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Rotator cuff disease in humans and apes: a palaeopathological and evolutionary perspective on shoulder pathology

Rotator Cuff Disease in humans and apes: a palaeopathological
and evolutionary perspective on shoulder pathology

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Abstract

Humans are unique amongst the hominoids in having evolved habitual bipedalism. The upper limb has been freed from a locomotor role and has become specialised to perform manipulatory tasks. The shoulders of humans and other hominoids are morphologically similar, although the human shoulder includes specialisations representing adaptation to use of the upper limb below the shoulder. The human shoulder joint is susceptible to degenerative joint disease (DJD), most commonly taking the form of rotator cuff disease (RCD). Mention of RCD is extremely rare in the palaeopathological record, and does not represent the spectrum of disease recognised clinically; RCD is entirely absent from literature on non-human primate pathology. Palaeopathology and comparative primate pathology have the potential to provide perspective on DJD in modern humans, as well as providing insight into the relationship between form and function. This project comprises three studies, aiming 1) to investigate whether the wider spectrum of pathology now recognized as RCD could be identified in human skeletal remains; 2) to test the palaeopathological diagnostic criteria for RCD in a cadaveric study; and 3) to investigate whether RCD could be identified in the skeletons of other hominoids. The results confirm that degenerative changes consistent with a diagnosis of RCD may be seen in both human and non-human primate skeletal material. The rates of enthesopathy in humans were extremely high compared with gorillas and chimpanzees. In the absence of relevant differences in bony architecture, it is suggested that these high rates of change in the human relate to mechanical factors, and provide support for the incomplete use hypothesis; in this context, the shoulder is a joint in which the predisposition to degenerative change reflects a relatively sudden change in use with the adoption of habitual terrestrial bipedalism in hominids.

Dedication and Acknowledgements

I would like to thank the Department of Anatomy, University of Bristol, for giving me the opportunity to pursue this part time PhD. I am also grateful to the University for allowing me to take a year's leave, both to film with the BBC, but also allowing me time to write up this thesis.

I am enormously grateful to my PhD advisory team: Kate Robson-Brown, Jonathan Musgrave and Mike Adams. Juggling a part-time PhD with the teaching demands of being a full-time clinical anatomist, not to mention the demands of the RAE, has not been without its trials and tribulations, and the support I have received from my advisors has been invaluable. I am also immensely grateful to my colleagues, Tim Peters and Mark Perry, both of whom share a profound ability to cut through the Gordian knot of statistics.

When I arrived in the Department of Anatomy in 1998, as a medical demonstrator, Jonathan Musgrave encouraged me to develop my interest in 'old bones' and introduced me to the late Juliet Rogers, to Kate Robson-Brown and her then PhD student, Louise Loe. Juliet was herself a clinician turned academic, and encouraged my interest in palaeopathology; Louise took me under her wing and showed me how to 'lay out a skeleton', in the dark basement of the BRI; on days when I wasn't teaching in the dissection room, I attended Kate's inspirational lectures on human evolution. Their support and encouragement was essential to my decision to leave clinical medicine and pursue an academic career.

Thanks are due to all the curators and institutions that have granted me access to their collections: Maggie Bellati at the Duckworth Collection, Cambridge; Malcolm Harman at the Powell-Cotton Museum, Quex House; Rob Kruczynski at the Natural History Museum; Mark Redknap at the National Museum of Wales. I am also deeply indebted to the generous individuals who bequeathe their bodies to medical teaching and research.

Finally, one person has kept me going with endless encouragement, threats, incentives and good cooking; I probably wouldn't have finished this without Dave Stevens.

Author's Declaration

I declare that the work in this dissertation was carried out in accordance with the Regulations of the University of Bristol. The work is original, except where indicated by special reference in the text, and no part of the dissertation has been submitted for any other academic award. Any views expressed in the dissertation are those of the author.

Signed:

Date:

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1. Introduction

1.1 Prologue

Palaeopathology, the study of disease in ancient and usually skeletal remains, is an area of research that has the potential not only to inform archaeological investigation, but also to provide insight into the aetiology and epidemiology of diseases that still afflict us today (Jurmain & Kilgore, 1995; Miller et al. 1996; Rogers & Dieppe, 1990).

By studying the patterns and prevalence of diseases in ancient populations, a great variety of lifestyle factors, including aspects of nutrition and physical activity, suddenly become available for scrutiny. The wide variety of lifestyles characterising past societies provides a counterbalance to the post-industrial, urban lifestyles of the majority of populations examined in modern clinical epidemiology (Jurmain & Kilgore, 1995).

Comparative skeletal pathology, particularly in the non-human primates, provides an even wider perspective. Studying non-human primates provides an opportunity to investigate the variation in patterns of disease in animals with differing locomotor and postural behaviours. In particular, when areas of the skeleton which may appear to be superficially similar in structure and function between humans and their close phylogenetic relatives, comparative studies including sister taxa may help to elucidate the relationship between form and function, as well as to highlight factors which may cause dysfunction and disease. Details of the relationship between structure and function which may not be immediately obvious are thrown into relief by pathology which disrupts normal structure and function.

Osteoarthritis is amongst the most common ailments afflicting modern populations, as well as being the most common disease seen in archaeological human remains, and relatively easy to diagnose in dry bones (Aufderheide & Rodriguez-Martin, 1998; Jurmain & Kilgore, 1995). Studies of osteoarthritis in past populations have yielded interesting variations in patterns relating to changing lifestyles, such as an increasing prevalence in knee osteoarthritis since the post-Medieval period in Britain (Waldron, 1997). Comparative studies of osteoarthritis in primates have suggested that humans are unusually susceptible to osteoarthritis compared with non-human primates (Jurmain, 1989; Rothschild & Woods, 1992, Lovell, 1990a,b), although it has yet to be seen how these patterns relate to locomotor mode.

Jurmain and Kilgore (1995) emphasised the value of comparative primate studies in assessing the effect of varying mechanical loads in the development of osteoarthritis. They also expressed the need for detailed studies of osteoarthritis, focussing on specific affected areas within or around a joint, as well as for clinical correlations to be sought through the use of macerated anatomical or surgical specimens. It is important that palaeopathological diagnostic criteria are standardised and brought as close as possible to clinical criteria, to facilitate comparisons between different ancient populations, and between ancient and modern populations (Miller et al. 1996; Rogers et al. 1987; Roberts 2007).

The shoulder is an interesting region to approach from a palaeopathological and comparative primatological perspective. The shoulders of humans and other hominoids appear similar in terms of bony architecture, but there is considerable variation in the function of the upper limb amongst the living apes. On a very general level, gibbons are specialized brachiators, chimpanzees and gorillas engage in knuckle-walking, whilst the human upper limb has been freed from locomotion (Aiello & Dean, 1990). Instead of using their arms to move within their environments, humans tend to use their arms to move elements of their environment around them. The shoulder is also a common site of degenerative change in modern humans, and there is growing recognition in the clinical literature for the multi-faceted nature of the principal disorder of this joint and its associated tissues: rotator cuff disease (Bigliani & Levine, 1997a; Fremerey et al. 2000; Frost et al. 2002; Michener et al. 2003; Soohoo & Rosen, 1996). In younger individuals, rotator cuff disease (RCD) is particularly associated with athletes who frequently use the upper limb in over-head positions, such as in throwing (Arroyo et al. 1997; Bigliani & Levine, 1997b). In older individuals, heavy and repetitive manual tasks may predispose to RCD; another position that has been suggested to be conducive to the development of RCD is the support of body weight on the upper limb, such as leaning on a stick (Miles, 1996).

RCD has received very little attention in the palaeopathological literature; in particular, there have been no systematic palaeopathological studies of the whole suite of degenerative changes that comprise RCD. Evidence for subacromial impingement, a component of RCD, has been reported in archaeological human skeletal remains (Miles, 1996, 1999, 2000). Whilst these cases demonstrate that RCD is not a 'new' disease, it is certainly unclear whether it was generally present in ancient populations, or whether the wider spectrum of pathologies now recognised as RCD may also be seen in the bones of ancient individuals. There has been no systematic attempt

to validate the palaeopathological diagnosis of these degenerative changes around the shoulder using macerated anatomical specimens.

No detailed comparative primatological investigation of degenerative changes at the shoulder has been published; indeed, there is not a single reported case of RCD in other primates in the veterinary clinical literature. In humans, the anatomy of the shoulder seems to quickly reach its functional limitation when the upper limb is habitually used in overhead positions, predisposing to the development of RCD. Other hominoids also possess a large acromial projection index, and use overhead positions of the upper limb as part of their locomotor and postural repertoire, during brachiation and arm-hanging, as well as supporting their weight on their arms during knuckle-walking. So the observation that overuse of the arm in abduction, and possibly supporting body weight on the upper limb, can lead to RCD in humans provokes the question, as yet unanswered, of whether this pathology is to be seen in other hominoids: in extant apes, (or indeed in the fossil remains of ancestral hominoids). It is possible that RCD is a uniquely human disease, a condition linked to overuse of the upper limb in an overhead position, creating stresses on a shoulder which is, uniquely amongst the apes, adapted for use below the shoulder.

The three studies that comprise this investigation attempt to provide some information in these areas, as described in the Aims below. The literature relevant to each will be discussed more thoroughly in the introductions within Chapters 1 to 3.

1.2 Aims of the project

Aim 1:   To investigate whether the range and pattern of pathologies, now recognized clinically as RCD, could be identified in human skeletal remains (Chapter 2)

Aim 2: To investigate the relationship between pathological changes in soft and hard tissue (at dissection) and pathological changes in dry, macerated bones, in order to validate the palaeopathological diagnostic criteria for RCD. (Chapter 3)

Aim 3:   To investigate whether RCD could be identified in the skeletons of other apes (Chapter 4)

1.3 Notes on form and function in the hominoid upper limb

Form and function are intimately related, and each largely determined by the other. In a group of closely phylogenetically related species, such as the African apes and humans, various aspects of morphology may relate either to a shared ancestry, or to new adaptive specialisations. It can be difficult to tease apart these differences, but studies of locomotor and postural behaviour in extant species form an essential framework within which to consider the variations in musculoskeletal anatomy between species. A full understanding of the form and function of the upper limb requires the context of comparative and evolutionary anatomy.

Functional interpretation of fossil specimens also depends on data gathered from studies of comparative primate morphology and behaviour.

This section begins with a discussion of the variation in hominoid locomotor and positional behaviour, particularly in relation to use of the upper limb, followed by a detailed description of the human and comparative primate musculoskeletal anatomy of the shoulder complex.

1.3.1 Hominoid locomotor and postural behaviour

There is a large body of research relating to positional and locomotor behaviour, both in individual primate species, and in a comparative context. Some of the literature deals with observational studies of hominoids in the wild (Fleagle, 1976; Hunt 1991a, 1992), and some from primates in captivity (Alexander, 1994; Larson, 1988; Whitehead & Larson, 1994). Although observations of wild animals provides a better representation of normal locomotor and positional behaviour, the use of captive animals facilitates the employment of specialized techniques such as electromyography, cineradiography, motion capture and *in vivo* strain measurement. Cineradiography can be used to demonstrate the actual positions of bones and joints during locomotion (Jouffroy & Gasc, 1974; Whitehead & Larson, 1994; Schmidt & Fischer, 2000). Motion capture techniques, mostly using reflective markers and cameras, have been widely used in captive humans (Andriacchi et al. 1998; Turner-Stokes & Reid, 1999; Webb et al. 1994), and in a few studies of some non-human primates. Tardieu et al (1993) employed an ingenious method involving trackable markers attached to body stockings, (Figure 1.2), to compare bipedal locomotion in humans and chimpanzees. Some studies have combined data from motion capture with measurement of dynamic forces, for instance, Chang et al. (1997) borrowed techniques from terrestrial gait analyses to measure dynamic load components during brachiation, and Demes et al. (1998) recorded patterns of strain in the macaque ulna during a variety of activities.
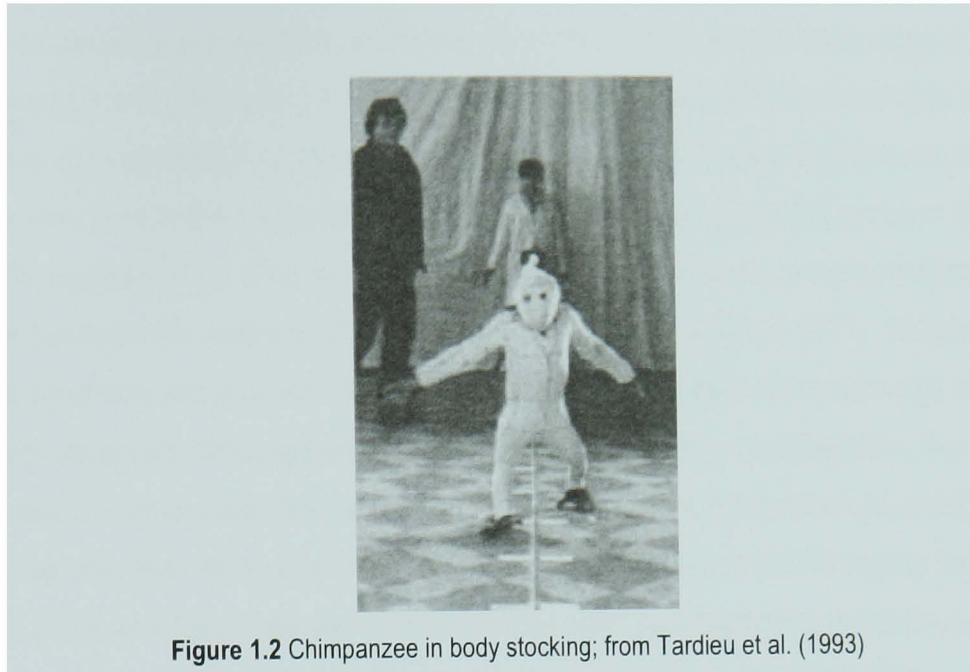
Figure 1.2 Chimpanzee in body stocking; from Tardieu et al. (1993)

It is clear, even from cursory inspection, that humans are unusual amongst the hominoids in having adopted habitual bipedalism, thereby freeing the upper limb from locomotion. However, there is danger in oversimplifying: locomotor and postural modes are varied and complex. Humans are not the only hominoids to engage in bipedality (as shown in figure 1.2), but they are unique in having developed straight-legged, efficient and habitual bipedalism (Crompton et al. 1998). Although the human upper arm has been freed from a habitual role in locomotion, and whilst humans do not knuckle-walk like their close cousins, the gorillas and chimpanzees, humans still possess the ability to climb and hang from their arms, even if this behaviour is occasional and more prevalent in children than in adults. The mobility and prehensility of the human upper limb, whilst ultimately inherited from an arboreal ancestor, has become subtley modified and specialised to fulfil new functions such as manipulation, lifting, carrying and throwing objects.

In spite of the wealth of information about positional and locomotor behaviour in extant primates, researchers have found it remarkably difficult to pin down the shared derived behaviour, representing the locomotor mode of a common ancestor, which could explain the similarities of anatomy amongst the living apes, and that differentiate them from monkeys. The history of this debate is long and tortuous (Hunt, 1991b). Defining this shared derived behaviour is useful to understanding the relationship between form and function in the upper limb of hominoids; whilst some morphological features may represent ancestral characters, others may be adaptations to novel mechanical demands.

