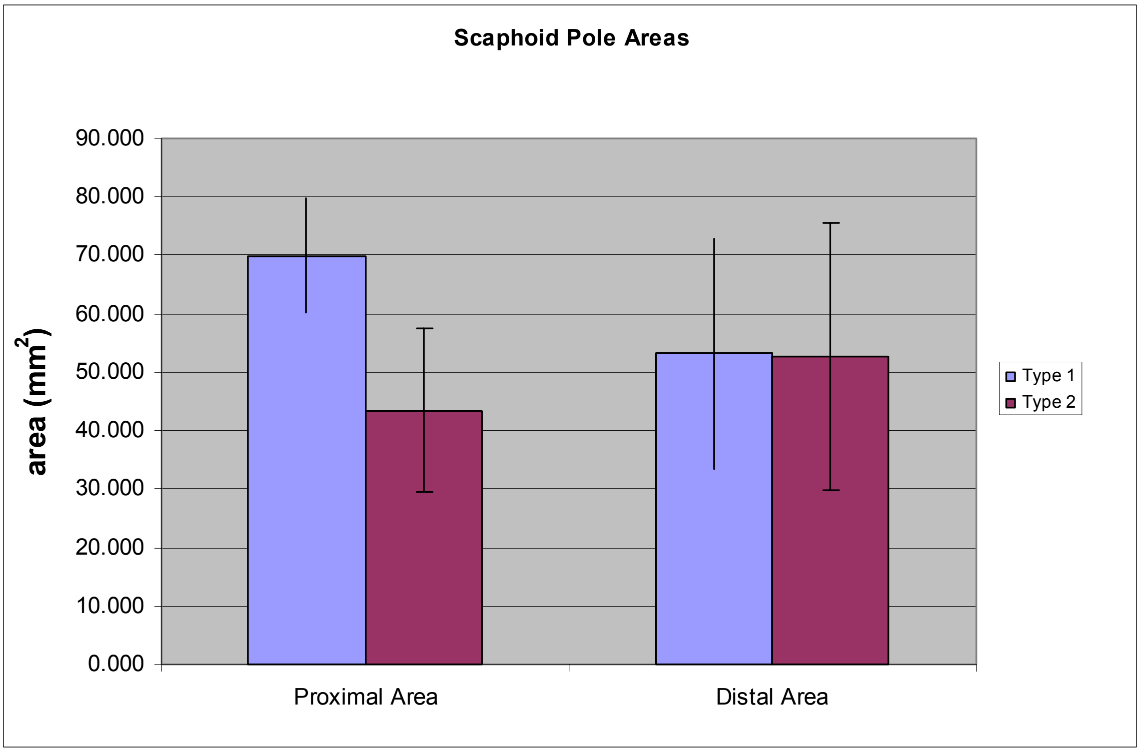

Figure 4.6 Mean scaphoid pole area. The areas of the proximal and distal scaphoid poles were measured for each type of wrist.

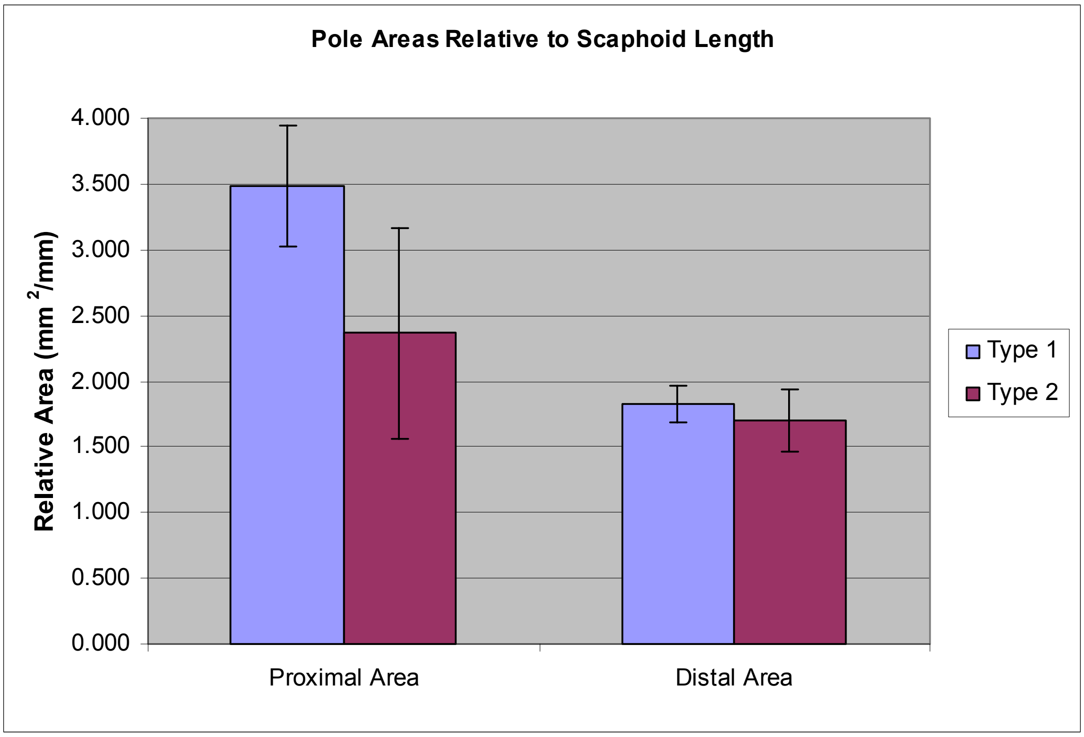

Figure 4.7 Mean relative scaphoid pole area. The areas of the proximal and distal scaphoid poles were calculated relative to the maximum length of each scaphoid.

Indices of the relative pole lengths (proximal scaphoid pole length/distal scaphoid pole length) and areas (proximal scaphoid pole area/distal scaphoid pole area) were calculated for each type. The mean of the type one pole length indices (1.0±0.26) was significantly greater than the mean of the type two pole length indices (0.626±0.383; $p < 0.05$; figure 4.8). The mean of the type one pole area indices (1.9±0.15) was significantly greater than the mean of the type two pole area indices (1.346±0.404; $p < 0.05$; figure 4.8). Significant relationships were observed between the indices within each type of wrist. Calculation of Pearson's correlation coefficient for the pole measurements of each type confirmed this suggestion. Type one measures of proximal and distal pole length relative to scaphoid length were marginally correlated ($r = 0.563$; $p < 0.05$), whilst the type two lengths were strongly correlated (r = 0.908; $p < 0.05$). Type one measures of proximal and distal pole areas relative to scaphoid length were strongly correlated (r= 0.862, $p < 0.05$), as where the type two areas (r= 0.779, $p < 0.05$).

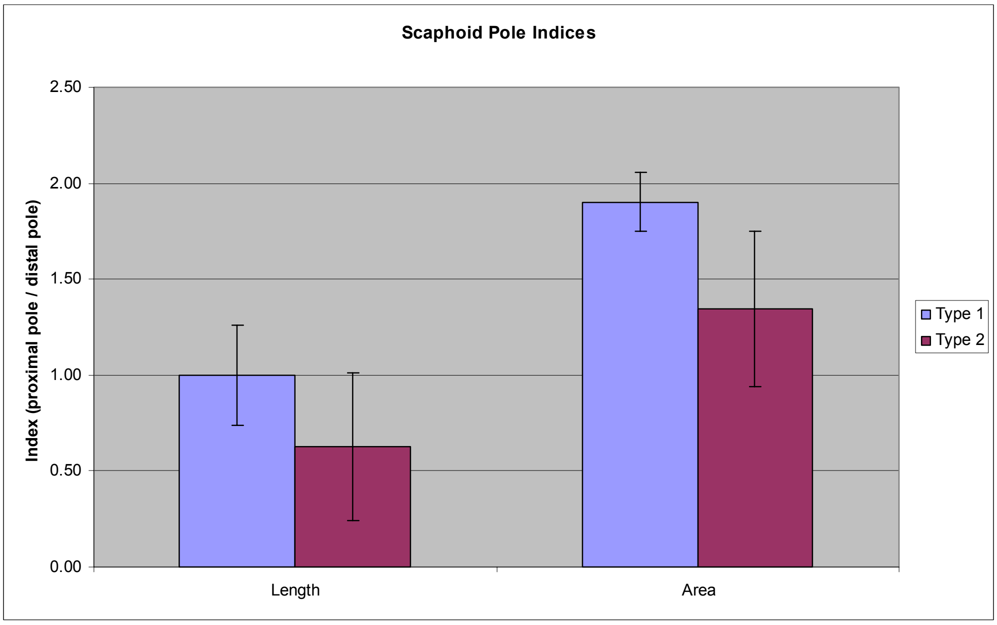

Figure 4.8 Mean scaphoid pole indices. The scaphoid pole index for each specimen was calculated by dividing the proximal value by the distal value.