In 1971, Lewis was expressing the consensus view when he asserted that brachiation represented the ancestral locomotor pattern of the apes; he claimed that adaptations to brachiation were particularly evident in the shared anatomy of the wrist, with the ulna excluded from the joint. Later in the same decade, other researchers argued that the common ancestral mode was quadrumanous climbing, based on studies of locomotion in living hominoids (Fleagle, 1976) and comparative anatomy of extant hominoids (Cartmill & Milton, 1977). Fleagle (1976) recorded locomotor and postural modes in siamangs, showing that, whilst siamangs brachiated to cover large distances, climbing became important during feeding – and therefore, that this could be the basic locomotor mode that united the apes. From a climbing common ancestor, the lesser apes would have then developed brachiation later. Cartmill & Milton (1977) argued that the similarity of the wrist joint in hominoids and lorisines reflected adaptations to cautious arboreal locomotion, and that other hominoid features that had previously been interpreted as adaptations to brachiation, including the long vertebral border of the scapula, enlarged infraspinous fossa, craniolaterally-orientated glenoid, and a wide range of supination and pronation in the forearm, were also seen in lorisines, and therefore better explained as adaptations to climbing.

Hunt (1991b) also argued that the brachiation hypothesis could not be sustained as many apes, in particular gorillas and orangs, engaged in very little brachiation. However, he also found drawbacks in the quadrumanous climbing hypothesis, as it was too vague and inclusive, and did not explain aspects of anatomy which seemed to relate to arm-hanging. His solution to the problem of identifying a common positional behaviour amongst hominoids was a combination of vertical climbing as the main locomotor mode and arm-hanging as the main postural mode.

A few years later, Gebo (1996) argued that climbing could not be identified as the shared feature of the common ancestor of the apes, as it was a generalized catarrhine mode of locomotion. He identified shared features of the thoracic and antebrachial anatomy in apes and atelines, and suggested that the best explanation for these was a combination of brachiation and arm-hanging.

As well as controversy over shared features, there has been considerable debate about how the unique locomotor patterns that characterise each of the extant ape species, including humans, emerged. The history of this debate reflects disagreements about phylogeny and the relationship between humans and other apes. Determining the timings of divergence of species is crucial to any attempt to understand current modes of locomotion in terms of both ancestral and more recently acquired behavioural and anatomical characteristics. Discussions about the evolution of

extant hominoid locomotor modes are informed by constructions of the phylogenetic relationship between humans and the Asian and African apes. Before modern molecular phylogenies, this relationship was far from clear, and the origin of the hominid lineage, marking the split from the other apes (both great and lesser), was postulated to be around 20 million years ago. So, for Oxnard in 1969, it made sense to propose a 'minimum evolutionary pathway' for the human shoulder straight from that of a totally arboreal ape, functionally similar to the modern orang utan. Genetic and morphometric studies have clarified the phylogenetic relationships between the African great apes and humans (Goodman et al. 1998; Lockwood et al. 2004; Ruvolo, 1994, 1997), including the existence of a *Pan-Homo* clade. Sequencing of the chimpanzee genome and comparison with the human genome suggested a chimp-human split occurring at about 6 million years ago (Li & Saunders, 2005).
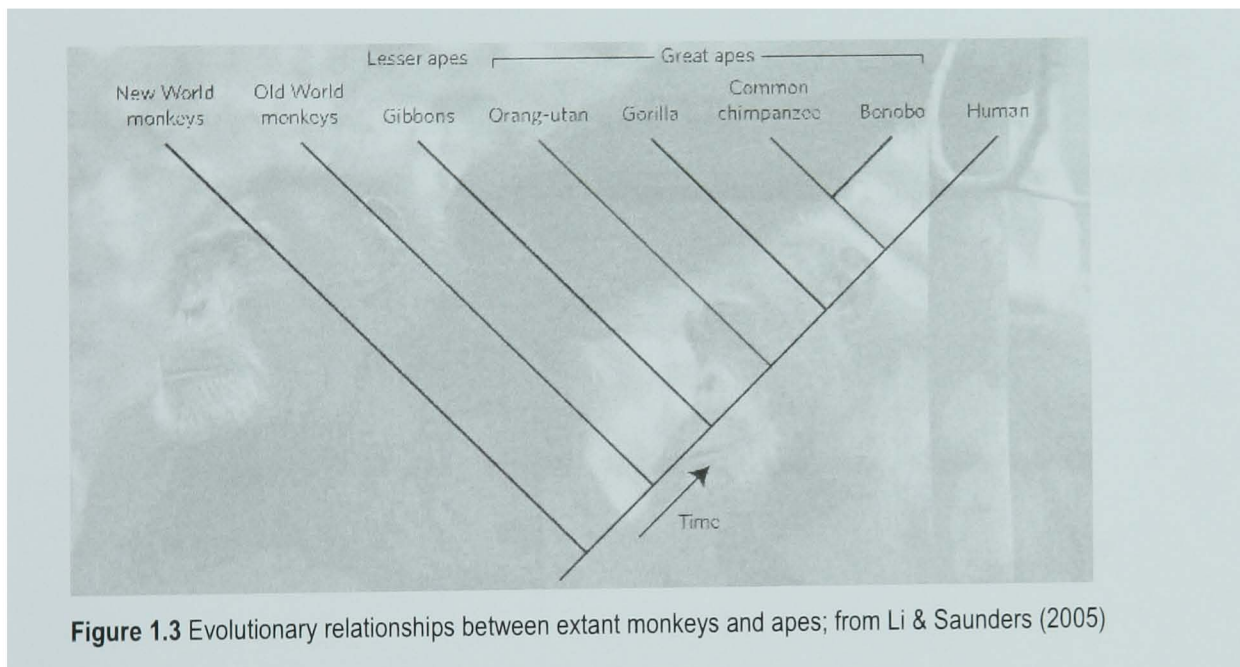
Figure 1.3 Evolutionary relationships between extant monkeys and apes; from Li & Saunders (2005)

This places humans firmly in a clade with knuckle-walking sister taxa (Figure 1.3). Both before and since this phylogenetic clarity emerged, many researchers argued that hominids and African apes shared anatomical features, particularly in the wrist, that represent adaptations to knuckle-walking (Corruccini, 1978; Corruccini & McHenry, 2001; Gebo, 1996; Richmond & Strait, 2000, 2001; Richmond et al. 2001; Tuttle, 1969). Tuttle (1969) argued that many features of the human upper limb that had been described as adaptations to brachiation could be better explained as shared derived features related to terrestrial knuckle-walking. Richmond & Strait (2000) argued that wrist morphology in early hominids as demonstrated specialisations associated with knuckle-walking, and that functional analysis of the upper limb as a whole strongly supported the existence of a knuckle-walking ancestor of humans and the African apes (Richmond et al. 2001). Gebo (1996) postulated that hominids evolved from an arboreal climbing phase, through a

brachiating and forelimb suspensory phase, in the common ancestor of the hominoids, then via an arboreal and knuckle-walking phase including the common ancestor of the African apes and humans, and thence to bipedalism.

However, other researchers have argued that the anatomical 'knuckle-walking' features could relate instead to stabilisation of the wrist as an adaptation to vertical climbing, and that knuckle-walking arose independently in each of the gorilla and chimpanzee lineages (Dainton, 2001). Dainton points to the different ontogeny of knuckle-walking in gorillas and chimpanzees, as well as to the observation that orang utans occasionally engage in knuckle- and finger-walking. He argues that knuckle-walking may be regarded as a general predisposition shared by all the great apes, rather than something that arose specifically in an ancestor of the African great apes.

The debate is ongoing, and in this context, the anatomy of the human upper limb should be discussed in relation to specialisations related to novel functions such as manipulation and carrying, but also to potential ancestral adaptations to climbing, brachiation, arm-hanging and knuckle-walking.

1.3.2 Comparative musculoskeletal anatomy of the shoulder complex

Human legs and pelves are anatomically very distinct from those of other hominoids, being specialised for habitual bipedalism, and the comparative functional morphology of the lower limb has been extensively studied. Variation in the hominoid upper limb is less marked than that in the lower, and comparative studies fewer. Humans share many common features of shoulder morphology with other apes, inherited from a common ancestor, but there are also differences in humans that relate to adaptations to mobility below the shoulder (Ashton & Oxnard, 1964; Ashton et al. 1976, Oxnard, 1967).

The shoulder or glenohumeral joint is a multiaxial spheroidal synovial joint and the most mobile joint in the human body, allowing positioning of the upper limb for optimal use of the grasping hand at its extremity (Soames, 1995; Armfield et al. 2003). However, the function of the glenohumeral joint cannot be considered on its own, as movement at this joint occurs in conjunction with movements at the other joints of the pectoral girdle. The 'shoulder complex' may be considered as a dynamic system consisting of three bones, the scapula, clavicle and humerus, as well as their articulations with each other and the thorax (Inman et al. 1944). These articulations include the glenohumeral joint, the sternoclavicular and acromioclavicular joints, the pseudoarticulation between the humerus and coracoacromial arch, and the pseudoarticulation between the scapula and thorax (Apley & Solomon, 1994).

Although this project is osteological in nature, the anatomy of the bones cannot be understood without references to the soft tissues structures that also contribute to joints, nor in the absence of an appreciation of muscle attachments to bone and the actions of muscles upon joints. An appreciation of both the function and pathology of this system depends on an understanding of the anatomy and the dynamic relationships between the bony, ligamentous and muscular components.

The following notes relate to the osteology, arthrology and muscular anatomy of the shoulder complex. The human condition is described first for each bone, joint or muscle, followed by a brief discussion of comparative primate anatomy.

Bones

Scapula

Human anatomy and embryological development

The human scapula lies on the dorsolateral aspect of the thorax, overlapping ribs 2 to 7. It is classified as an 'irregular bone', as it fails to fit into any standard morphological categories, such as 'long bone'. The scapula is roughly triangular, with superior and inferior angles and a lateral angle which narrows at the anatomical neck before widening to form the glenoid cavity. The floor of the glenoid cavity is slightly raised, just below its centre, to form the glenoid tubercle; the articular cartilage is thinner at this point, and may change to fibrocartilage (Prescher, 2000). The scapula possesses three borders: superior, medial or vertebral, and lateral or axillary. The lateral border is sharp along most of its length, but thickens superiorly to form the triangular infraglenoid tubercle. The supraglenoid tubercle, for the intra-articular origin of the long head of biceps, is a small, roughened projection lying between the superior margin of the glenoid and the base of the coracoid process. The ventral or costal surface is smooth and slightly concave, and comprises the subscapular fossa; the dorsal surface is divided by the spine into a supraspinous fossa and a larger infraspinous fossa. The point at which the spine meets the medial border, slightly less than a third of way down, is known as the trigonum spinae. The curve of the lateral border of the spine forms the spinoglenoid or greater scapular notch. The dorsal crest of the spine extends laterally to form the acromion, with the crest and lateral border of the acromion meeting at the acromial angle. The short medial border of the acromion bears an oval facet for the acromioclavicular joint. The coracoid process projects anterolaterally to provide a lever-like attachment for muscles. The superior border is separated from the base of the coracoid process by the suprascapular notch. The acromion, coracoid process and thicker parts of the scapula contain trabecular bone, whereas most of the body or blade of the scapula is composed of compact bone which is so thin as to be translucent (Soames, 1995).

The primary ossification centre of the body of the scapula appears close to the surgical neck, and endochondral ossification spreads medially and laterally, whilst intramembranous ossification in-fills superiorly and inferiorly, to form the flat blade of the scapula. Deficiencies in ossification of the body of the scapula leave holes filled by fibrous membranes (Soames, 1995). A separate primary ossification centre for the coracoid process appears in the first year of life, and the coracoid fuses with the scapula at about 14-15 years; this reflects the evolutionary history of the

scapula, as the coracoid and scapula are independent bones in most vertebrates. Numerous secondary epiphyses, at the coracoid, acromion, glenoid, inferior angle, and vertebral border appear in late childhood, and fuse throughout adolescence; by 23 years of age, the last epiphyses have fused (Ogden & Phillips, 1983; Scheuer & Black, 2000).

Anatomical variation and sexual dimorphism in humans

Some clinicians suggest that the shape of the acromion is subject to anatomical variation, and may be flat, curved or hooked, as viewed laterally on a radiograph (Bigliani et al. 1986; Bigliani & Levine, 1997a; Miller et al. 1998; Nicholson et al. 1996). However, others have argued that these bony variations are not innate feature but a represent changes with age (Bonsell et al. 2000; Kevin et al. 2001; Lee et al. 2001; Liotard et al. 1998; Prescher, 2000; Shah et al. 2001; Speer et al. 2001; Wang & Shapiro, 1997; Worland et al. 2003). Some investigators even suggest that apparent differences in acromial morphology are merely radiological artefacts (Meskers et al. 2002; Liotard et al. 1998).

A less controversial variation of the acromion is os acromiale, or a bipartite acromion: the condition in which the acromial epiphyses fail to fuse with the basiacromion, forming a separate bone. The junction between the two parts of the acromion, which may be a diarthrosis or a synchondrosis, often bisects the acromioclavicular joint (Prescher 2000; Scheuer & Black, 2000). Population differences in the frequency of os acromiale suggest that there is a genetic basis for this variation (Case et al. 2006; Sammarco, 2000), although there may also be a link with physical activity: Stirland (1993) suggested that the unusually high rate of os acromiale amongst skeletons recovered from the Mary Rose could be associated with the use of a heavy mediaeval longbow.

The size of the glenoid varies considerably, and displays sexual dimorphism (Churchill et al. 2001; Iannotti et al. 1992; Lorenzo et al. 1998). The glenoid cavity is also variable in shape: Prescher and Klumpen (1997) found the glenoid cavity to be oval in 45% of cases, and pear-shaped, due to a distinct glenoid notch, in 55%; the latter may be caused by the tendon of subscapularis muscle exerting pressure on the anterior margin of the glenoid, causing resorption of bone. In 4-8% of scapulae, the glenoid cavity is retroverted, a condition which predisposes the glenohumeral joint to dorsal subluxation (Prescher, 2000).

Comparative primate anatomy

The position of the scapula, with necessary implications for the length of the clavicle, varies with locomotor and positional behaviour. Most primates possess a dorsoventrally deep thorax, parasagittally positioned scapulae and ventrally orientated glenoid fossae. Hominoids are unique amongst primates in their adaptations to arm-hanging and climbing, which include a dorsoventrally flattened thorax, dorsal position of the scapula and craniolaterally facing glenoid fossa (Ashton & Oxnard, 1964; Aiello & Dean, 1990; Ward, 1993). This means that, whilst the thoraco- and scapulohumeral muscles in most primates act in a parasagittal plane, as flexors/extensors of the upper limb, homologous muscles in hominoids lie in a coronal plane and act as abductors/adductors. The craniolateral orientation of the glenoid in hominoids provides the wide range of circumduction necessary in climbing (Ciochon & Corruccini, 1976).

However, the human glenoid is directed laterally, rather than craniolaterally as in other apes, reflecting the use of the human arm below the shoulder (Aiello & Dean, 1990). Similarly, the human clavicle lies in a horizontal position, whereas the orang utan clavicle lies on a steep angle, raising the shoulder high above the rib-cage (Schultz, 1930).

In his comprehensive review of the structure and function of the primate scapula, David Roberts (1974) described in detail how the morphology of the scapula varied with locomotor mode. The hominoid scapula is distinctly different from that of quadrupedal monkeys. Terrestrial quadrupedal monkeys, including baboons and macaques, possess a long, narrow scapula similar to that of the dog, another semicursorial mammal. Arboreal species tend to possess large scapular fossae, relating to an increased need for muscular stabilization and active abduction at the shoulder joint. In a monkey such as the macaque, the scapula is long and narrow along the axis of the spine, whereas the ape scapula is extended along its craniocaudal length, and the long vertebral border provides excellent leverage for muscles acting to rotate the scapula (Aiello & Dean, 1990; Ashton & Oxnard, 1964; Oxnard, 1968; Roberts, 1974; Swindler & Wood,1973). The fossae of the hominoid scapula are large: large rotator cuff muscles are needed to stabilise the glenohumeral joint during climbing or arm-hanging (Larson & Stern, 1986; Roberts, 1974). Differences in scapular shape between common and bonobo chimpanzees correlate with differences in locomotor repertoire: for instance, the more arboreal *Pan paniscus* has a longer, narrower scapula than *Pan troglodytes* (Doran, 1993; Shea, 1986). The human scapula fits the hominoid pattern, but the fossae are relatively smaller than in other apes, reflecting the use of the arm below the shoulder (Ashton et al. 1976; Roberts, 1974). The orientation of the scapular spine is also important, as this influences the line of action of infraspinatus, which has been shown by

EMG studies to be important in suspensory postures and locomotion in chimpanzees; the spine is angled very steeply in hylobatids, whereas it is close to horizontal in humans, reflecting use of the arm below shoulder level. The width of the infraspinous fossa at the neck of the scapula is wider in more suspensory or acrobatic primates, and widest in humans, providing infraspinatus with a mechanical advantage in lateral rotation of the humerus. Hominoids tend to have an expansion of the subscapular fossa, relating to the importance of subscapularis in the 'pull up' phase of vertical climbing (Larson, 1995).

In apes compared with monkeys, the glenoid cavity is broader and shallower, allowing an increased range of movement, and the supraglenoid tubercle is reduced to a mere bump; the acromion and coracoid process are more prominent in apes, increasing the mechanical advantage of the deltoid in abducting the arm, whilst providing stabilisation to the exceptionally mobile shoulder joint (Aiello & Dean, 1990; Ciochon & Corrucini, 1977; Swindler & Wood, 1973).

Clavicle

Human anatomy and embryological development

The human clavicle lies almost horizontally across the base of the neck. It is an s-shaped bone: the medial two-thirds of the bone is convex anteriorly, and the lateral third is convex posteriorly. The rounded medial or sternal end articulates with the manubrium sterni to form the sternoclavicular joint; the flattened lateral or acromial end bears a small oval facet, which articulates with the medial surface of the acromion to form the acromioclavicular joint. The superior surface of the clavicle is smooth, whereas the inferior surface bears markings relating to muscle and ligament attachments: the inferior surface of the medial end is marked by the attachment of the costoclavicular ligament, which merges with the capsule of the sternoclavicular joint medially (Cave, 1961). The lateral half of the inferior surface is grooved for the attachment of subclavius muscle, enclosed by the clavipectoral fascia. The inferior surface of the lateral extremity bears the conoid tubercle, at the apex of the lateral curvature, and trapezoid line extending laterally, where the corresponding parts of the coracoclavicular ligament attach; the clavipectoral fascia blends with the conoid ligament laterally (Gumina et al. 2002; Soames, 1995).

Black & Scheuer (1996) described the clavicle as 'a non-conformist'. Although categorised as a long bone, the clavicle is unusual in that it lacks a medullary cavity, possessing trabeculae along

its entire length. It is the only limb bone to be mainly formed through intramembranous ossification in the fetus (Prescher, 2000), and this seems to relate to its phylogenetic origin as a dermal bone linking the pectoral fin to the skull of an ancient fish (Kardong, 1998). The lateral, flattened part of the clavicle develops by intramembranous ossification, whereas the more rounded medial end forms by endochondral ossification, probably from 2 separate ossification centres. A secondary ossification centre develops in the medial epiphysis in early adolescence, and starts to fuse with the shaft after 16 years; complete fusion occurs between 22 and 30 years of age. Although some sources claim that the clavicle lacks a lateral epiphysis, others that report an ephemeral structure, which appears and then quickly fuses at around 19-20 years. Alternatively, the active ridge-and-furrow of the juvenile lateral clavicle may simply smooth over with new bone growth (Scheuer & Black, 2004).

Anatomical variation and sexual dimorphism in humans

The clavicle varies between sexes; the female clavicle is shorter (by about 10%), thinner, straighter and smoother than the male (Kaur et al. 2002; Soames, 1995). The left clavicle is usually longer than the right, which Kaur et al (2002) identify as an acquired characteristic, as this difference is not present at birth, and appears to correlate with the development of an increased curvature in the right clavicle in right-handed people. Increased curvature of the clavicle, as well as increased robusticity, has also been noted in manual workers. Variation in clavicle curvature between different populations has also been recorded (Kaur et al. 2002).

Other variations in the clavicle include tubercles projecting at the attachments of deltoid and trapezius, and accessory canal passing sagittally through the shaft, transmitting part of the medial supraclavicular nerve (Prescher, 2000). The area of attachment of the costoclavicular (rhomboid) ligament, at the medial end of the inferior surface of the clavicle, is also subject to variation. It may appear as a roughened ridge, a smooth area, or a fossa, ranging from a shallow groove to a deep pit (Rogers et al. 2000). In a study of 344 clavicles, Rogers et al (2000) found rhomboid fossae to be more common in males than in females, and to be most pronounced in males of 20-30 years of age; indeed, the authors suggested that presence or absence of a rhomboid fossa on the left clavicle could be used as a reliable indicator of sex. However, there do seem to be population differences; in a study of 789 pairs of North Indian adult clavicles, Jit & Kaur (1986) found bilateral rhomboid fossae in 58.70% of males and 54.14% of females, whilst unilateral fossae were seen in 13.29% of males and 16.56% of females, but with no significant sex

difference. This study also found unilateral fossae to be more common on the right side, which may suggest an association with relatively heavy usage.

The costoclavicular ligament usually contains a bursa, but, very rarely, this may develop to establish a synovial costoclavicular joint; Cave (1961) found an articular facet in 4 of 158 clavicles investigated.

The coracoclavicular ligament is subject to anatomical variation; it may be separate or continuous with the transverse scapular ligament inferiorly, and may occasionally form a synovial joint (Gumina et al. 2002; Harris et al. 2001). The coracoclavicular joint is indicated on the dry bone by a round articular facet on the conoid tubercle. Reported frequencies of coracoclavicular joint range widely, and studies show much higher frequencies in Asian than in European populations (Gumina et al. 2002; Kaur & Jit, 1991). Cockshott et al (1992) combined data from published literature with their own radiological survey, and found that the highest rates of coracoclavicular joints occurred in Chinese populations (over 40%), with very low rates in native American, European and African populations (<1%). A study of 102 clavicles from Korean individuals found coracoclavicular joints to be present in 10 (9.8%), equally in males and females, and only in those aged over 40 years (Cho & Kang, 1998). However, a study of the incidence of coracoclavicular joints in 240 South African skeletons showed no differences between populations, and instead suggested that these joints were more likely in individuals possessing relatively larger scapulae and clavicles (Nalla & Asvat, 1995). It seems that the presence of a coracoclavicular joint is both genetically determined, as it varies between some populations, and with size of bones, as well as being an age-related change; it does not appear to be related to sex or occupation, or to the degree of curvature of the clavicle (Gumina et al. 2002; Kaur & Jit, 1991).

The medial epiphysis of the clavicle may remain unfused, and the frequency of this seems to vary between populations. This variant, where the medial epiphysis has either failed to form or has been resorbed, presents as a deep, smooth pit in the medial clavicle, distinctly different from the billowed appearance of an active metaphyseal surface (Scheuer & Black, 2000).

Comparative primate anatomy

Primates are unusual mammals in possessing a well developed clavicle. Badoux (1974) described the general function of the primate clavicle as a strut, designed to resist laterally directed tensile and compressive forces at the shoulder joint. Amongst other primates, the hominoid clavicle is relatively long, projecting the shoulder joint more laterally to enhance the range of movement (Ashton & Oxnard, 1964). Rhesus macaques have a longer clavicle then stump-tailed macaques; this has been interpreted as adaptation to arboreal versus terrestrial quadrupedalism (Pan et al. 1991).

Aiello and Dean (1990), writing from a comparative anatomical perspective, called the clavicle 'one of the most poorly studied bones in the body'. Voisin (2006) took up the gauntlet, and made a comparative study of primate clavicles. However, the numbers were small, and the results were presented using some rather unhelpfully confusing anatomical terminology. The study did little more than to confirm some of the variations noted by previous workers, although Voisin did present some interesting discussion around functional correlates of morphological variations.

The shape of the clavicle varies considerably amongst primates, and even amongst the hominoids. Viewed from above, the gibbon clavicle is C-shaped with a single, anteriorly convex curvature; orang utan clavicles are straight; gorilla clavicles are straight, except for a slight anterior angulation of the lateral end; chimpanzee and human clavicles are both S-shaped (Schultz, 1930; Voisin, 2006). The medial curvature is more pronounced in humans than in chimpanzees; Voisin (1996) argues that the tendency to straightness in the chimpanzee, and even more so in the gorilla, strengthens the clavicle in compression and represents an adaptation to knuckle-walking.

The primate clavicle is usually flatter at its lateral extremity, with the human clavicle representing an extreme example of this. Hominoid clavicles also tend to possess a cranial angulation of the flattened lateral end (torsion of the clavicle), although this is absent in the human clavicle (Ashton & Oxnard, 1964). Torsion of the lateral end of the clavicle, which Voisin (2006) refers to as a 'superior curvature' in a dorsal view, may reflect the position and angulation of the clavicle relative to the thorax.

Muscle and ligamentous attachments to the clavicle are similar amongst the apes, with sternocleidomastoid and pectoralis major attaching to the superior surface medially, and trapezius and deltoid attaching laterally. The chimpanzee clavicle has a particularly prominent conoid tubercle (Swindler & Wood, 1973).

Humerus

Human anatomy and embryological development

The head of the humerus articulates with the glenoid fossa to form the shoulder (glenohumeral) joint. The human humeral head is usually described as being slightly less than a hemisphere, although a very precise investigation by Iannotti et al (1992), showed it to be spherical in the centre, but elliptical at the periphery, as the coronal diameter was on average 2mm less than the axial diameter. The humeral head is directed medially, superiorly and slightly posteriorly, towards the glenoid cavity. A slight constriction just distal to the articular margin marks the anatomical neck, where the capsule of the glenohumeral joint attaches, except inferiorly, where it descends by about 1cm onto the shaft (Soames, 1995).

The neck of the humerus is marked by two prominences, the greater and lesser tuberosities, which provide attachment for the rotator cuff (or short scapular) muscles. The lesser tuberosity gives attachment to the tendon of subscapularis, and to the transverse ligament. The greater tuberosity bears three impressions for the attachment of supraspinatus, infraspinatus and teres minor, from anterior to posterior. The attachments of subscapularis and teres minor extend inferiorly onto the metaphysis of the humerus. The areas of attachment of the rotator cuff tendons are smooth, but the anatomical neck and the lower parts of the tuberosities are peppered with vascular foramina. The tuberosities are separated, on the anterior surface of the humeral neck, by the bicipital (intertubercular) sulcus or groove, which is bridged by the transverse ligament of the humerus. This sulcus accommodates the tendon of the long head of biceps brachii as it runs upwards to enter the shoulder capsule. The surgical neck of the humerus lies below the tuberosities. The internal bony architecture of the humerus is typical of a long bone; the head and neck of the humerus are composed of trabecular bone with a thin cortex of compact bone, whereas the shaft is a cylinder of compact bone containing a medullary cavity. With age, the medullary cavity encroaches on the neck, and makes fractures across the surgical neck more likely (Prescher, 2000; Soames, 1995).

The humerus undergoes endochondral ossification, starting with a primary centre appearing in the middle of the cartilaginous shaft at around 8 weeks. Ossification spreads proximally and distally, so that the shaft of the humerus is ossified at birth, but the epiphyses are still cartilaginous. An ossification centre appears within the head either shortly before, or within 6 months after birth. A separate ossification centre for the greater tuberosity appears in infancy and fuses with the head to create a compound epiphysis in early childhood. The origin of the lesser tuberosity is a subject of some debate, and may appear as a separate ossification centre, or through a downgrowth from the head. The proximal growth plate, which contributes about 80% of the increase in length of the growing bone, starts to close in early adolescence, and is usually fully fused by 17 years in females and by 20 years in males (Scheuer & Black, 2000).

Anatomical variation and sexual dimorphism in humans

The head of the humerus is the most sexually dimorphic part of the bone: measurement of head diameter is a useful discriminator for determining sex, although the level of sexual dimorphism varies between different populations (Iscan et al. 1998; Lorenzo et al. 1998). In a large sample of prehistoric remains from California (n=370), measurements of the maximum transverse and vertical diameters of the humeral head were found to be most useful, indeed slightly more so than maximum femoral diameter, in determining sex (Dittrick & Suchey, 1986). The humeral head also varies in size with hand dominance: Stirland (1993) found significant asymmetry in the horizontal width of the humeral head in samples from both the Mary Rose and a medieval cemetery in Norwich (n = 100), with the right side being larger than the left, which he argued was related to right hand dominance.

Various angles of the humerus also show variation. The angle of inclination of the humeral head on the neck varies; in a study of the geometry of adult humeri (n = 65), designed to inform the design of humeral prostheses, the angle of inclination was found to range between 123° to 136°, with a mean of 130° (Boileau & Walch, 1997). Humeral torsion, as the angle between the axis of the humeral head and the perpendicular to the interepicondylar axis, averages 74°; the angle is greater in adults compared with juveniles, and with males compared with females (Edelson, 1999; Soames, 1995). Clinicians use the other component of this angle, i.e.: between the axis of the head and the interepicondylar axis, known as the angle of retroversion. While a practical working figure of 25°- 35° is generally accepted for the angle of retroversion, studies have shown that the range can be much wider: as low as -7° and as high as +74° (Boileau & Walch, 1997; Edelson,

1999); the angle varied between left and right humeri, between sexes, and between different populations. The depth and the angle of the medial border of the bicipital sulcus vary, and both affect the relative risk of subluxation of the long head of biceps (Prescher, 2000).

Comparative primate anatomy

The configuration of the humerus is similar in humans, chimpanzees and gorilla, although the gorilla humerus is much larger and more robust than those of its cousins. The hominoid humeral head and neck are designed to enhance mobility at the glenohumeral joint. The spherical humeral head provides a great range of motion, and compared with a quadrupedal monkey such as *Papio*, where the greater tuberosity projects cranial to the head, the tuberosities of the hominoid humerus lie well below the head (Ciochon & Corruccini, 1976; Swindler & Wood, 1973). The shape and orientation of facets on the humeral neck also varies: the facet for infraspinatus tends to be laterally oriented in cercopithecoids, and more superolaterally orientated in hominoids, allowing infraspinatus to act as an abductor, and reflecting the importance of arm-raising in the hominoid locomotor repertoire (Larson, 1995). The subscapularis facet tends to be longer in hominoids than in anthropoid monkeys; Larson (1995) argues that a longer subscapularis attachment confers a finer level of control over the movements of the glenohumeral joint.