4.5 Discussion

4.5.1 Computed Tomographs

The variable relationship between the scaphoid and the capitate is observable *in situ* with the aide of computed tomography (figure 4.9). Differentiation of scaphoid landmarks is difficult on standard roentgenographs (Compson *et al*, 1997), making a distinction between scaphoid types unlikely. Variation in wrist position and film orientation may alter the perception of the film, such that erroneous conclusions are met. However, computed tomographs reveal the distinct differences in the orientation of the capitate facet when specific scaphoid angle tomographs are taken in accordance with Bain *et al* (1995). Computed tomographic images through the longitudinal axis of the scaphoid reveal the capitate head within the capitate facet of the scaphoid as the ulnar margin of the scaphoid is approached.

The type one wrists differed from the type two wrists. The type one wrists had scaphoids that were longer, had greater proximal areas and greater proximal lengths than the type two wrists. There was no significant difference in distal pole area, but the distal pole of the scaphoid in the type two wrists was significantly longer than that of the type one wrists. The relative pole length and area indices of the type one wrists were significantly greater than those of the type two wrists. These suggest that the proximal values (length and area) contribute more to the scaphoid in the type one wrists than in the type two wrists. This suggests that the type one wrists have a greater structural relationship between the scaphoid and the lunate. This may be expected if the scaphoid and the lunate of the type one wrists are moved together. The suggestion of a lesser structural relationship

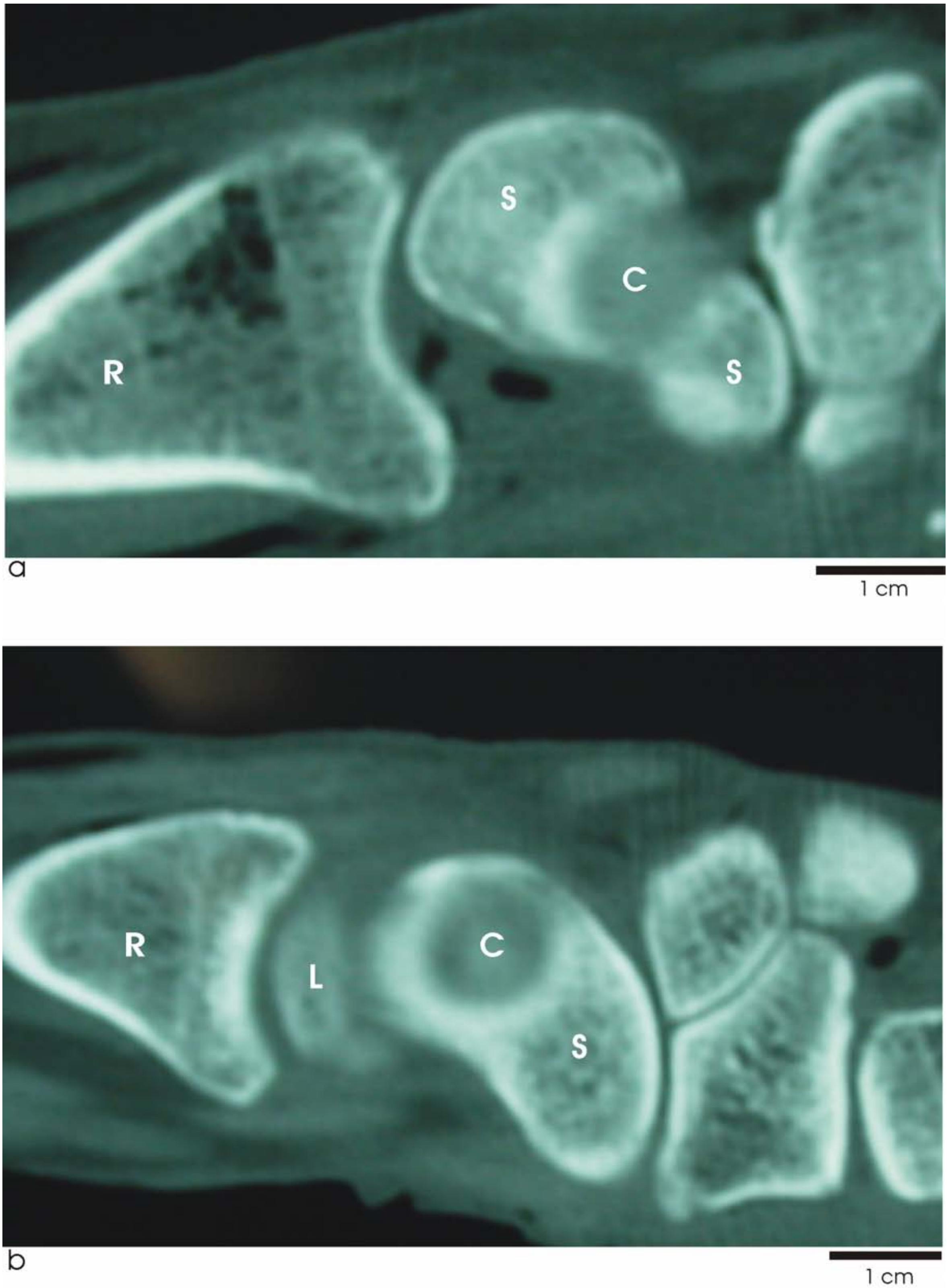

Figure 4.9 Scaphoid angle computed tomographs. a - type one scaphoid (S) with capitate head (C) emerging evenly between the two poles; b -type two scaphoid (S) with capitate head (C) emerging proximally against the scaphoid; R - radius, L - lunate.

between the scaphoid and the lunate in the type two wrists may indicate less uniform movements between the two bones, or even opposite movements. Similar suggestions are found in the kinematic literature (Craigen and Stanley, 1995; Moojen *et al*, 2003; Moritomo *et al*, 2000; Nakamura *et al*, 2000; Wolfe *et al*, 2000).

The potential motion of the scaphoid in the two types of wrist was also suggested by the position of the capitate head. The head of the capitate in the type one wrists was evenly placed between the two poles of the scaphoid. This is best illustrated in the relative scaphoid pole length index (figure 4.6). The head of the capitate in the type two wrists was positioned more proximally along the ulnar aspect of the scaphoid. A difference in scaphoid may be suggested based on these results. The scaphoid within a type one wrist is evenly placed about the capitate head. In this orientation the scaphoid may be moved in any direction about the head of the capitate. It therefore may be flexed/extended, where the point of articulation with the capitate head need not change (the head acting as a fulcrum). The scaphoid may also be rotated about its longitudinal axis, where it would be moved palmarly around the capitate head in internal rotation, and dorsally around the capitate head in external rotation. The large proximal pole also suggests that the scaphoid in the type one wrists may be translated ulnarly. In order to be translated ulnarly, as may happen in radial deviation of the wrist (Craigen and Stanley, 1995; Moojen *et al*, 2003), the scaphoid must not impact upon the styloid process of the radius, and therefore cannot rotate about a point on the capitate head.

The position of the capitate head against the scaphoid may determine the movement of the scaphoid. The capitate head may act as a fulcrum about which the scaphoid is rotated. For such a movement to occur force must be directed to either side of the fulcrum in order to displace either pole. Radial deviation of the wrist may be initiated by proximally-directed force from the trapeziotrapezoid complex (Berger, 1996) forcing the radial side of the carpus to compress. Such a force on a scaphoid with a more distally orientated capitate head, such as in the type one wrists, may be conducive to translation of the scaphoid (figure 4.10a). The force may be directed proximal the fulcrum (point of contact with the capitate head) and therefore move the proximal pole of the scaphoid about the capitate head. Conversely, if the head of the capitate were positioned more proximally on the scaphoid, such as in the type two wrists, the proximally directed force may pass distal to the fulcrum (point of contact with the capitate head), resulting in flexion of the scaphoid (figure 4.10b). Flexion may be the only movement that can occur at the scaphocapitate joint without translation due to the position of the radial styloid process and the body of the capitate (Berger, 1996).

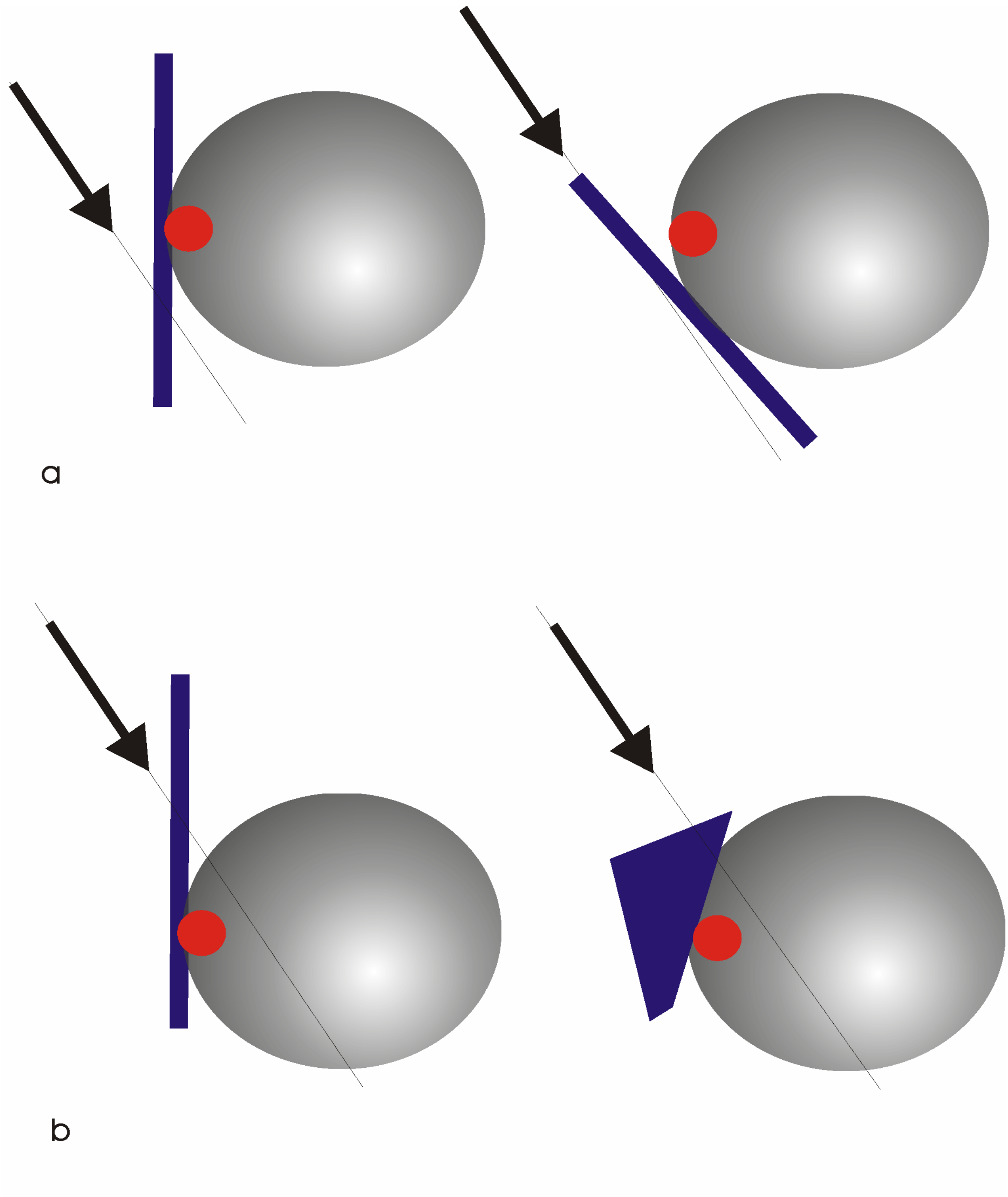

Figure 4.10 Theoretical effect of capitate head position on scaphoid motion. a - in the type one wrists the capitate head (ball) was positioned evenly along the ulnar aspect of the scaphoid (blue line). Force transmitted proximally from the trapeziotrapezoid complex (arrow) may be concentrated proximal to the neutral point of contact between the scaphoid and the capitate (red dot). This may result in the proximal pole of the scaphoid being forced to translate ulnarly. The large proximal pole of the type one scaphoid may facilitate pushing the lunate ulnarly to enable this movement; b - in the type two wrists the capitate head (ball) was positioned proximally along the ulnar aspect of the scaphoid (blue line). Force transmitted proximally from the trapeziotrapezoid complex (arrow) may be concentrated distal to the neutral point of contact between the scaphoid and the capitate (red dot). This may force the scaphoid into flexion as the distal pole of the scaphoid cannot be moved ulnarly into the body of the capitate.

4.6 Conclusion

Variation in the scaphoid articulation with the capitate between wrists can be observed *in situ* with the aid of computed tomography. The difference can be observed as a change in the position of the head of the capitate between the proximal and distal poles of the scaphoid. In the type one wrists the capitate head was evenly positioned between either pole of the scaphoid with the wrist in a neutral position. In the type two wrists the capitate head was proximally positioned along the ulnar aspect of the scaphoid. This was observed as a proximal pole smaller in area and shorter in length than the distal pole.

The observed variation between wrists may be suggestive of variable carpal motion. The *in situ* variations may therefore be observed in a clinical environment. This may be used to identify wrist type and therefore apply a suitable course of treatment for the type of motion the carpal bones are likely to exhibit. This may improve the post-operative outcomes of surgical procedures aimed at improving wrist dysfunction.

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Chapter 5

Integrated Discussion and Conclusions

5.1 Integration of Results

The data discussed in this thesis combine to form a consistent theory of scaphoid motion within the sample population. The type one scaphoids discussed in chapter one were matched with the type one wrists discussed in chapter three. Likewise, the type one wrists discussed in chapter three included all of the type one wrists discussed in this chapter four. This was also reflected in the type two scaphoids/wrists. It may therefore be suggested that there are two types of scaphoids, rotating and flexing/extending. This suggestion is supported by the morphology of the scaphoid (chapter one), the ligamentous support of the scaphoid (chapter three) and the *in situ* position of the scaphoid relative to the capitate (chapter four). The concept of a rotating scaphoid and a flexing/extending scaphoid is also supported by kinematic studies (Moojen *et al*, 2002b; Moritomo *et al*, 2000).