Quadrupedal monkeys have a dorsally directed humeral head, whereas the hominoid humeral head is rotated medially in relation to the axis of the elbow, i.e.: showing a high degree of torsion. Amongst the apes, the gibbon has the smallest degree of humeral torsion; Larson (1988) relates this 'lateral set' of the humerus to the extreme lateral rotation required in the gibbon's trailing arm, at the end of the support phase of brachiation. In contrast, a high degree of humeral torsion, orienting the elbow in a sagittal plane, facilitates knuckle-walking in gorillas and chimpanzees, and manipulation in humans, allowing use of the forearm and hand anterior to the body (Larson, 1988). Some have suggested that humeral torsion is a sign of a knuckle-walking in a common ancestor of chimpanzees, gorillas and humans (Richmond et al. 2001). Larson (1988) argues that early hominids seem to show a lesser degree of humeral torsion, suggesting that the high degree of humeral torsion in humans was a later development, but the resolution of this debate will depend on the discovery and analysis of more complete hominid humeri.

The position and size of the bicipital sulcus is affected by the degree of humeral torsion; a high degree of humeral torsion brings the groove to lie medially, encroaching on the lesser tuberosity

(Inman et al. 1944). In a monkey such as *Papio*, the lesser tuberosity is larger and the sulcus wide and shallow, whereas, in apes, the lesser tuberosity tends to be smaller, and the bicipital groove sulcus to be narrow and deep (Aiello & Dean, 1990; Swindler & Wood, 1973). There is variation amongst hominoids: in the African apes, the sulcus is extremely deep and narrow, undercutting the lesser tuberosity, whereas the hominid bicipital sulcus is shallow in comparison (Hill & Ward, 1988).

The deltoid tuberosity occupies a more distal position on the lateral humerus in hominoids compared with quadrupedal monkeys, giving it a mechanical advantage in shoulder abduction (Aiello & Dean, 1990; Swindler & Wood, 1973). In humans, the distal extent of deltoid insertion occupies a position intermediate between that of the other apes and quadrupedal monkeys, similar to the position in *Ateles* and *Alouatta* (Ashton & Oxnard, 1964).

Joints and ligaments

Glenohumeral joint

The human shoulder joint is extremely mobile, much more so than the hip joint, which is less mobile but accordingly more stable. The shoulder joint allows a large range of movements in wide arcs that are graphically illustrated when combined in 'windmilling' or circumduction. The wide range of mobility at the glenohumeral joint is facilitated by the shallowness of the socket and laxity of the fibrous capsule, leaving the muscles around the shoulder to maintain stability and congruity. The bony configuration of the joint offers very little indeed in terms of stability: the glenoid fossa is extremely shallow, and its surface area is only about a quarter of that of the humeral head (Soslowsky, 1992). The head of the humerus is covered with hyaline cartilage, as is the glenoid fossa. A fibrocartilaginous labrum around the glenoid margin slightly deepens the socket to provide increased congruity between the articulating surfaces. As with any synovial joint, the fibrous capsule itself may be considered as contributing to the congruity and stability of the joint. The capsule is reinforced anteriorly by condensed fibrous bands: the superior, middle and inferior glenohumeral ligaments, which are visible on its internal surface (Prescher, 2000; Soames, 1995). The capsule attaches around the anatomical neck, except inferiorly, where it attaches about 1cm caudally, creating an axillary recess which allows some caudal movement of the head of the humerus during abduction, allowing the greater tuberosity to slide under the acromion. The long head of biceps runs within the shoulder capsule, and contributes to the stability of the shoulder joint superiorly. Inferiorly, the glenohumeral joint is supported to some extent by the tendon of the long head of triceps inserting on the infraglenoid tubercle (Prescher, 2000).

The next layer of structural support of the glenohumeral joint is considered to be the most important in dynamic stabilisation: the short scapular or rotator cuff muscles. These muscles spring from the scapula and converge on the neck of the humerus, where their tendons become enmeshed together to form the eponymous 'cuff', their deep surfaces merging with the capsule of the glenohumeral joint (Miller et al. 1998). The rotator cuff group comprises subscapularis, supraspinatus, infraspinatus and teres minor muscles. These muscles act to stabilise the joint both at rest and when other muscles are moving the joint, when they act to keep the humeral head centred and prevent it from sliding across the glenoid fossa, particularly during the mid-

range of movement when the capsular ligaments are lax (Bigliani et al. 1996; Wuelker et al. 1998). They also act in concert with other muscles to actively move the humerus.

The insertions of the rotator cuff muscles are blended with each other: the fibres of their tendons become interwoven to form a tendinous cuff around the anatomical neck of the humerus, so that forces generated by one muscle are transmitted to adjacent tendons (Clark & Harryman, 1992; Miller *et al.*, 1998). The insertion of the cuff is interrupted at the bicipital sulcus between the tuberosities, where the tendon of the long head of biceps brachii runs up the groove to enter the shoulder capsule, running over the head of the humerus to its intra-articular insertion on the supraglenoid tubercle and glenoid labrum. The interruption of the cuff at the bicipital sulcus, between the tendons of supraspinatus and subscapularis, is described as the 'rotator interval'. The two adjacent tendons are reinforced by the superior glenohumeral ligament and the coracohumeral ligament to form the biceps pulley, or transverse humeral ligament, which retains the tendon of the long head of biceps in the bicipital sulcus (Boon et al. 2004; Habermeyer et al. 2004; Miller et al. 1998; Soames, 1995), as shown in figure 1. The bicipital sulcus itself is lined with fibrocartilage (Prescher, 2000).
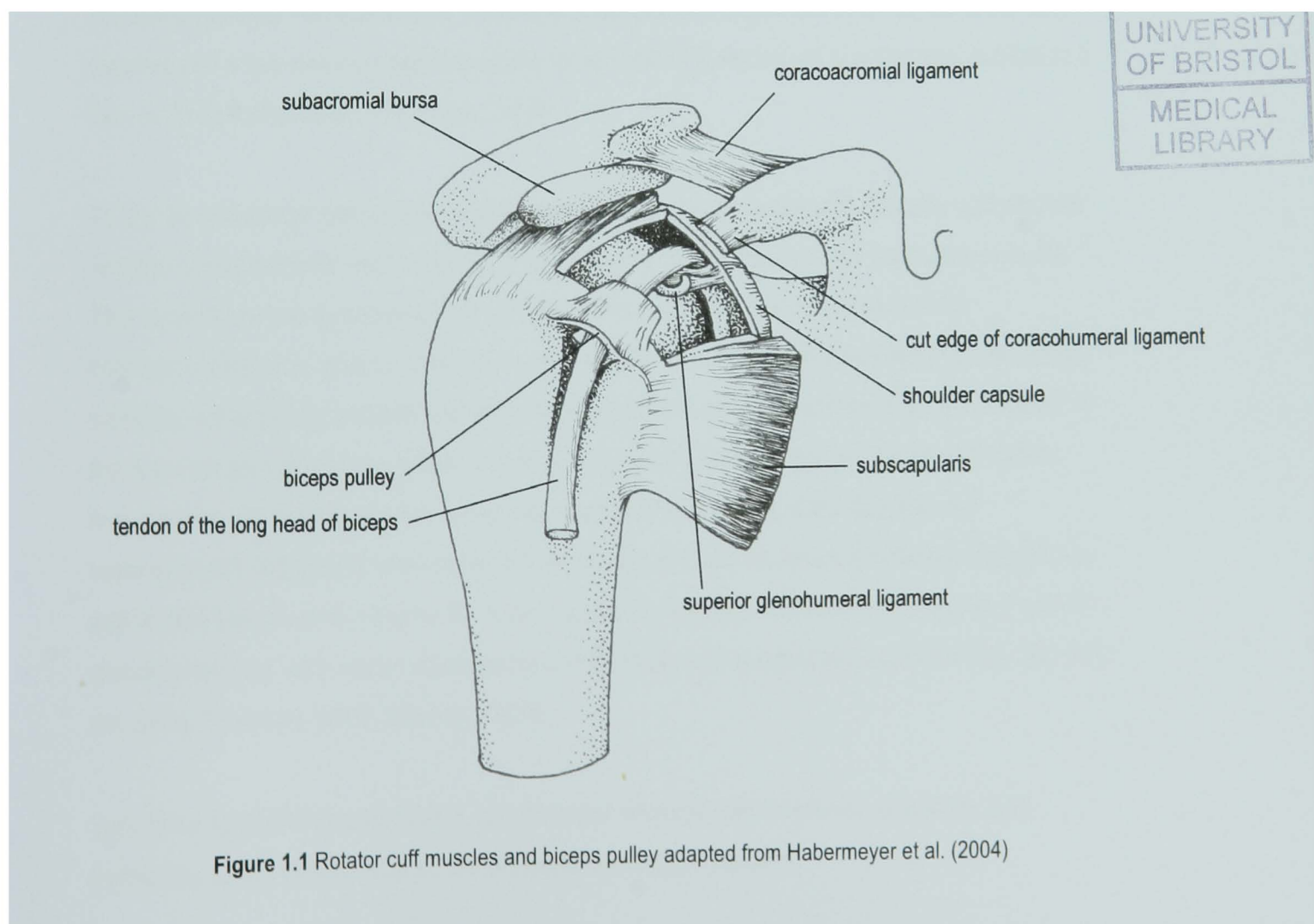
Figure 1.1 Rotator cuff muscles and biceps pulley adapted from Habermeyer et al. (2004)

The coracohumeral and coracoacromial ligaments provide stability to the joint superiorly. The coracohumeral ligament arises from the lateral coracoid process and blends with the supraspinatus tendon and upper fibrous capsule, inserting onto the greater tuberosity and reinforcing the biceps pulley, as already mentioned (Prescher, 2000; Soames, 1995). The coracoacromial ligament unites the acromion posteriorly to the coracoid process anteriorly. Together, the acromion, coracoacromial ligament and coracoid process form the coracoacromial arch, which arcs over the shoulder joint (Ciochon & Corruccini, 1977; Fremerey et al. 2000). The coracoacromial ligament is a triangular structure with distinct medial and lateral bands, which vary in their degree of separation to produce either single or bipartite variants (Fremerey et al. 2000; Prescher, 2000). A tripartite variant, has also been noted during clavicle resections (Pieper et al.1997). The coracoacromial ligament also varies in the extent of its attachment to the undersurface of the acromion (Miles, 1998). Although some authors describe the function of the coracoacromial ligament as preventing upward displacement of the humerus (Ciochon & Corruccini, 1977), this can only be the case when the normal stabilising structures of the shoulder have been disrupted. It seems instead that the function of this ligament is to stabilise the bony projections of the scapula. Prescher (2000) reported on a biomechanical study by Putz, published in German journal *Therapiewoche*: when the coracoacromial ligament was cut, the acromion experienced a ten-fold increase in bending forces, whilst the coracoid process was subject to a two- to three-fold increase (Prescher, 2000).

As the glenohumeral joint moves, a sliding movement occurs between the rotator cuff tendons and the coracoacromial arch, and this is facilitated by the presence of the subacromial bursa. This bursa therefore represents a pseudoarticulation between the humerus and the coracoacromial arch, and is sometimes even referred to as a subacromial joint (Kessel, 1982), whilst the subacromial and subdeltoid bursae together have been referred to as the 'co-joint' of the shoulder joint (Prescher, 2000). There are many other bursae around the shoulder joint, including the subscapular bursa, which lies deep to the tendon of subscapularis and communicates with the glenohumeral synovial cavity through an opening between the superior and middle glenohumeral ligaments. A subcoracoid bursa also regularly communicates with the glenohumeral articular cavity, whereas the subacromial and subdeltoid bursae are separate from the cavity (Prsecher, 2000; Soames, 1995).

Superficial to all of these structures, covering the shoulder joint anteriorly, superiorly and posteriorly, is the deltoid muscle, the principal abductor of the arm.

The glenohumeral joint is similar amongst the hominoids.

Scapular pseudoarticulation

The pelvic girdle is very firmly attached to the axial skeleton at the sacroiliac joints, allowing safe transmission of considerable forces from the lower limb to the axial skeleton during locomotion. In contrast, the shoulder girdle (scapula and clavicle) is very loosely fixed to the thorax. Indeed, the scapula has no direct articulation with the axial skeleton, being connected indirectly by the supporting and anchoring strut of the clavicle, and by a 'pseudoarticulation' of muscles including trapezius, the rhomboids, levator scapulae and serratus anterior. This arrangement means that the pectoral girdle is extremely mobile: the scapula effectively floats on the ribcage, and may move in all directions on this surface. The scapular pseudoarticulation is similar amongst the hominoids, although the size and extent of attachment of various muscles varies.

Clavicular joints

The human clavicle attaches the scapula indirectly to the axial skeleton, articulating with the acromion of the scapula laterally, and with the manubrium sterni and adjacent part of the first costal cartilage medially (Prescher, 2000).

Both the clavicular joints are atypical synovial joints: they are lined with fibrocartilage instead of hyaline cartilage, and each possesses an articular disc. The acromioclavicular joint, between the medial surface of the acromion and the flattened lateral end of the clavicle, is a plane joint. The fibrocartilaginous articular disc is usually a crescentic structure in the upper part of the joint, although it is occasionally more extensive and may even completely divide the joint (Poncelet et al. 2003; Soames, 1995). The joint is supported by the fibrous capsule, which is strengthened superiorly by the acromioclavicular ligament; the fibres of this ligament blend with the adjacent trapezius and deltoid aponeuroses. Whilst the acromioclavicular joint is closely related to the coracoacromial ligament inferiorly, the most important ligament stabilising the joint is the coracoclavicular ligament, which attaches from the medial surface of the coracoid process to the lateral undersurface of the clavicle, and is divided into a medial conoid part and a lateral trapezoid part (Prescher, 2000).

The sternoclavicular joint, like the acromioclavicular, is lined with fibrocartilage, and is usually completely divided by a fibrocartilaginous intra-articular disc. Articular discs exist to ensure congruency throughout the range of movement in complex joints that combine several axes of movement, including the clavicular joints, the temporomandibular joints and the knee joints. The costoclavicular ligament stabilises the sternoclavicular joint, limiting elevation, protraction, retraction and axial rotation of the clavicle. Depression of the clavicle compresses the costoclavicular ligament and its bursa, and is limited by the interclavicular ligament and by the sternoclavicular articular disc (Cave, 1961; Yood & Goldenberg, 1980).

Comparative primate anatomy

The sternoclavicular and acromioclavicular joints are similar amongst the hominoids and other primates. The sternoclavicular ligament is morphologically similar in different primates, and indeed in different claviculate mammals, and represents a lateral extension of the sternoclavicular capsule to form an inferior ligament supporting the joint; Cave (1961) dissected the ligament in a range of species and described it as displaying an 'almost monotonous similarity'. However, he does distinguish the human costoclavicular ligament in terms of its large size, and its possession of a bursa, and relates this to the upper limb having been uniquely freed from a locomotor role in humans compared with other primates. The occurrence of coracoclavicular joints is not a uniquely human variation: Haramati et al. (1994) performed a radiographic study of non-human primates and recorded frequencies of coracoclavicular joints, on the basis of well-defined articular facets, in silver-leaf langurs (4/9), lowland gorillas (2/9) and white-handed gibbon (1/6). In all these cases, the joints were present bilaterally.