It may be suggested that the type one scaphoids may be translated about the capitate head (figure 5.1). This may in part be due to the elongated capitate articular facet of the ulnar aspect of the scaphoid (chapter one) and the distal position of the capitate head whilst the scaphoid is in a neutral position (chapter four). Similar computed tomographs with the wrist in radial and ulnar deviation are required to validate this suggestion. It can be hypothesised that the capitate head will be observed in different positions corresponding to the proximal and distal extremes of the elongated capitate articular facet of the scaphoid. To facilitate a greater range of radial deviation the type one scaphoid could also be rotated about its longitudinal axis. This movement may enable the trapeziotrapezoid complex to slide proximally across the distal articular surface of the scaphoid. This suggestion is

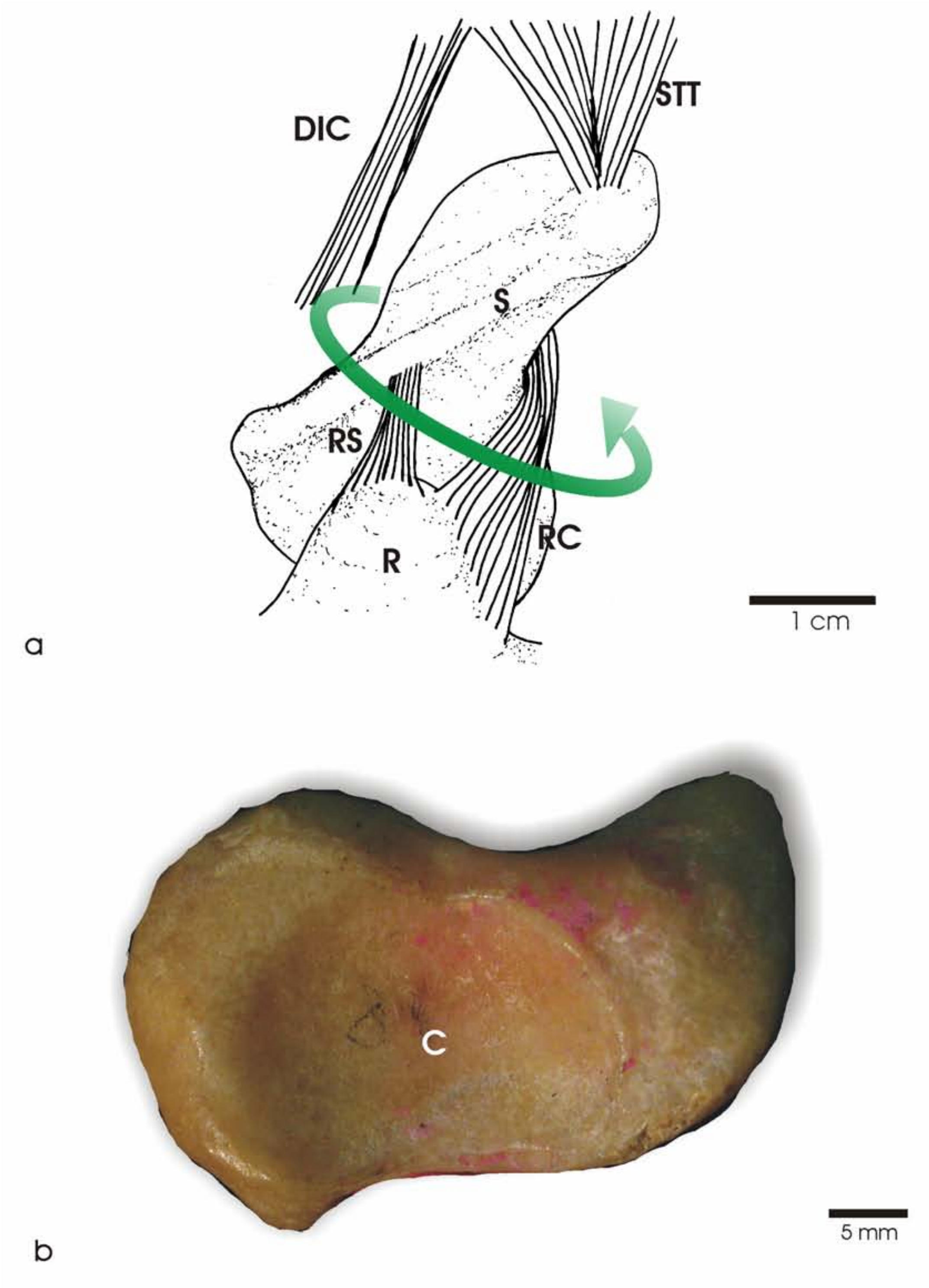
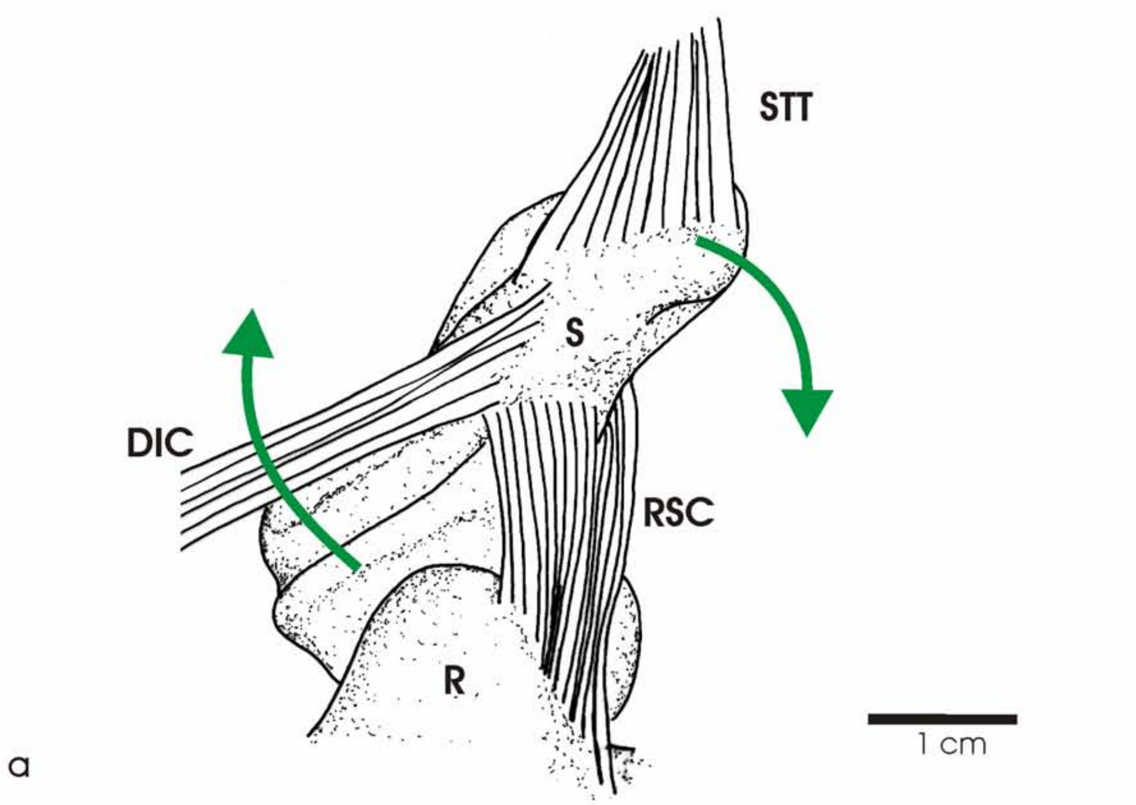


Figure 5.1 The type one (rotating) scaphoid. a - the ligamentous support of the rotating scaphoid. The scaphotrapeziotrapezoidal (STT) ligaments distally and the combination of the radioscaphoid ligament (RS) and the articulation with the capitate head (not shown) determine an axis about which the scaphoid may be rotated (arrow). This axis may be close to the longitudinal axis of the scaphoid. The scaphoid may be supported by the sling-like dorsal intercarpal (DIC) and radiocapitate (RC) ligaments, despite their lack of attachment to the scaphoid; b - the ulnar aspect of the rotating scaphoid with an elongated capitate articular facet (C), which suggests that the scaphoid may be translated against the capitate head to facilitate radial deviation of the wrist; R - radius, S - scaphoid

supported by the shallow capitate articular facet of the scaphoid, which reduces the likelihood of the scaphoid impacting upon the capitate and the ligamentous support of the type one wrist. The ligaments supporting the scaphoid in the type one wrists were such that the scaphoid might be rotated about an axis determined by the scaphotrapezoid and radioscaphoid ligaments (approximately the longitudinal axis of the scaphoid). This movement may be facilitated by the "slings" around the waist of the scaphoid formed by the radiocapitate, scaphocapitate and dorsal intercarpal ligaments. These ligaments may also limit flexion/extension of the scaphoid by limiting palmar/dorsal movements of the poles of the scaphoid.

The type two scaphoids may be moved differently to the type one scaphoids (figure 5.2). The deep semi-spherical capitate articular facet of the scaphoid and the proximal position of the capitate head against the scaphoid suggest that the scaphoid of the type two wrists is flexed/extended. The deep capitate articular facet of the type two scaphoid could limit the movement of the scaphoid against the capitate (Hamrick, 1996). The deep, congruent articulation between the scaphoid and the capitate may allow only flexion/extension of the scaphoid about the point determined by the capitate head. Translation or rotation of the scaphoid may be limited by the skeletal restraints of the articulation. The axis about which the scaphoid may be flexed/extended could be reinforced by the ligamentous support of the scaphoid (figure 5.2a). The dorsal intercarpal ligament and the scaphoid band of the radioscaphocapitate ligament converge upon similar points on the radial-dorsal aspects of the scaphoid. The orientation of these attachments in relation to the position of the capitate head suggests that the ligamentous attachments and the capitate head may jointly determine the axis of flexion/extension of the type two scaphoid. Flexion/extension of the type two scaphoid is further suggested by the



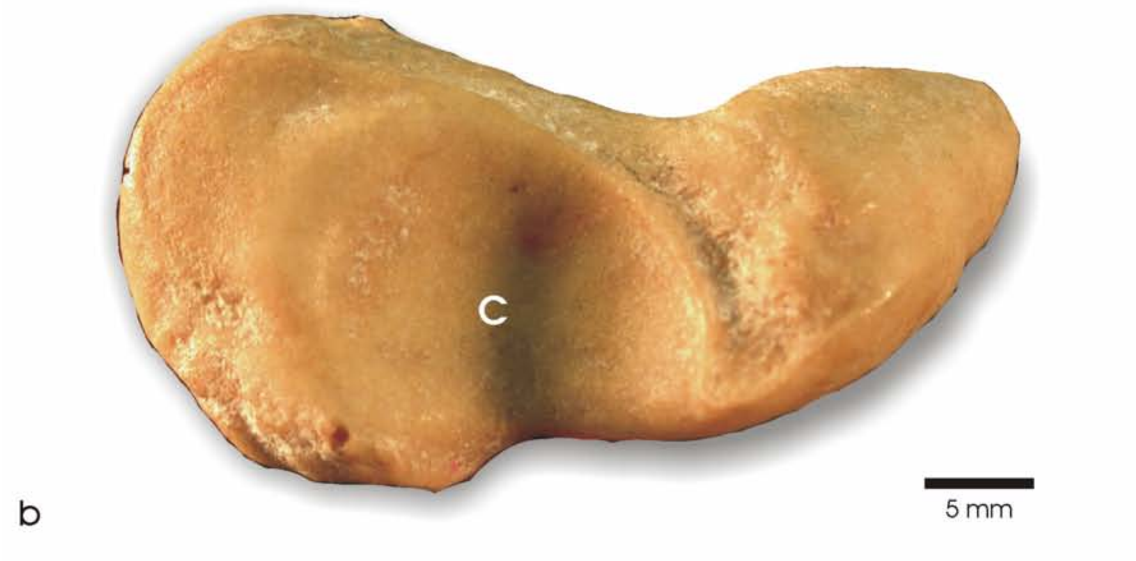


Figure 5.2 The type two (flexing) scaphoid. a - the ligamentous support of the flexing scaphoid. The scaphotrapeziotrapezoidal (STT) ligaments distally and the combination of the dorsal intercarpal ligament (DIC), radioscaphocapitate ligament (RSC) and the articulation with the capitate head (not shown) limit the rotation/translation of the scaphoid and may determine an axis about which the scaphoid may be flexed/extended. b - the ulnar aspect of the flexing scaphoid with a more spherical capitate articular facet (C), which suggests that the scaphoid may be locked in position against the capitate head, limiting scaphoid motion to flexion/extension; R - radius, S - scaphoid.

arrangement of the scaphotrapezial ligaments. The broad proximal (scaphoid) attachment of these ligaments suggests that the type two scaphoid is unlikely to be rotated about its longitudinal axis to any great degree. The scaphotrapezial ligaments, in conjunction with the dorsal intercarpal and radioscaphocapitate (scaphoid band) are likely to become taut with very little palmar translation or internal rotation of the scaphoid. The type two scaphoid also had less area for articulation with/ligamentous attachments to the lunate, suggesting that the two bones may not be moved together. Kinematic studies suggest that the scaphoid and lunate are flexed and extended to oppose the movement of the other, thus creating space in which the other carpal bones may be moved (Craigen and Stanley, 1995; Kauer, 1986; Kobayashi *et al*, 1997; Moojen *et al*, 2002a; Nakamura *et al*, 2000). This may facilitate generation of the full range of wrist motion.

5.2 Clinical Applications and Implications

The typing of the wrist discussed in this thesis is able to be identified clinically with the aid of computed tomography. Scaphoid angle computed tomographs as described by Bain *et al* (1995) enable the capitate head to be observed between the two poles of the scaphoid. Variation in this arrangement is suggestive of variation in the movement of the scaphoid. Differentiation between rotating and flexing/extending scaphoids can therefore be made with little modification to standard practice.

The detailed description of scaphoid morphology and variation may influence clinical practice. Improved understanding of the anatomical features of the scaphoid could enhance interpretation of many clinical findings. The use of the specific landmarks of each type of scaphoid is likely to improve visualisation of the scaphoid in normal medical imaging modalities. Compson *et al* (Compson *et al*, 1997) suggested that a detailed knowledge of scaphoid anatomy enhanced the ability to interpret roentgenographic images of the scaphoid. This may be further applied to computed tomographs, magnetic resonance images and other forms of modern media. Improved interpretation alone may influence the course of clinical management for wrists dysfunctions and injuries.

Variation in scaphoid morphology and the consequent variation in carpal mechanics may alter physical examination of the wrist. Current physical examination techniques and dysfunction-specific tests are reliant upon the sound anatomical knowledge of the examiner and type of carpal movements expected in a normal wrist. The morphology has been shown to differ, which suggests that the carpal movements may also differ. Therefore, manipulation of wrists with mechanical dysfunction could be modified to investigate either rotation or flexion/extension of the scaphoid. However, it is unlikely that the morphological variations of the scaphoid observed in this study will be discernible upon physical examination. Physical examination of the wrist may be important in determination of the cause of dysfunction, primarily when radiologic findings are inconclusive (Yamaguchi *et al*, 1998).

Exploratory techniques could be utilised to visualise the variations suggested in this thesis. Arthroscopy of the joints discussed may facilitate visualisation of the variations in ligamentous support of the radial side of the carpus. Such procedures may be used to augment understanding of a patients functional typing. This is likely to clarify radiologic interpretations where accurate typing of the patient is not possible from the available images. Treatment of wrist dysfunction using modalities such as arthroscopy are still debated (Ruch and Paterson Smith, 2001), with some approaches (such as arthroscopic debridement followed by pinning of the damaged joint) remaining controversial. Better understanding of the mechanism of the carpus may dictate what procedures are appropriate for each individual. This may improve post-operative results for the individual, success rates for a group of patients and reduce the likelihood of controversy arising from choice of procedure.

The suggestion of variable scaphoid motion may influence the surgical management of wrist dysfunctions (Nuttal *et al*, 1998). Application of a procedure intended to stop or limit scaphoid flexion may be inappropriate for an individual with a rotating scaphoid. Likewise a procedure intended to stop or limit rotation of the scaphoid could be inappropriate for an individual with a flexing/extending scaphoid. Further understanding of the variation in motion of the scaphoid and other carpal bones may facilitate the modification or development of surgical techniques suitable for each pattern of carpal motion. The surgical repair of the unstable wrist is commonly attempted with a soft tissue repair or a limited arthrodesis (Szabo *et al*, 2002). The support for soft tissue repair has been favoured by many (Ishida and Tsai, 1993; Kleinman, 1987; Szabo *et al*, 2002) in respect to the post-operative range of motion of the wrist. The post-operative range of motion of the wrist may be severely limited following an arthrodesis (Kleinman, 1987; Szabo *et al*, 2002), but may still be favoured to treat a variety of wrist dysfunctions, such as rotary subluxation of the scaphoid or progressive wrist instabilities (like SLAC wrist) (Middleton *et al*, 2003). Others (Rahimtoola and Rozing, 2003) suggest that improved understanding of carpal mechanics will facilitate the development of new carpal prostheses that would replace dysfunctioning or damaged bones through arthroplastic procedures. The incidence of arthroplasty revision is still high (Kleinert *et al*, 1985; Vogelin and Nagy, 2003), suggesting that further advances in the understanding of carpal structure and function, and hence prosthesis design, are required. Therefore, the suggestion of variable scaphoid motion (and hence variable patterns of carpal mechanics) could be indirectly supported by the results of surgical treatment of wrist dysfunction. Where carpal bones are replaced (arthroplasties) the results seem worse than carpal bone fusions (arthrodeses), or soft-tissue repositions (such as capsulodeses).