Movements and muscles

Human anatomy

The great range of movement at the proximal end of the upper limb combines movements of the shoulder girdle with movements at the glenohumeral joint. For example, abduction at the glenohumeral joint is accompanied by cranial rotation of the lateral angle of the scapula, as well as rotation at the clavicular joints.

The glenohumeral joint is a multiaxial spheroidal joint, with 3 degrees of freedom, moving in flexion, extension, abduction, adduction and circumduction. The joint is loose-packed in most positions, but becomes close-packed in full abduction with lateral rotation (Soames, 1995).

When the arm hangs at rest, the glenoid faces anterolaterally, so movements at the shoulder should be considered relative to this plane rather than to anatomical planes (Soames, 1995). Therefore, flexion moves the humerus anteromedially, whilst extension operates in a posterolateral direction. Abduction and adduction occur in the plane of the scapula, orthogonal to the plane of flexion and extension. The extent of glenohumeral abduction in the human is around 90 -120°; an additional 60° of movement in the same plane is contributed by movement at the clavicular joints. After the first 20-30° of abduction, which occurs at the glenohumeral joint only, movement then occurs at the glenohumeral and clavicular joints simultaneously, with a ratio of about 2:1. A wide range of accessory movements (i.e.: against resistance) may also occur at the glenohumeral joint, including translation in any direction. When hanging from the arms, the humerus may be distracted from the glenoid cavity (Soames, 1995).

The clavicle forms a strut, maintaining the separation of the scapula and the sternum as the scapula moves on the thoracic wall, and preventing the scapula from sagging anteriorly and inferiorly: it is a necessary stabiliser for a scapula positioned on an anteroposteriorly flattened thorax with a laterally directed glenoid. However, its importance in the human shoulder complex is somewhat unclear: whilst some surgeons claim that clavicle malunion of clavicle fractures causes shoulder instability (Chan et al. 1999), others claim that congenital shortening or surgical resection of the clavicle has only a minimal effect on upper limb function (Beals, 2000; Guidera et al. 1991; Rockwood et al. 1991). Indeed, in congenital absence of the clavicle, there seems to be no loss of power in the upper limb, and no restriction of movement (Scheuer & Black, 2000).

The human acromioclavicular joint allows anteroposterior gliding and rotation of the acromion on the clavicle: any scapular movement (elevation and depression, protraction and retraction, rotation of the inferior angle laterally and medially) is accompanied by movement at the acromioclavicular joint. During elevation and depression, the movements at this joint tend to be angulations; in protraction, the lateral end of the clavicle slides to its most posterior position with respect to the acromion. The sternoclavicular joint is sellar in shape, allowing movement in vertical and anteroposterior planes, as well as an element of rotation. As the shoulder girdle moves, sliding movements occur at the sternoclavicular joint, in the opposite direction to that at the scapulothoracic articulation. When the scapula is elevated, by rotation at the sternoclavicular joint, the sternal end of the clavicle also glides inferiorly on the articular disc. When the scapula is depressed, with rotation at the sternoclavicular joint, the sternal end of the clavicle slides superiorly. In scapular protraction, the sternal end of the clavicle moves posteriorly; in retraction, it moves anteriorly (Soames, 1995)

During lateral rotation of the inferior angle of the human scapula, the acromioclavicular and then the sternoclavicular joints each rotate through 30°, in the plane of abduction at the glenohumeral joint, thereby allowing 60° of scapular rotation on the thoracic wall (Soames, 1995). The s-shaped clavicle also acts like a crankshaft during abduction, rotating along its length, to further elevate its lateral end (Inman et al. 1944).

Comparative primate anatomy

Just as with their bones and joints, the musculature of monkeys and hominoids varies in accordance with differences in locomotor patterns. Muscles whose principal role is stabilisation of joints, including the rotator cuff muscles, the rhomboids, the cranial part of serratus anterior and subclavius, are similar in quadrupeds and brachiators. The muscles performing the 'power stroke' in brachiation and climbing, latissimus dorsi and pectoralis major, are more powerful and more cranially orientated in hominoids. Muscles that act to elevate the arm above the shoulder, including deltoid, the upper parts of trapezius and the caudal parts of serratus anterior, are also larger (Ashton & Oxnard, 1964). The same muscles also take the strain during arm-hanging. Electromyography (EMG) provides a means of direct measurement of muscular function during different behaviours, and can be used to define specific functional roles of individual muscles (Larson, 1995; Larson & Stern, 1986; Tuttle & Basmajian 1978a,b). EMG studies – in humans and other primates - have demonstrated a degree of refinement in the action of skeletal muscles

that has made the old classification of muscles, as 'prime movers', 'antagonists', etc., largely obsolete, as well as challenging the concept of 'muscle chains' (Jungers & Stern, 1980; Tuttle & Basmajian, 1978a). Such studies have also helped to reveal how forces are shared between muscles, ligaments and tendons; for instance, EMG studies in knuckle-walking gorillas have shown that tensile stress is resisted by shoulder muscles as well as by osseoligamentous structures (Tuttle & Basmajian, 1974a).

EMG studies have been used to establish relationships between muscle activity, muscle mass and bony morphology (Inman et al. 1944; Larson 1988, 1995; Larson & Stern, 1986, 1989; Larson et al. 1991; Stern et al. 1980a,b; Tuttle & Basmajian, 1974a,b; Tuttle & Basmajian 1978a,b). Such studies can aid in the identification of mechanically meaningful morphological features of bones, improving an understanding of the relationship between form and function in extant creatures, as well as facilitating the functional interpretation of fossil material (Larson, 1995). EMG studies have also prompted caution in making predictions about locomotion from skeletal evidence alone. For instance, patterns of EMG activity in back muscles have been found to be conservative across primate species during quadrupedal walking, and similar in chimpanzees, gibbons and humans walking bipedally. It seems that neural control imposes a preferred pattern of gait and interlimb co-ordination, and this has implications for predictions of locomotion based purely on skeletal evidence (Shapiro & Jungers, 1994; Shapiro et al. 1997). This emphasizes the need to view bones as elements in an even wider context, taking into account not only the muscles, tendons and ligaments which attach to and move the bones, but also the nervous system which controls that movement.

In general, the human shoulder musculature is similar to the other hominoids in some ways: in the transverse orientation of the pectoral muscles (as opposed to the cranial direction seen in quadrupeds); in the possession of a powerful deltoid; in the attachments of trapezius; in the large size of the caudal digitations of serratus anterior. In other ways, the human anatomy is closer to that of the quadrupedal anthropoids: in the large size of the pectoral muscles; in the thinness of trapezius of and latissimus dorsi; in the relatively few digitations of the caudal part of serratus anterior (Ashton & Oxnard, 1963, 1964). This miscellany of features is taken to indicate an ape with ancestral adaptations to arm-hanging and climbing, but with newer adaptations to use of the arm below the shoulder.

Rotator cuff muscles, teres major and deltoid

Human anatomy

Supraspinatus takes its origin from the supraspinous fossa, and its fibres pass laterally, as a single fascicle, to insert on the superior facet of the greater tuberosity. A muscular slip may pass to pectoralis major (Soames, 1995).

Infraspinatus originates from the infraspinous fossa and from the deep surface of the infraspinous fascia; its fibres converge to insert on the middle facet of the greater tuberosity. The tendon is sometimes separated from the glenohumeral capsule by a bursa. Teres minor, which may be fused with infraspinatus, attaches from the upper half of the lateral edge of the infraspinous fossa, and inserts on the most posteroinferior of the three facets on the greater tuberosity; Johnson et al. (1996) recorded an anatomical variant where the insertion extended down to the surgical neck of the humerus, and also note that this insertion may replace the more usual attachment to the greater tuberosity, in which case teres minor does not contribute to the rotator cuff itself. Teres minor is also distinguished by having a different nerve supply from infraspinatus.

Subscapularis originates from the subscapular fossa of the scapula, as a dense, interwoven bundle of fibres, the functional significance of which has not been explained, passing laterally to insert on the lesser tuberosity of the humeral neck (Johnson et al. 1996). Variations are rare, but a distinct muscular slip may pass from subscapularis to the glenohumeral capsule or to the bicipital sulcus (Soames, 1995).

Most of the movements occurring at the glenohumeral joint are brought about by muscles with greater mechanical advantage than the closely related rotator cuff muscles, but the latter muscles are extremely important in stabilising the joint whilst other muscles move it. Supraspinatus acts to draw the greater tubercle of the humerus medially and assists in abduction of the arm, acting in particular to initiate abduction, before the more powerful deltoid begins to act. The other rotator cuff muscles counteract the strong upward forces exerted by deltoid during abduction. With the arm at rest and hanging by the side, supraspinatus acts to prevent the humerus slipping downwards. The rotator cuff muscles have rotational actions on the arm, as their name suggests: the lower, oblique fibres of infraspinatus and teres minor both act as lateral rotators, and also provide exert a downward force to balance the upward shear force during deltoid contraction;

Johnson et al (1996) distinguish a different function of the upper transverse fibres of infraspinatus, which are orientated in such a way as to extend an already abducted arm. Subscapularis is a medial rotator of the pendant arm. Supraspinatus also has a rotational action, acting to further laterally rotate an already laterally rotated arm, and to further medially rotate an already medially rotated arm (Ihashi et al. 1998; Johnson et al. 1996; Soames, 1995).

Teres major arises from the dorsal surface of the lower lateral border of the scapula, and the tendon passes laterally, posterior to the tendon of latissimus dorsi, from which it is separated by a bursa, and inserts on the medial lip of the bicipital sulcus. Anatomical variations include fusion of teres major with the uppermost, scapular fibres of latissimus dorsi, and the presence of a slip passing to the long head of triceps or the brachial fascia. Teres major acts to adduct and medially rotate the arm (Soames, 1995).

Deltoid originates from the lateral clavicle, acromion and spine of the scapula, and inserts on the deltoid tuberosity of the humerus, and is a powerful abductor of the glenohumeral joint. Johnson et al. (1996) identified 5 parts of the muscle: 3 parts originating from the anterior, lateral and posterior aspects of the acromion, and forming a multipennate structure, an anterior part attaching to the lateral clavicle, and a posterior part springing from the scapular spine, each containing parallel bundles of fibres, and converging on the deltoid tuberosity. The spinous, acromial and clavicular parts of the muscle may be separated; the clavicular part may fuse with pectoralis major, or receive muscular slips from trapezius or the lateral border of the scapula. The anterior parts of deltoid act with pectoralis major to flex and medially rotate the arm, whilst the posterior parts act with latissimus dorsi and teres major to extend and laterally rotate the arm. The multipennate, acromial portion of deltoid is a powerful abductor, and may assist supraspinatus in resisting downward forces from carried loads (Soames, 1995). However, Johnson et al (1996) also note that no satisfactory explanation for the multipennate nature of this part of the muscle has been advanced.

Comparative primate anatomy

The rotator cuff muscles are similar amongst the *Anthropoidea*. Slight variation is seen in supraspinatus, which is long and thin in quadrupeds, humans and orangs, and relatively broad in the other apes. Infraspinatus and teres minor are fused in quadrupeds, semibrachiators and the lesser apes, but separate in the great apes, including humans (Ashton & Oxnard, 1963). Although

often considered as a stabilising 'unit', the rotator cuff muscles operate individually, as demonstrated in EMG studies of chimpanzees during reaching and hanging (Larson and Stern, 1986).

Teres major is similar in all the Anthropoidea, although the fleshy origin from the inferior angle of the scapula is larger in quadrupeds and in humans than it is in brachiators (Ashton & Oxnard, 1963).

In quadrupeds, deltoid is relatively small, with marked separation between the 3 heads (pars clavicularis, pars acomialis, pars spinalis). In semibrachiators, deltoid is larger, with less separation between the heads. The hominoid deltoid is particularly large, with coalescence of the 3 heads, and a powerful angle of pull. In most hominoids, the pars spinalis takes its origin from the full length of the scapular spine, and deltoid inserts about 2/3 of the way down the humeral shaft. In humans, the pattern is closer to the semibrachiating monkeys such as *Ateles*: pars clavicularis arises from the lateral half of the scapular spine, and the muscle inserts halfway down the humerus (Ashton & Oxnard, 1963; Ciochon & Corruccini, 1977).

Levator scapulae and the rhomboids

Human anatomy

Levator scapulae comprises 4 fascicles, arising from the transverse processes of C1 to C4, and inserting on the superior angle of the scapula. The vertebral attachment may vary: Johnson et al (1996) noted a variation with a 5th fascicle arising from C5 transverse process. The muscle fibres twist on their descent so that the fibres arising highest on the cervical spine inserted lowest on the scapula, and vice versa.

Rhomboid minor comprises 2 fascicles: one arising from the lower part of the nuchal ligament and one from the spinous process of C7, inserting either side of the trigonum spinae on the medial border of the scapula. Rhomboid major possesses 4 fascicles, arising from the spinous processes of T1 to T4, and inserting along the lower part of the medial border of the scapula (Johnson et al. 1996). The scapular attachments of the rhomboids and of levator scapulae may be more extensive, extending onto the dorsal and ventral surfaces of the scapula (Bharioke & Gupta, 1986). A muscular slip, rhomboideus occipitalis or capitis, may extend from rhomboid

minor to the occiput, and appears to occur more frequently in association with aneuploidy (Aziz, 1981). Atlantoscapularis muscle is a rare variant in humans (Ashton & Oxnard, 1963).

Levator scapulae assists trapezius in elevating the scapula, or to brace the shoulder against a carried load. Johnson et al. (1996) describe levator scapulae and the rhomboids as being 'the only suspensory muscles of the scapula'. Levator scapulae, the rhomboids and pectoralis minor also act together to rotate the scapula to depress the lateral angle. The rhomboids join trapezius in retracting the scapula (Soames, 1995).

Comparative primate anatomy

Levator scapulae is recognised as a discrete muscle in hominoids, but subsumed within serratus anterior in other primates (see below).

Atlantoscapularis is a slender muscle that originates on the lateral mass of the atlas. In quadrupeds it is inserted into the acromion of the scapula; in semibrachiators and hominoids, it inserts into the lateral clavicle, and in humans, it is usually absent, although it does crop up as an unusual anatomical variation (Ashton & Oxnard, 1963).

The rhomboid muscle(s) vary considerably amongst the higher primates, but with no apparent correlation with locomotor mode. Whilst the insertion is fairly constant, the muscle possesses an occipital origin in quadrupeds and semibrachiators, whereas it usually originates from the ligamentum nuchae and thoracic spines only in hominoids (including in humans); additional occipital heads may arise as anatomical variations (Ashton & Oxnard, 1963).

Trapezius and serratus anterior

Human anatomy

The medial attachments of trapezius are from the medial third of the superior nuchal line on the occiput, from the ligamentum nuchae, and from the spinous processes and supraspinous ligament of C7 to T1. Johnson et al (1996) distinguished 2 parts of trapezius: one part attaching to the lateral third of the clavicle and the other to the medial margin of the acromion and the scapular spine, each comprising several distinct fascicles; the central fascicles composed of horizontally-running fibres are the largest. Variations in this muscle include an extension of the clavicular attachment, sometimes as far as sternocleidomastoid.