5.3 Future Directions

The precise movements of the carpal bones have yet to be explained, and it is hoped that this anatomical study may assist in achieving that aim. Biomechanical testing of the theories discussed in this thesis is required, as is a more extensive histological study of the ligamentous support of the wrist. General histological sections of the entire carpus may improve the understanding of ligamentous support of the complete carpus, whilst a more detailed approach to the scaphoid and triquetrum (radial and ulnar mobile components of the carpus) and to the lunate (central mobile component) may provide a more detailed description of the ligamentous restraints placed acting upon these bones. In is anticipated that these may be attempted in the near future.

Recent investigations by the author and colleagues have suggested that the theories discussed in this thesis may apply to the entire carpus. Two distinct carpal morphologies can be observed (figure 5.3) which suggest that the two wrists may be moved differently. These were originally identified whilst analysing range of motion results for “four corner fusion” arthrodeses (performed by Dr Aman Sood, personal communication). Those wrists with a flexing/extending scaphoid (according to this study) may have a flexing/extending

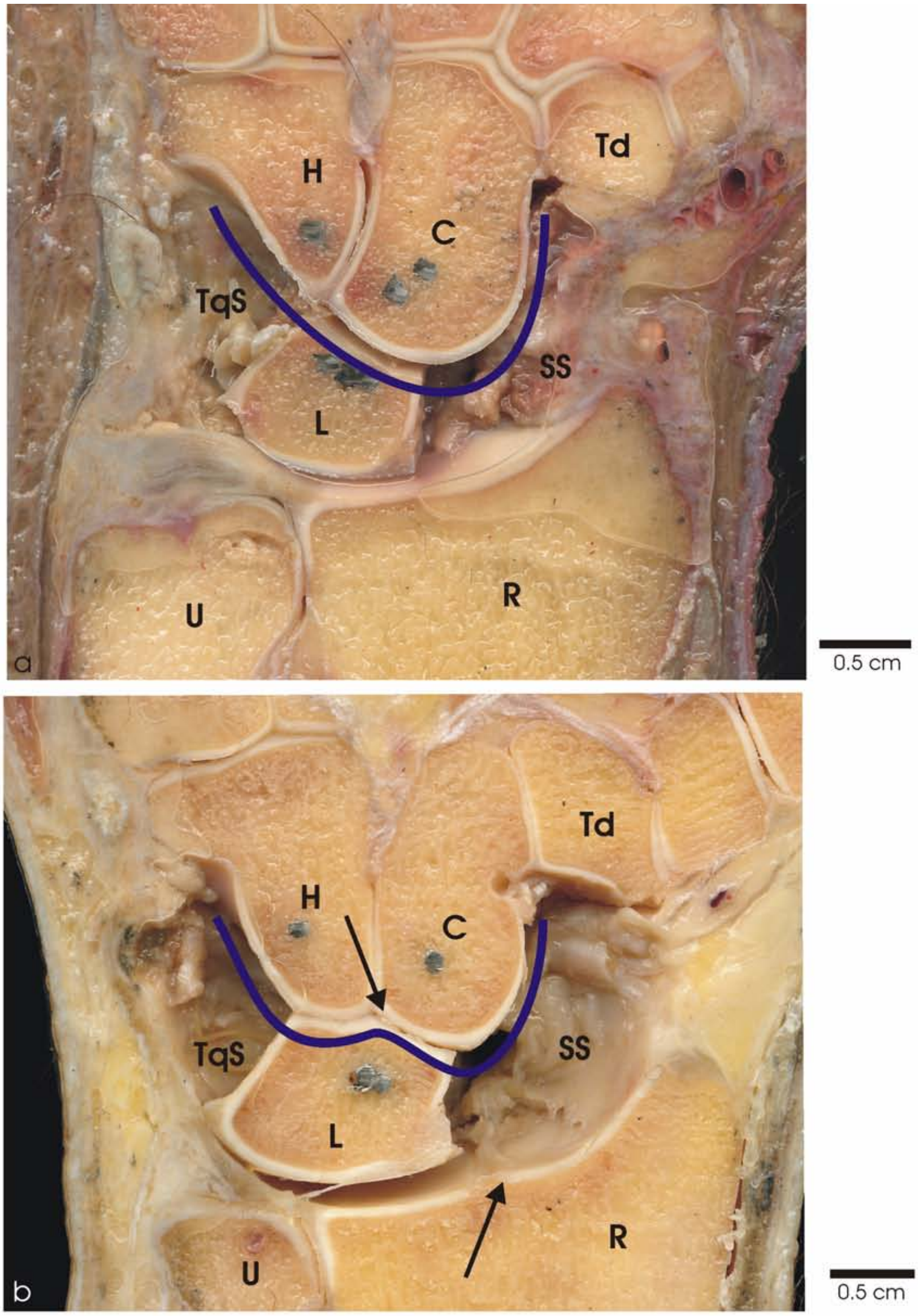


Figure 5.3 Example of global variation in wrist function. a - a type one (rotating) wrist in which the capitate (C) and hamate (H) together constitute a unicondylar surface (line) about which the proximal row of carpal bones may translate; b - a type two (flexing) wrist in which the capitate (C) and hamate (H) together constitute a bicondylar surface (line) about which the proximal row of carpal bones may be flexed/extended. The articular surfaces are divided into facets by cartilaginous crests (arrows); R - radius, U - ulna, L - lunate, SS - space for scaphoid, TqS - space for triquetrum, Td - trapezoid; Coronal sections of "Four corner fusions" performed by Dr Aman Sood.

lunate (type II) and triquetrum. The capitohamate complex of this wrist type resembles a bicondylar joint such as the knee. The other type of wrist may have a rotating/translating proximal row. The capitohamate complex of this wrist type resembles a unicondylar joint such as the hip. It is hoped that these suggestions may be investigated further.

5.4 Conclusion

Two distinct morphologies within the radial side of the carpus have been identified. The types have been consistently identified by gross examination of bones, gross and histologic examination of ligamentous supports, and computed tomographic examination of intercarpal relations. These differences have been discussed in reference to the theoretical movement of the scaphoid, and have been related to numerous kinematic studies. The theory of two types of scaphoid motion is supported across the three methods of investigation, and by the kinematic data reported by others (Craigen and Stanley, 1995; Kauer, 1986; Kobayashi *et al*, 1997; Moojen *et al*, 2002a; Nakamura *et al*, 2000).

The identification of scaphoid typing and its relation to functional variation may be of significance to surgical management of wrist dysfunction. The differences, identifiable clinically with the aid of computed tomographs, may influence the choice of surgical treatment. This may improve outcomes from the surgical treatment of wrist dysfunction and reduce the likelihood of revision of these procedures. The influence this could have on the patient and the health system may be profound.

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Appendices

Appendix I The Embalming Process of the Ray Last Anatomy Laboratory

All cadaveric specimens used in this study were from the Ray Last Anatomy Laboratory, Department of Anatomical Sciences, the University of Adelaide. The specimens were embalmed using the standard procedure of the Ray Last Anatomy Laboratory.

For a 20L mix:

55% ethanol (100% undenatured)

5% formalin (40w/v)

5% phenol (88% aqueous)

20% propylene glycol

15% hot water

This mix is introduced to the cadaver via a cannulated common carotid artery with the mix suspended at ceiling height to generate a pressure of approximately 12psi.

The cadaver is then stored at four degrees celsius for a minimum of three months in order to allow the water content of the specimen to evaporate under the influence of the fixative.

This embalming protocol ensures that the specimen is available for long term usage, with only slight discolouration, no fungal growth, low levels of airborne toxins and excellent flexibility and tissue differentiation. The specimens are also suitable for histological investigation as the cellular content of most tissues remains undisturbed.

This embalming procedure was therefore appropriate for this study and facilitated the multi-discipline approach to the investigation.

Appendix II Processing of Histological Specimens

i. Decalcification

The specimens selected for histologic examination were first decalcified. The initial solution used consisted is listed below:

ethylenediaminetra-acetic acid (EDTA, $[CH_2N(CH_2COOH)\ CH_2COONa]_2\ 2H_2O$) saturated in 90.5mL of distilled H_2O

1% sodium acetate ($NaCH_3$)

9.5mL hydrochloric acid (HCl)

The large specimens used made this solution impractical, as adequate decalcification (determined by x-ray) was only achieved after long periods (weeks to months).

As an alternative, the following solution was used:

1% EDTA

9.5% nitric acid (HNO_3)

distilled H_2O

Each specimen was placed in a container decalcifying solution of a volume approximately four times that of the specimen. The container was then sealed and placed on an agitator to stir the solution. The agitation was a vital component of the process, as this maximised the usage of the solution by exposing all of the solution to the specimen.

Consequently, the process was accelerated by the change in solution and the change in procedure. The decalcifying solution was changed either daily or when the solution turned deep yellow in colour (indicating saturation of the solution with calcium), whichever came first. Initially, the progress of the decalcification was checked twice weekly by x-ray (Courtesy of Dr Rob Moore and thanks to Mr Greg Smith and Mrs Beverly Johnson***, Spinal Research Unit, Institute of Medical and Veterinary Science, Adelaide). This regime was accelerated to once every two days, as total decalcifying time dropped below two weeks. The majority of specimens were ready for the next stage of processing within three to five days.

ii. Single-Embedding (and why it didn't work)

Decalcified specimens were processed before embedding them in paraffin wax. The initial procedure was as follows:

70 % alcohol (C_2H_5OH)	overnight
80% alcohol	all day
95% alcohol	overnight
absolute alcohol	3 x 2 hours
Chloroform ($CHCl_3$)	overnight
dry on paper	
immerse in liquid paraffin wax	20 minutes
vacuum to 15Pa in liquid paraffin wax	30 minutes
vacuum to 20-25Pa in liquid paraffin wax	2 x 1.5 hours

The result of this procedure was poor. The specimens were brittle and could not be cut consistently without the slices falling apart. In light of this an alternative procedure was adopted.

iii. Double-Embedding

The double-embedding procedure was adopted to combat the difficulties faced with the single-embedding procedure. The double-embedding procedure was as follows:

50% alcohol	all day
70% alcohol	overnight
95% alcohol	all day
absolute alcohol	1.5 hours, then change for overnight
50% alcohol:50% diethyl-ether	half day
1% cellulose nitrate in	
50% alcohol:50% diethyl-ether	half day, overnight, half day
chloroform	2 hours
dry on paper	
immerse in liquid paraffin wax	20 minutes
vacuum to 15Pa in liquid paraffin wax	30 minutes
vacuum to 20-25Pa in liquid paraffin wax	2 x 1.5 hours

The addition of diethyl-ether and cellulose nitrate, and the reduction of chloroform exposure greatly improved the quality of the specimens.

iv. Moulds and Block Orientation

The processed specimens were embedded in paraffin wax. The moulds were improvised from materials within the lab as the size of the blocks far exceeded any of the orthodox moulds available. Once suitably sized moulds were constructed they were lined with wax and the specimen was placed in the mould. The orientation of the block was predetermined such that they desired cutting surface was exposed and could be placed face-down in the mould. Liquid paraffin was then poured around the block and allowed to set. The pre-cut surfaces were in either the sagittal or coronal plane and enabled the blocks to be placed flat upon the wax lining of the mould. Occasional movement of the mould or specimen block resulted in the cutting plane being slightly different to the desired sagittal or coronal planes.

Appendix III Sliding Microtome Sections

All of the histologic sections used in this study were cut using a Jorge Sliding (Sledge) Microtome (figure A.1) in the Department of Anatomical Sciences, the University of Adelaide.

i. Thickness Selection

The specimens were to be cut as thin as possible to permit the clearest examination of the tissues as possible. Suitable sections were cut as small as 12µm, but this was not consistently achievable. The section thickness varied between blocks, but most where done at 15µm. A smaller number of blocks had to be cut at 20µm. It may be suggested that the bones within these specimens were either of poor quality before death, or were unable to withstand the intensive embedding procedure.

ii. Dealing with Variable Outcomes from Processing

Several techniques were used to ensure optimal sectioning of the tissue and to accommodate difficulties in particular blocks or in particular regions of a block. Prior to cutting each block was placed on a cold plate to get the block as cold as possible. This was found to improve the initial cutting/trimming of the block as the superficial wax held together better when cold. Once the full surface of the block was being cut and sections were ready to be selected, the block was moistened with warm water and allowed to penetrate the wax. This facilitated smooth cutting of the block and assisted in keeping the