Serratus anterior attaches from the anterolateral aspect of the upper ribs to the ventral surface of the medial border of the scapula, with the fibres unequally distributed so that a focal point of attachment is formed at the inferior angle, where most of the lower fascicles converge, and a lesser focal point is formed opposite the trigonum spinae; Johnson et al (1996) argue for a biomechanical division of the muscle into 2 parts: one part attaching to the inferior angle and the other to the rest of the medial border of the scapula. The number of fascicles arises from the ribs varies, from 7 to 10, often with bilateral asymmetry in number (Johnson et al. 1996). The muscle may be fused with levator scapulae superiorly, or with external intercostals or the external oblique muscle (Soames, 1995).

Trapezius and serratus anterior are important stabilisers of the scapula, keeping it steady while other muscles move the arm. The upper portion of trapezius acts to resist forces exerted by loads carried below the shoulder, and to assist levator scapulae in elevating the scapula, albeit indirectly, through its attachments to the lateral clavicle (Johnson et al. 1994; 1996). The lower part of trapezius works with the rhomboids to retract the scapula. Trapezius and the lower digitations of serratus anterior act together to rotate the scapula, elevating the lateral angle as the arm becomes fully abducted. Serratus anterior protracts the scapula, with pectoralis minor, keeping it pressed against the chest wall when the upper limb is used in pushing and reaching. Upper fascicles of serratus anterior assist levator scapulae in suspending the shoulders and resisting downwards forces on the shoulder (Soames, 1995).

The cranial and caudal parts of trapezius are of equal thickness in quadrupeds; the cranial part is thicker in semibrachiators, and even more so in hominoids. In this respect, the human trapezius muscle is more like the quadruped version. The attachments of the muscle to the cranium and to the shoulder girdle vary. In quadrupedal monkeys, trapezius attaches to the medial end of the superior nuchal line, to the spine of the scapula and sometimes to the acromion as well. In semibrachiators and hominoids, the origin varies between an attachment to ligamentum nuchae only (e.g.: *Ateles*, *Hylobates* and *Symphalangus*), to the external occipital protuberance or medial part of the superior nuchal line (e.g.: *Lagothrix, Gorilla, Pan, Pongo, Homo*) to a more extensive attachment along the entire superior nuchal line (e.g.: *Alouatta*). Both semibrachiators and brachiators possess a clavicular as well as a scapular insertion. The insertion on the scapular spine is oriented differently and is more extensive in humans compared with other hominoids, reaching to the medial border of the scapula, (Ashton & Oxnard, 1963). The angle of insertion of trapezius in the human is closer to the arrangement in quadrupeds than in the apes (Oxnard, 1967), reflecting the habitual use of the arm below the shoulder.

In non-human primates, serratus anterior is divided into two parts that reflect the biomechanical division proposed for the muscle in the human by Johnson et al (1996): a pars cranialis and a pars caudalis. However, the most cranial part of the pars cranialis in monkeys corresponds with levator scapulae: serratus anterior pars cranialis consists of fibres originating on cervical transverse processes and inserting into the superior angle of the scapula, and digitations from the upper ribs inserting into the medial border of the scapula. Although Ashton & Oxnard (1963) distinguish the cervical part of this muscle in hominoids as a separate unit, levator scapulae, the cervical and thoracic parts of the muscle are also separated in quadrupeds and semibrachiators, if only by a thin intermuscular septum. Serratus anterior pars caudalis comprises a series of digitations arising from the lateral surface of the ribcage and inserting into the inferior angle of the scapula. In quadrupeds, there are 6 digitations, 8-9 in semibrachiators and 9-10 in hominoids; the number is reduced to 4-5 in the human.

Pectoralis major *et* minor and latissimus dorsi

Human anatomy

Pectoralis minor attaches by way of 3 fascicles, from the 3rd to 5th ribs and passes, under cover of pectoralis major, to the coracoid process (Johnson et al. 1996). It may attach from the 2nd to 4th, or 2nd to 5th ribs and a rare variation involves a slip arising from the first rib. The fibres attaching to the coracoid process may continue into the coracoacromial ligament and even into the coracohumeral ligament or shoulder capsule (Ashton & Oxnard, 1963; Soames, 1995). Pectoralis minor assists serratus anterior in drawing the scapula forward onto the chest, and also assists levator scapulae and the rhomboids to rotate the scapula and tilt the lateral angle inferiorly (Soames, 1995).

Pectoralis major arises from the medial half of the clavicle, from the sternum and the 1st-7th costal cartilages, and from the aponeurosis of the external oblique muscle of the abdomen. The fibres converge to form a tendon inserting on the lateral lip of the bicipital sulcus. The tendon is bilaminar, with the clavicular fibres lying superficially to the sternocostal fibres. The posterior lamina has extensions that line the bicipital sulcus, blend with the glenohumeral capsule, and join the deep brachial fascia. Variations in pectoralis major include the absence of the slip from the external oblique, variation in the costal attachments and variable separation of the clavicular and sternocostal parts. Vertical slips, called rectus sternalis, may attach to the sternum or to the sternocleidomastoid muscle (Soames, 1995). A muscular slip, called chondroepitrochlearis, may pass from the inferior border of pectoralis major, into the groove between biceps and coracobrachialis on the arm, to insert into the medial epicondyle of the humerus. Another muscular slip may arise below pectoralis major and insert into the coracoid process (Ashton & Oxnard, 1963). Pectoralis major and minor may also be congenitally completely or partially absent (Soames, 1995).

Pectoralis major acts as a whole to assist adduction and medial rotation of the humerus against resistance. Its clavicular part, acting in concert with the anterior deltoid and coracobrachialis, flexes the extended arm. With latissimus dorsi, teres major and the posterior deltoid, the sternocostal part of pectoralis major acts to bring the flexed arm back to the side of the body, against resistance. The same muscles act to bring the trunk up and forwards to the fixed, flexed and abducted arm in climbing (Soames, 1995).

Latissimus dorsi is a muscle with an extremely extensive origin, with an aponeurotic attachment extending from the lower 6 thoracic spinous processes and supraspinous ligament, the thoracolumbar fascia, to the iliac crest. Additional fleshy slips may arise from the medial end of the iliac crest, from the lowest 1-3 ribs, or from the inferior angle of the scapula (Ashton & Oxnard, 1963). The muscle converges to a narrow tendon that inserts into the floor of the bicipital sulcus. The muscle fibres twist as they pass the scapula, so that those with the lowest origin achieve the highest insertion, and vice versa. Latissimus dorsi may receive fibres from the inferior angle of the scapula, and a slip (the 'axillary arch') may cross the axilla to join the pectoralis major, coracobrachialis or the fascia overlying biceps (Georgiev et al. 2006; Soames, 1995).

Latissimus dorsi acts to adduct, extend and medially rotate the humerus. It is an important climbing muscle, functioning to lift the body up to a flexed or abducted arm, and also helps to limit the shear forces at the glenohumeral joint when the arm is elevated. It is also used in transfers of body weight, especially in those with impaired lower limb hemiplegia. Conversely, it can be used to drag a load backwards (Bogduk et al. 1998). With the arm elevated, the upper fibres of latissimus dorsi also help to keep the inferior angle of the scapula apposed to the chest (Soames, 1995).

Comparative primate anatomy

In quadrupedal primates, pectoralis major is large, cranially directed and incompletely divided into sternoclavicular and sternocostal heads. A distinct muscle, pectoralis abdominis, arises from the lower costal cartilages and the aponeurosis of external oblique, and passes craniolaterally, with the tendon of pectoralis minor, to insert on the shoulder capsule. In hominoids, pectoralis major is relatively smaller in size, and the parts are usually more definitely separated, by spaces filled with areolar tissue. Hominoids lack pectoralis abdominis, but instead possess a third part of pectoralis major: pars abdominis, which may be homologous with pectoralis abdominis. Pars abdominis is often absent in the human; a low muscle slip running inferiorly to pectoralis major and attaching to the coracoid process has been reported in humans, and may also be homologous with pectoralis abdominis (Ashton & Oxnard, 1963).

Pectoralis minor is more extensive and more cranially directed in quadrupeds compared with hominoids; it has a more extensive insertion in quadrupeds, attaching to the capsule of the shoulder joint and to the greater tuberosity, as well as onto the coracoid process. In gibbons and

siamangs, pectoralis minor attaches to both the coracoid process and the coracoacromial ligament, as sometimes seen as an anatomical variation in humans. In the orang, the insertion of pectoralis minor may be limited to the coracoid process, or may extend to the shoulder capsule, and even the adjacent clavicle and acromion. Similarly, pectoralis minor in the chimpanzee may insert either on the coracoid process or the shoulder capsule, or more extensively on the coracoid process, shoulder capsule, coracoacromial ligament and even the greater tuberosity. The anatomy and anatomical variations present in the human pectoralis minor follow this hominoid pattern (Ashton & Oxnard, 1963).

In quadrupedal monkeys compared with semibrachiators and hominoids, latissimus dorsi is thinner, smaller and lacks any attachment to the sacrum and iliac crest. In semibrachiating monkeys and the true brachiators, gibbons and siamangs, latissimus dorsi attaches to the sacrum and iliac crest by way of the thoracolumbar fascia. Latissimus dorsi is larger and more powerful in the apes compared with monkeys. In gorillas, chimpanzees and orangs, the thoracolumbar fascia provides an attachment of latissimus dorsi to the medial half of the iliac crest, while fleshy fibres originate from the lateral half. In the human, the attachment to the iliac crest is normally via the thoracolumbar fascia, though fleshy slips may arise from the iliac crest. In all the apes, the muscle also receives slips from the lower ribs, as is sometimes the case in humans. In orangs and chimpanzees, some cranial fibres of latissimus dorsi detach themselves and insert with teres major.

Epitrochlearis is a slender muscle that arises from the close to the scapula and runs down into the arm, alongside triceps, in prosimians, monkeys and apes (Swindler & Wood, 1973). In quadrupeds, the muscle arises from the fascia over the axillary border of subscapularis, and inserts into the medial epicondyle of the humerus, the olecranon and the extensor fascia of the forearm. In semibrachiating monkeys, the muscle also attaches to latissimus dorsi, and inserts on the medial epicondyle. In gibbons and siamangs, the muscle inserts on the fascia over triceps, the distal medial intermuscular septum and the medial epicondyle; the insertion is similar in orangs, although the epicondylar insertion is variable. In chimpanzees, epitrochlearis inserts on the medial epicondyle and supracondylar ridge; in gorillas, epitrochlearis forms a distinct tendon inserting onto the medial epicondyle. Epitrochlearis is present as an anatomical variation in the human, attaching from latissimus dorsi to the deep fascia of the arm, in about 5%, forming the axillary arch (Ashton & Oxnard, 1963).

Coracobrachialis, biceps and triceps brachii

Human anatomy

Coracobrachialis originates on the apex of the coracoid process, and from the short head of biceps, and inserts onto the middle of the medial surface of the humerus. Muscular slips may pass from coracobrachialis to the lesser tuberosity of the humerus, or distally to its medial epicondyle. Coracobrachialis acts to flex the arm and, with the anterior parts of deltoid, to stabilise the axis of abduction (Soames, 1995).

Biceps brachii usually has, as its name suggests, two heads: a short head attached to the coracoid process, and a long head attached to the supraglenoid tubercle. The biceps tendon inserts on the radial tuberosity. In around 10%, a third head arises from the upper part of brachialis. Biceps acts to prevent upward translation of the humeral head while deltoid abducts the arm (Soames, 1995).

Triceps brachii arises by a long head from the infraglenoid tubercle, and by medial and lateral heads from the posterior surface of the humerus. The major action of triceps, as biceps, is on the elbow joint, but the long head assists in adducting the abducted, extended arm (Soames, 1995).

Comparative primate anatomy

The origin of coracobrachialis, on the coracoid process, is constant, but insertions vary: in the macacque, the muscle possesses a deep part, inserting on the surgical neck of the humerus, and a more superficial part, inserting on the humeral shaft. In the chimpanzee and human, the muscle lacks the deep part. Biceps brachii is similar in macaques, chimpanzees and humans. The attachment of the long head of triceps varies, attaching from an extensive area on the axillary border of the scapula in the chimpanzee, compared with a more discrete attachment, to the infraglenoid tubercle of the scapula, in humans. Epitrochlearis constitutes a fourth muscle of the arm in most primates, but is absent in the human (Swindler & Wood, 1973).

Subclavius

Human anatomy

This small muscle attaches from the costochondral junction of the first rib, to the inferior surface of the middle third of the clavicle. It may instead attach to the coracoid process, or to the superior border of the clavicle. Its actions have not been investigated, but it probably depresses the shoulder and compresses the sternoclavicular joint (Soames, 1995).

Comparative primate anatomy

The insertion of subclavius into the clavicle varies between locomotor groups; in quadrupeds and in humans, it inserts into the middle third, in semibrachiators and most hominoids, it inserts into the lateral half, with some fibres inserting into the coracoclavicular ligament.

1.3.3 Warning against an overly simplistic approach to form and function

The preceding notes on anatomy and locomotion may appear to imply an extremely straightforward relationship between form and function. However, it is very important not to assume a simple, direct correlation between anatomy and locomotor or positional behaviour.

As the EMG studies have shown (Shapiro & Jungers, 1994; Shapiro et al. 1997), locomotor behaviour may be constrained by anatomy, but is also influenced by patterns of neural control. Locomotor and positional behaviour also varies within anatomical constraints according to size, which also affects morphology (McNeil Alexander, 1985; Pilbeam & Gould, 1974; Ruff, 2000). Extrinsic factors, such as availability of food, risk of predation, climate and ecology, also influence locomotor behaviour. Climate may directly influence behaviour, but will also create selection pressures that influence body size and shape (Katzmarzyk & Leonard, 1998; Ruff, 1994). The skeletons of Neanderthals demonstrate cold adaptation in their proportions, as well as adaptations to heavier musculature in their robusticity, when compared with modern humans (Holliday, 1997; Holliday & Ruff, 1997). The combination of intrinsic and extrinsic factors influencing locomotor and postural behaviour means that it is important for predictive models to include data from studies of anatomy, behaviour and ecology (Fleagle, 1985; Gebo & Chapman, 1995a).

Some comparative locomotor ecology studies have demonstrated a very tight relationship between species' locomotor anatomy and habitat, even down to the choice of stratum in a forest canopy (Cannon & Leighton, 1994). This determination of ecological niche by locomotor specialisations may effectively separate some similar, sympatric species, thus reducing competition between them (Warren & Crompton, 1997). However, other studies have shown conservatism in some primate positional behaviour, which could confound attempts to correlate habitats with morphology. For instance, a study of colobus monkeys showed them to be actively selecting similar supports in different forest types (McGraw, 1996).

Locomotor and positional modes also vary between different activities, such as travelling and feeding. This means that using known overall frequencies of various positional and locomotor modes are not particularly useful in constructing a predictive model for a primate's behaviour (Gebo & Chapman, 1995b). Society may also play a role: the arboreal activity of lowland gorillas

varies with physical morphology, habitat and tree structure, but also with social context (Remis, 1995).

Although studies of functional anatomy in extant species may be drawn on to predict positional behaviour in fossil taxa, it is dangerous to be oversimplistic. Pathological findings may provide further insight, indicating areas of the skeleton which have been under stress and implying particular patterns of physical activity; for instance, the presence of Scheuermann disease in the spine of *Australopithecus afarensis* specimens is indicative of a behavioural repertoire including lifting, carrying or climbing (Collins Cook et al.1983). However, whilst palaeopathology offers useful additional information, data on the structure of primate societies and palaeoecology should also be included in any predictive models of hominid positional behaviour.