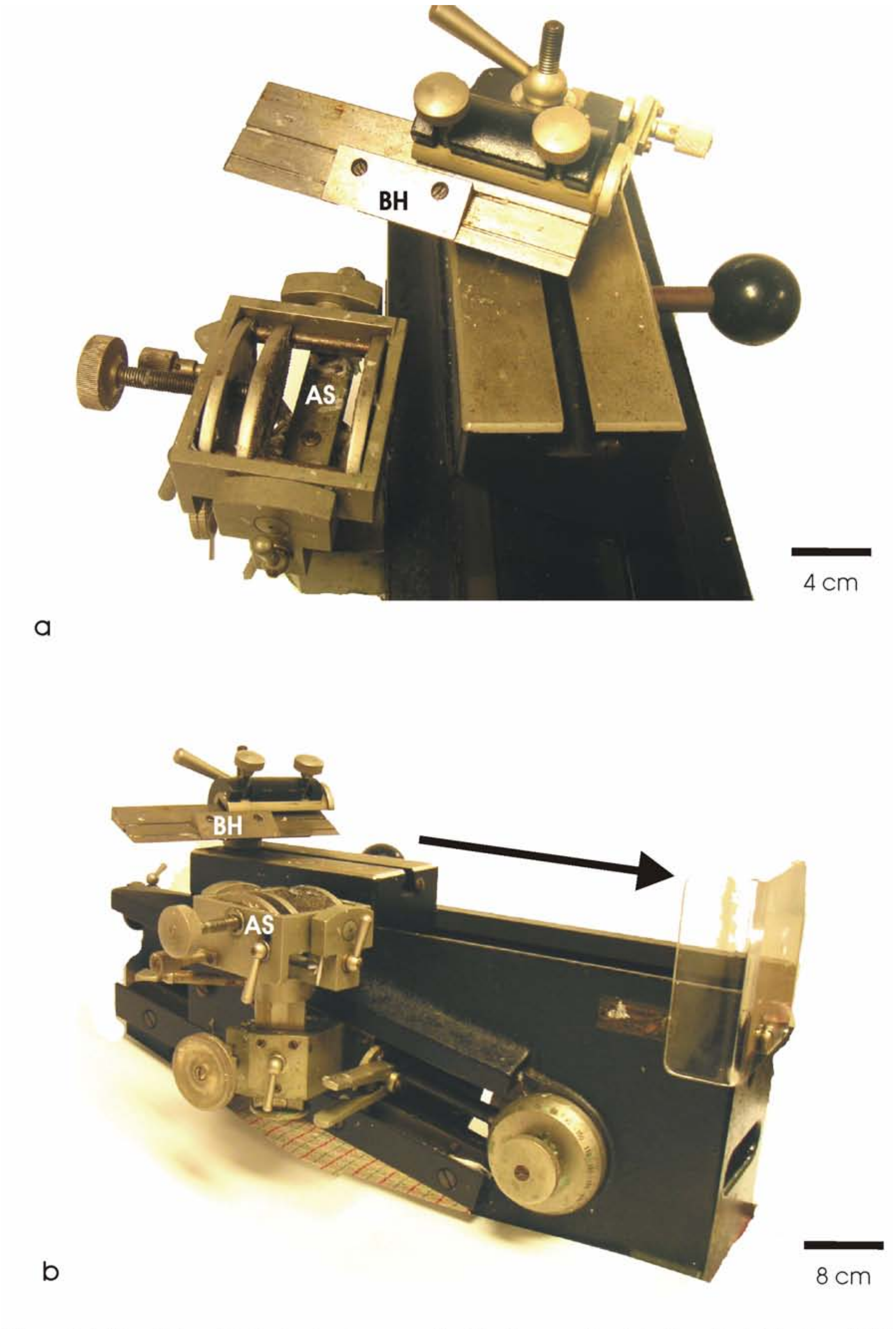

Figure A.1 The sliding (sledge) microtome. a - the blocks were fixed to the adjustable stage (AS) whilst disposable blades were attached to the blade holder (BH); b - the blade holder (BH) was pulled backwards (arrow), drawing the blade through the tissue block held in place by the stage (AS). Slow cutting speed and even pressure, both controlled manually, were essential for optimum sectioning of the tissue.

section together as it was raised across the blade. This may also have softened the specimen slightly, facilitating smooth drawing of the blade through the specimen, essential for suitable sections. If the sections still continued to fall apart, or the block was cutting poorly, a solution of 1% cellulose nitrate in alcohol was painted across the block surface and left to form a gel. This coating penetrated the block and held subsequent sections together. These techniques were repeated as necessary throughout each block to ensure section quality.

iii. Slide Coating and Weighting

To facilitate section adhesion to the slides each slide was coated with a gelatin mixture.

<u>Solution</u>

2.5g gelatin

0.25g chromium III potassium sulphate ($CrK(SO_4)_2\ 12H_2O$)

500mL distilled water

Gelatin dissolved into 250mL distilled water on medium heat with stirrer

Chromium dissolved in 250mL of distilled water

Gelatin solution added to chromium solution through filter paper.

<u>Procedure</u>

Slides were cleaned with soapy water

Rinsed in warm water

Placed in warm gelatin solution and carefully removed to avoid creating bubbles on the slide surface.

Placed in oven (50^0C) overnight

Sealed in airtight container until used

Appendix IV Modified Masson's Trichrome Staining

Ingredients

Ponceau de xylidine

Acid fuchsin

Light green SF

Hydrochloric acid

Phosphomolybdic acid

Glacial acetic acid

Wiegert's A and B[1]

Stains

1. Cytoplasmic Red

A = 1% ponceau de xylidine in 1% acetic acid

B = 1% acid fuchsin in 1% acetic acid

Mix together in a ration of 2A:1B

To make 300mL

A = 2g ponceau de xylidine + 2mL acetic acid in 200ml H_2O

B = 1g acid fuchsin + 1mL acetic acid in 100mL H_2O

The final pH ≈ 3.05

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[1] Mixed solutions of Wiegert's A and B will only last for 2 days

2. Light Green

2g Light Green SF + 2mL acetic acid + 100mL H_2O

Final pH ≈ 2.85

Procedure

Bring sections to water

Stain in Wiegert's Haematoxylin (A +B) for 5 minutes

Rinse in tap water

Differentiate in 1% HCl (2-3 quick dips)

Rinse in tap water

Blue in running tap water for approx. 10 minutes

Check that only nuclei are stained

Stain in Cytoplasmic Red for 1 minute

Rinse in two washes (dips) of 1% acetic acid

Displace in 4% phosphomolybdic acid for 2 minutes

Rinse in 1 wash of 1% acetic acid

Stain with Light Green for 35-70 seconds (may have to vary time)

Rinse in 1 wash of 1% acetic acid

Blot, dehydrate, clear and mount with Pix mounting media

This procedure was modified from the standard Masson's trichrome procedure by replacing an ammonia water wash with gently running tap water for ten minutes (finer control over "bluing" of sections). The red and green staining times were also reduced, particularly the green staining time, to enable finer control over the strain. Staining times of the original procedure resulted in heavy staining of all structures and subsequent loss of detail within each section.

Appendix V Digital Photography

i. The camera

The majority of the photos in this thesis were taken using the Nikon CoolPix 995 and the Nikon CoolPix 4500 digital cameras. All photos were taken at the highest resolution, utilising the 3.1 and 4.0 effective megapixels of the cameras.

All photos were taken with the camera in “manual” mode, allowing complete control over shutter speed, aperture, white balance, focus *et cetera*. The camera was stabilised with the aid a boom-arm tripod, enabling the camera to “hang” over the specimen from short distances. This facilitated the capture of “close up” macroscopic photographs, highlighting fine details of the specimens.

ii. The Lights

All of the photos were taken with the aid of artificial lighting. Two standard studio lights were used to highlight specific structures on the specimens and to ensure that the specimens were properly aligned for digital measurement. The latter was achieved by positioning each light separately to yield consistent shadow on the opposite side of the specimen or of a particular structure within the specimen. Even shadow from either light ensured that select structures would be in the same plane when photographed, and hence could be measured with the same scale.

Floor plan of setup (overhead)

B&W photo of setup (artistic)

iii. Photo Formats

The photos were taken at the highest resolution possible with each camera. It was determined that there was no significant difference between high resolution compressed JPEG images and uncompressed TIFF images with either camera. To maximise storage on the camera memory cards, all photos were subsequently saved a JPEG images. Once downloaded from the camera, the images were saved as TIFF files to ensure resolution wasn’t lost after saving edited versions of the files. The detail achievable was sufficient for A4 prints of the photos to be produced with no apparent loss of quality.

Appendix VI Digital Measurements with Image J

i. Image J

The "shareware" program Image J (Rasband, 2002) was used for all digital measurements. The program enabled lengths, areas, perimeters and angles (amongst many other things) to be measured on the digital images captured of each specimen. Accuracy of measurements may have been enhanced in this way, as the images were often magnified to several times their actual size (on a large monitor), enabling landmarks to be more clearly demarcated.

ii. Scale setting

The Image J program facilitated scale setting for each specimen. An initial measurement in pixels of a known distance was used to determine the scale of the image. All remaining measurements were translated into the correct scale and recorded in Microsoft Excel.

iii. Digital Measurements

All measurements were made by dragging the cursor from one point to another, around a structure, or between several points. Selection of particular tools (length, area, angle) from the program's menu determined the measurement to be made. Accuracy of the selection could be checked by changing magnification of the image and then accepted or adjusted and remeasured.

Reference

Rasband W. 2002. Image J. In, 1.27 ed. Bethesda, Maryland, USA: National Institute of Mental Health.

Appendix VII Digital Survey of Wrist Anatomy

In addition to the specific work done in this study, the large sample of cadaveric specimens have been used to collect data for future studies. To do so, detailed digital photographs were taken of all aspects of each specimen, at each stage of dissection. In doing so, for example, a study could be undertaken to map the relationship between cutaneous veins and nerves. Likewise, similar studies to the one presented here could be done on other regions of the wrist, such as the ulnar carpal bones, the triangular fibrocartilaginous complex or variations in intrinsic muscle attachment.

Appendix VIII Ligament Measurements

The dimensions of all the ligaments observed in the gross investigation were measured. Only those measures pertinent to the study were included in the thesis. For example, the lengths of the radioscaphocapitate and radiocapitate ligaments were not important as the difference in attachment of the ligaments was enough to differentiate them.

i. Dimensions

Six measures were made for each ligament to determine its size and shape. The measures were proximal, middle and distal attachment widths, and radial, median and ulnar fibre lengths for ligaments orientated proximal-distal and obliquely within the wrist. Ligaments orientated radial-ulnar within the wrist had proximal, middle and distal fibre lengths, and radial, median and ulnar attachment widths measured.

ii. Angulation

The angle of ligaments where measured between the mid-points of either attachment site relative to the transverse plane of the carpus.