2. Palaeopathological patterns of arthropathy and enthesopathy in the shoulder complex in human skeletal remains

2.1 Introduction

This part of the study was written up as an article in the Journal of Anatomy: 'New light on old shoulders: palaeopathological patterns of arthropathy and enthesopathy in the shoulder complex' (Roberts et al. 2007). This chapter represents an extended and updated version of that article, with additional material added to the Introduction and Discussion in particular.

2.1.1 Rotator cuff disease: ancient and modern

Shoulder disorders are common in modern populations, with reported incidences of first episode shoulder problems ranging from 10-25% (Frost et al. 2002). Of all the causes of shoulder pain and disability, rotator cuff disease (RCD) is the most common (Bigliani & Levine, 1997; Fremerey et al. 2000; Michener et al. 2003; Soohoo & Rosen, 1996). The range and pattern of pathologies around the shoulder reflects the complexity of the anatomy in this region.

The term 'RCD' is often used in a way that suggests it is synonymous with subacromial (anterosuperior) impingement syndrome; this is indeed the most common pattern, but RCD represents a wider range of pathologies (Bigliani & Levine, 1997a; Budoff, 2005; Bunker, 2002; Michener et al. 2003). Pathology involving the rotator cuff and the tendon of the long head of biceps (LHB), the subacromial bursa, the coracohumeral, glenohumeral and coracoacromial ligaments, the glenoid labrum, and the glenohumeral and acromioclavicular joints are commonly found to be clinically associated. Lesions in one structure may lead to lesions in others, although the precise aetiology of individual lesions and progression to patterns of lesions is often unclear.

Subacromial impingement affects the supraspinatus tendon where it passes through the narrow channel of the supraspinatus outlet. When the arm is abducted, the protruding humeral tuberosities swing up under the coracoacromial arch, narrowing the supraspinatus outlet and compressing its contents (Graichen et al. 2001; Hyvonen et al. 2001; Lee et al. 2001; Meskers et al. 2002). This compression may become pathological, causing subacromial bursitis, and tendinosis and rupture of the supraspinatus tendon (Bigliani & Levine, 1997a; Cohen & Williams, 1998; Fremerey et al. 2000; Michener et al. 2003; Tytherleigh-Strong et al. 2001). A separate

impingement syndrome: subcoracoid impingement, may affect the lesser tuberosity, along with the subscapularis bursa and tendon (Burns & Whipple, 1993; Bigliani & Levine, 1997a; Rossi 1998). Degeneration of the subscapularis tendon may in turn lead to degeneration of the LHB tendon (Gerber & Sebesta, 2000). These impingement syndromes, though recognisable as clinically distinct entities, can produce instability at the glenohumeral joint, contributing to further impingement and a cascade of pathological changes (Jensen et al. 1999).

Rather surprisingly, RCD has received very little attention in the palaeopathological literature. The first mention of bony changes to the undersurface of the acromion appears to occur in a paper by Graves, published in the American Journal of Physical Anthropology in 1922. Graves describes becoming 'impressed with a series of changes in the scapula, which appears to be intimately associated with advancing years'. He painstakingly recorded the appearance and dimensions of a smooth, concave 'elevated plaque of bone' on the acromial undersurface, and postulated that this plaque could be due to ossification of the subacromial bursa, but did not pursue its aetiological origin any further. Similar changes in the subacromial region, together with enthesopathic changes around the humeral neck relating to RCD, in particular affecting the greater tuberosity, have been reported in studies of macerated cadaveric bones (Kerr et al. 1985). The first record of bony changes in archaeological human remains, in specific relation to RCD, was made by Miles in 1996, from observations of skeletal material from a burial ground on Ensay in the Western Isles, dating to between the 16th and 19th centuries. Miles concentrated on a narrow definition of RCD, focussing on changes associated with subacromial impingement, i.e.: bony changes on the undersurface of the acromion combined with changes on the greater tuberosity of the humerus. Miles also went on to document similar changes in the Spitalfields collection (Miles, 1999a). However, it remains unclear whether RCD was generally present in ancient populations, or indeed whether the wider spectrum of pathologies now recognised as comprising RCD may be seen in ancient bones.

2.1.2 Diagnosis in RCD

The diagnosis of subacromial impingement syndrome is based on clinical signs combined with information from radiographic, magnetic resonance (MR), ultrasound (US) or arthroscopic investigations (Bigliani & Levine, 1997a; Jensen et al. 1999). The patient usually complains of a painful, weak or stiff shoulder, and may have noticed difficulties in performing activities utilising overhead movements of the arm. The clinical signs include the 'impingement sign' or 'painful arc' where a patient experiences pain when elevating the arm between 70 and 120°, or after elevating the arm to 90° then internally rotating it (Bigliani & Levine, 1997a).

MR and US investigations are useful non-invasive imaging modalities for revealing the soft tissue pathology, i.e.: tendon tears, (Bigliani & Levine, 1997a; Graichen et al. 2001; Jensen et al. 1999; Martin-Hervas et al. 2001), and may also be used to measure the subacromial space (Graichen et al. 1998, 1999). Arthroscopy allows direct visualisation of the shoulder capsule and a definitive evaluation of tendon tears (Miller et al. 1998).

Plain radiography remains a useful tool in assessing bony changes related to RCD. The principal radiographic signs associated with subacromial impingement syndrome include bony changes at the greater tuberosity, such as subchondral cysts and sclerosis, and bony changes at the acromion, including sclerosis and spur formation anteriorly (Bigliani & Levine, 1997a; Jiang et al. 2002; Pearsall et al. 2003; Umans et al. 2001). Although Huang et al (1999) found no difference in rates of radiographic bony changes at the greater tuberosity between normal shoulders and those shown to have rotator cuff tears on MRI (n=108), the majority of studies indicate that such changes are useful indicators of RCD. Pearsall et al. (2003) compared 40 patients with known rotator cuff tears with age-matched controls and also found a high correlation between the radiographic presence of sclerosis, osteophytes, subchondral cysts and osteolysis at the greater tuberosity and full thickness rotator cuff tears. In a study of cadaveric shoulders (Jiang et al. 2002) documented cortical thickening of the greater tuberosity in all cases (5 of 5) of sonographically diagnosed rotator cuff tear, compared with only one fifth (2 of 10) of normal shoulders. Umans et al. (2001) found a positive correlation between the presence of proliferative and degenerative changes on the inferior acromion and superior greater tuberosity in patients with a complete supraspinatus tendon tear (n=153), concluding that conventional radiography could be used reliably to detect rotator cuff tears.

Some researchers recognise other signs as indirect indicators of RCD; these include anatomical and pathological features that may represent potential predisposing factors in the development of RCD, such as DJD at the acromioclavicular (ACJ) or glenohumeral joints, calcific tendinitis, and acromial morphology (Bigliani & Levine, 1997a; Cohen & Williams, 1998; Jensen et al. 1999). These indicators are more controversial than the more direct signs relating to degenerative changes on the greater tuberosity and acromion.

In an anatomical study looking specifically at the relationship between ACJ pathology and rotator cuff tears, Cuomo et al. (1998) found a significant correlation between the size and frequency of ACJ osteophytes and rotator cuff tears. However, the study carried out by Pearsall et al. (2003), on 40 patients with rotator cuff tears, and 84 age-matched, asymptomatic individuals, found no association between ACJ degeneration and rotator cuff tears, and the authors suggested that ACJ findings reported in other studies could simply represent incidental, age-related changes.

There is enormous controversy over the relationship between acromial morphology and subacromial impingement. Bigliani and his group proposed a classification of the acromion, based on its appearance on a supraspinatus outlet view radiograph, identifying three types of acromion: type I (flat), type II (curved) and type III (hooked). They reported a significant association between hooked acromia and full thickness rotator cuff tears (Bigliani et al. 1986). Other studies, clinical and cadaveric, have produced data which supports this association (Epstein et al. 1993; Gill et al. 2002; Panni et al. 1996). However, several studies have also reported a distinct lack of correlation between acromial morphology and rotator cuff tears (Hyvonen et al. 2001; Liotard et al. 1998; Pearsall et al. 2003). Even amongst those investigators who argue for an association between acromial morphology and rotator cuff tears, there is disagreement over whether the shape of the acromion is a causative factor, and indeed whether it is an innate or an acquired/degenerative characteristic. Some researchers believe the hooked acromion to be an innate characteristic, unrelated to age (Bonsell et al. 2000; Nicholson et al. 1996). Others argue that a hooked acromion is caused by the formation of traction osteophyte, increases in prevalence with age, and may indeed occur secondary to rotator cuff tendinopathy (Burns & Whipple, 1993; Kevin et al. 2001; Lee et al. 2001; Liotard et al. 1998; Mahakkanukrauh & Surin, 2003; Neer, 1972; Prescher, 2000; Shah et al. 2001; Speer et al. 2001; Wang & Shapiro, 1997; Worland et al. 2003). The objectivity of the Bigliani method of classification of acromial morphology has itself been called into question, with studies showing high degrees of interobserver error (Haygood, 1994; Jacobson et al. 1995). Meskers et al. (2002) found no

evidence for the Bigliani classification of acromial shape, and Liotard et al. (1998) even suggest that a type III or hooked acromion may be a radiological artefact. For these reasons, acromial morphology was not included in this investigation, although the presence of osteophyte on the acromion was recorded.

2.1.3   Aims

The principal aim of this part of the study was to establish whether such a range of pathologies may be seen in skeletal remains as is now recognised clinically. This was achieved by recording lesions on the head and tuberosities of the humerus, the glenoid fossa, acromion and the facets of the acromioclavicular joint. A secondary aim was to suggest a sequence or 'progressive cascade' of the development of pathology in these areas by recording the patterns of these lesions.

2.2 Material and Methods

2.2.1 Materials

A range of skeletal material from various British populations, drawn from Roman, medieval and post-medieval sites, was included in the investigation (Table 2.2.1). The selection criteria were that the bony elements of the shoulder system (scapula, clavicle and proximal humerus) should be well represented, preferably bilaterally, in skeletally mature individuals. The total number of individuals included in the sample was 86. The skeletons were determined as adult on the basis of epiphysial fusion, and sexed according to standard anthropological techniques (Brickley & McKinley, 2004).

Collection	Age	N
Maiden Castle (Duckworth Collection, Cambridge)	Iron Age	7
Comet Place (Duckworth Collection, Cambridge)	medieval	12
Worthy Park, Hampshire (Duckworth Collection, Cambridge)	Anglo-Saxon	5
Spitalfields (Natural History Museum, London)	18th-19th century	10
Llandough (National Museum of Wales, Cardiff)	medieval	49
Lawfords Gate (BORG, Bristol)	17th century	1
Bath, Royal Crescent (Time Team)	Roman	2
Total		86

Table 2.2.1 Source of skeletal material included in study

2.2.2 Osteological methods

The scapula, clavicle and proximal humerus were carefully inspected for any pathological lesions. Bony changes (pitting, osteophyte, altered bony contour and eburnation) were recorded on articular surfaces including the glenoid fossa, humeral head, acromioclavicular facet of the acromion, the lateral clavicle facet, the sternoclavicular facet of the sternum and the medial clavicle facet. Bony changes were also recorded on non-articular bony surfaces including the inferior surface of the acromion, the greater and lesser tuberosities, and the bicipital sulcus. Each articular surface was considered to show signs of DJD (DJD) if eburnation or two or more of the other signs (pitting, osteophyte, altered bony contour) were present, according to Rogers' diagnostic criteria (Rogers et al. 1987; Rogers & Waldron, 1995). For the purposes of this study, the non-articular surfaces were treated accordingly, with a diagnosis of 'degenerative change' proposed if eburnation or at least two of the other signs were present. Digital photographs were taken of any bony changes.

2.2.3 Statistical methods

The initial analysis of the data involved an assessment of the frequencies of degenerative change at each of the bony surfaces inspected in the 86 individuals. Since the data were collected from archaeological material, bony elements were often missing or broken. Each (relative) frequency was therefore calculated as the percentage of the total number of each element affected by degenerative change, according to standard palaeopathological reporting (Brickley & McKinley, 2004). Similar descriptive statistics were then obtained after combining data relating to the same joint, to investigate differences according to side and sex.

The second stage of the analyses investigated associations between degenerative changes across joints and surfaces. This was achieved first using simple descriptive statistics, but it became obvious that a more complex, epidemiological approach was required. At this point, I sought the assistance of Professor Tim Peters, then in the Department of Community Based Medicine, at the University of Bristol. Professor Peters applied exploratory factor analysis (Kline, 1994) to my data, employing standard varimax rotation and using Stata statistical software (StataCorp, 2003. *Stata Statistical Software: Release 8.0*. College Station, TX; Stata Corporation). Factor analysis involved modelling the correlations between the markers of degenerative changes, as a correlation matrix, in order to reveal any underlying patterns (latent variables) in the data. The impact of the requirement of these analyses for complete datasets was explored in sensitivity analyses after omitting measurements with relatively large amounts of missing data.

2.3 Results

2.3.1 Types of degenerative change and their relative frequencies

In terms of the relative frequencies of degenerative change in bony surfaces, those involved in the acromioclavicular and sternoclavicular joints were the most commonly affected (Figure 2.3.1). Degenerative change was observed in 47 (52%) of 90 lateral clavicle facets, and in 35 (47%) of 74 acromioclavicular facets of acromia. The facet of the medial clavicle was affected in 48 (46%) of 104 cases; the sternal facet for the sternoclavicular joint in 17 (38%) of 45 cases. The frequency of degenerative changes at the shoulder joint surfaces was much less: 14 (14%) of 100 glenoid fossae and 18 (17%) of 105 humeral heads. Of the non-articular bony surfaces, the lesser tuberosity exhibited the greatest relative frequency of degenerative bony changes, at 37% (39 of 106 cases), compared with only 15% (14 of 93 cases) of greater tuberosities and 12% (13 of 107) bicipital sulci. The inferior acromion showed degenerative changes in 17% (14 of 83). A single case of os acromiale was recorded in a left acromion, from Maiden Castle. In this case, the left glenoid fossa, humeral head, inferior acromion, greater tuberosity, lesser tuberosity, bicipital sulcus and acromial facet of the acromioclavicular joint were available for inspection, and all showed signs of degenerative change. The most frequent basis for a diagnosis of degenerative change, across all bony surfaces, was a combination of pitting and osteophyte (Figures 2.3.1 & 2.3.2). Eburnation was a relatively infrequent finding.
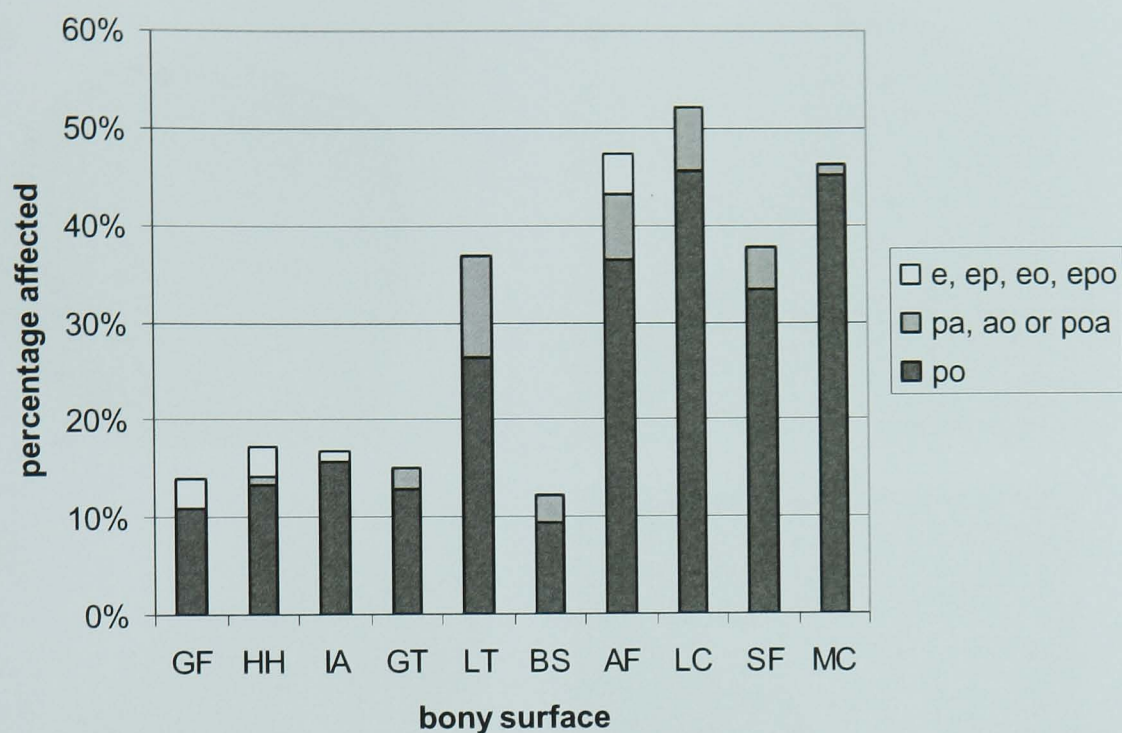
Figure 2.3.1 Relative frequency of degenerative changes at bony surfaces in the shoulder complex.
Key to legend - e: eburnation; ep: eburnation and pitting; eo: eburnation and osteophyte; epo: eburnation, pitting and osteophyte; pa: pitting and altered bony contour; ao: altered bony contour and osteophyte; poa; pitting, osteophyte and altered bony contour; po: pitting and osteophyte. Key to x-axis categories – GF: glenoid fossa; HH: humeral head; IA: inferior acromion; GT: greater tuberosity; LT: lesser tuberosity; BS: bicipital sulcus; AF: acromial facet; LC: lateral clavicle; SF: sternal facet; MC: medial clavicle
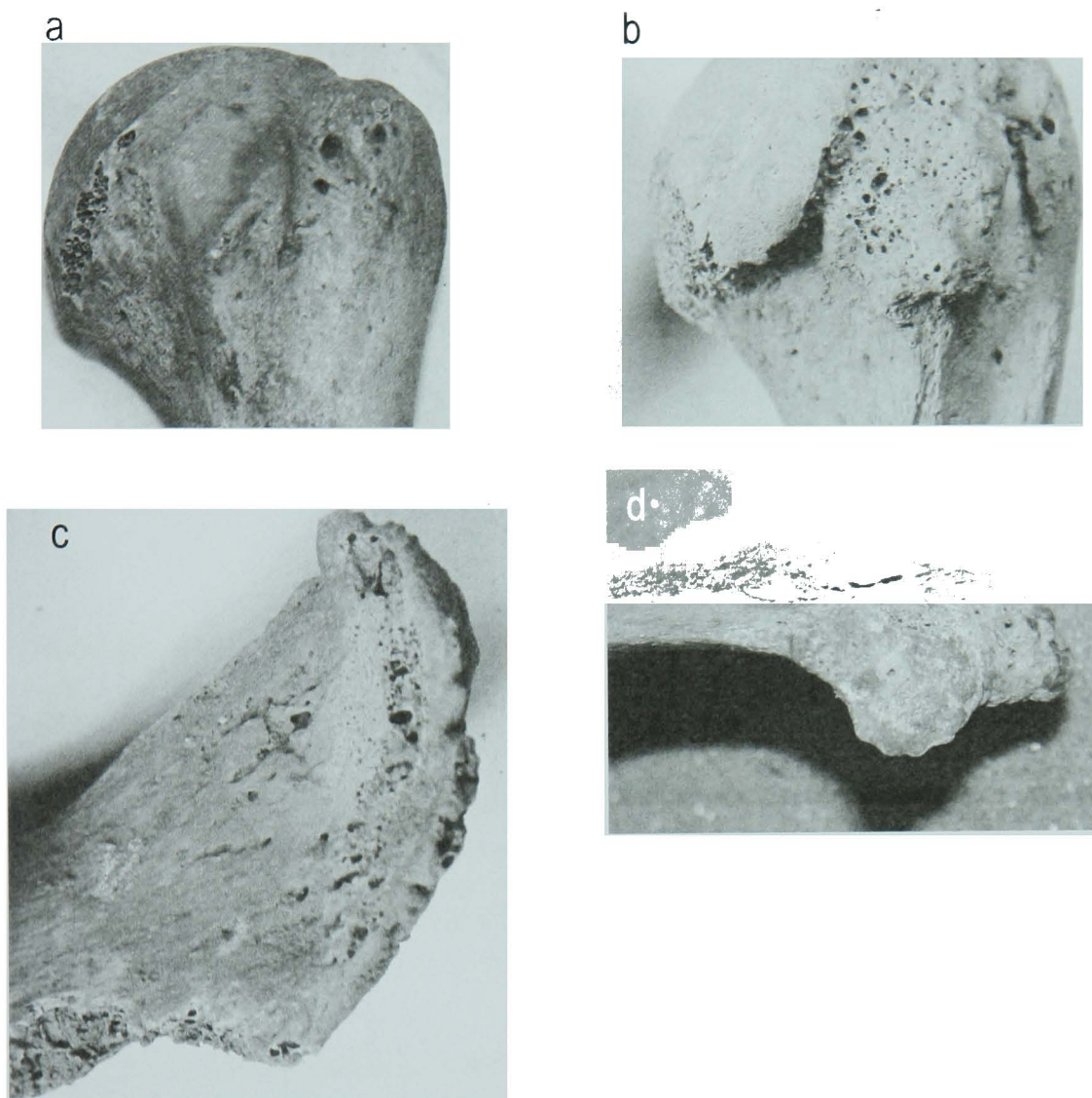
Figure 2.3.2 Appearance of normal humerus and examples of degenerative changes. (a) Humerus
with no pathological changes; note facet-like appearance of lesser tuberosity. (b) Humerus showing anterolateral
lipping of humeral head and florid osteophyte with pitting on lesser tuberosity. (c) Inferior aspect of a left acromion,
showing osteophyte spur at tip and raised, pitted facet inferiorly. (d) Left acromion with inferiorly projecting
osteophyte at acromioclavicular facet.

2.3.2 Degenerative change according to side and sex

Further descriptive analysis involved examining the data for patterns of degenerative change. The data were sorted by side and sex; this involved reducing the sample size to 74 individuals (39 male and 35 female), as specimens of indeterminate sex were not included. The data were also compressed by conflating the information from bony surfaces representing apposing sides of a joint, which reduced some of the gaps in the dataset due to missing or broken elements. In this way, the data for glenoid fossa and humeral head were conflated to produce a glenohumeral joint category; the acromial facet and lateral clavicle were considered together as the acromioclavicular joint, and the sternal facet and medial clavicle as the sternoclavicular joint (Table 2.3.1).

Categories	GHJ	IA	GT	LT	BS	ACJ	SCJ
Right	11/39(28%)	5/38(13%)	6/41(15%)	16/48(33%)	7/49(14%)	32/34(94%)	18/24(75%)
Left	12/40(30%)	10/38(26%)	8/44(18%)	20/48(42%)	6/47(13%)	26/34(76%)	21/22 (95%)
Female	10/44(23%)	11/40(28%)	8/51(16%)	21/54(39%)	6/53(11%)	30/36(83%)	20/23(87%)
Male	13/35(37%)	4/36(11%	6/34(18%)	15/42(36%)	7/43(19%)	28/32(88%)	19/23(83%)
Totals	23/79 (29%)	15/76(20%)	14/85(16%)	36/96(38%)	13/96(14%)	58/68(85%)	39/46(85%)

Table 2.3.1 Summary of relative frequencies of degenerative change from data sorted by side and sex
GHJ: glenohumeral fossa; IA: inferior acromion; GT: greater tuberosity; LT: lesser tuberosity; BS: bicipital sulcus; ACJ: acromioclavicular joint; SCJ: sternoclavicular joint

Figure 2.3.3 shows that there was very little difference in the frequency of degenerative changes between right and left sides. However, it does not indicate whether these changes are represented unilaterally or bilaterally within individuals. To address this question, a subset of the data, comprising intact pairs of each element, was analysed, and the results are presented in Table 2.3.2. The lesser tuberosity, acromioclavicular and sternoclavicular joints showed the strongest tendency towards bilateral involvement. Glenohumeral joint degeneration tended to affect joints unilaterally, affecting right and left sides equally. Tendencies towards unilateral versus bilateral involvement in the other bony surfaces cannot be deduced from this analysis, as the numbers are too small.

Figure 2.3.3 Comparison of the rates of degenerative changes in right and left sides
Key to x-axis categories – GHJ: glenohumeral fossa; IA: inferior acromion; GT: greater tuberosity; LT: lesser
tuberosity; BS: bicipital sulcus; ACJ: acromioclavicular joint; SCJ: sternoclavicular joint

Table 2.3.2 Patterns of unilateral and bilateral involvement
GHJ: glenohumeral fossa; IA: inferior acromion; GT: greater tuberosity; LT: lesser tuberosity; BS: bicipital sulcus;
ACJ: acromioclavicular joint; SCJ: sternoclavicular joint

		GHJ	IA	GT	LT	BS	ACJ	SCJ
Number of intact pairs		29	28	31	39	34	22	11
Degenerative change	Right only	6	2	2	0	2	3	0
	Left only	6	3	1	3	2	0	0
	Bilateral	2	3	3	13	2	18	11

The sample of 74 sexed individuals was then considered to investigate whether there were any significant sex differences in the rates of degenerative change at each bony surface (Figure 2.3.4). There was no substantial difference between the sexes in the frequency of degeneration of the clavicular joints or the tuberosities. However, there were suggestions of differences in the frequencies for: glenohumeral joint involvement (37% of males compared with 23% of females; two-sided P=0.21 from Fisher's Exact Test); inferior acromion (11% of males and 28% of females; P=0.089); and bicipital sulcus (19% versus 11%; p=0.56).
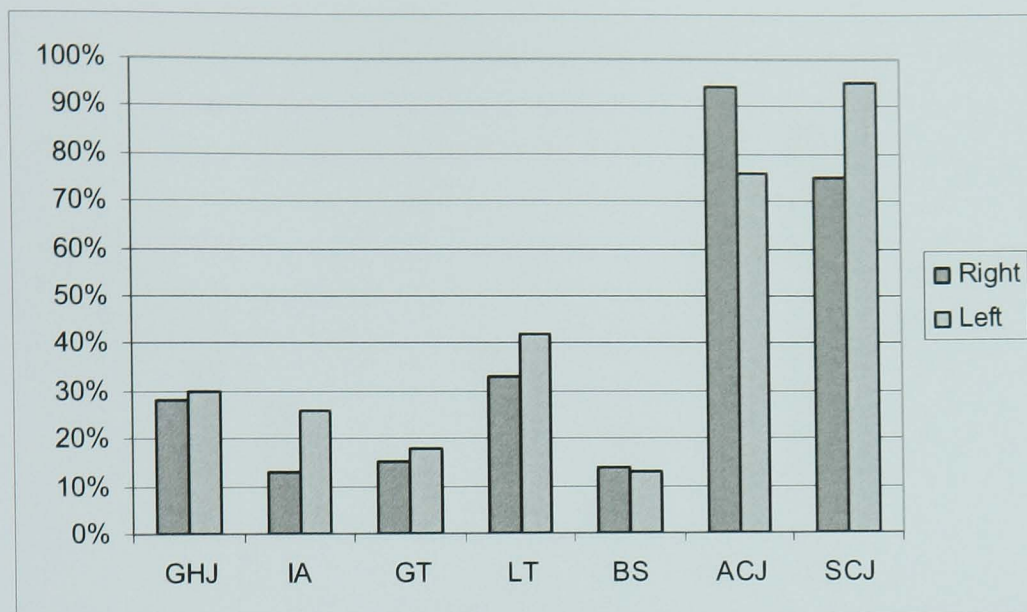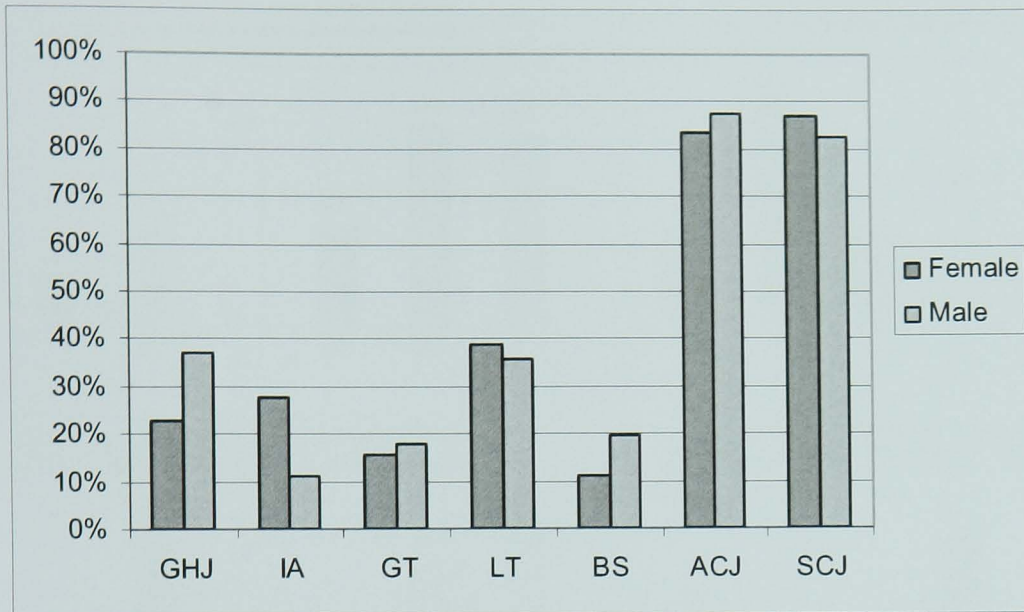
Figure 2.3.4 Comparison of the rates of degenerative changes in females and males
Key to x-axis – GHJ: glenohumeral fossa; IA: inferior acromion; GT: greater tuberosity; LT: lesser tuberosity; BS: bicipital sulcus; ACJ: acromioclavicular joint; SCJ: sternoclavicular joint

2.3.3 Patterns of degenerative change

As described in the Methods, the next stage of the analysis was to investigate the associations between degenerative changes at the various joints and bony surfaces. Initially, a basic analysis was performed to examine whether the frequencies of joint or surface involvement would vary with the presence of degenerative changes in one particular area. Thus, all cases of glenohumeral joint involvement were considered together, and the rates of involvement of the other joint surfaces in those particular cases assessed. A similar analysis was carried out for each joint and surface in turn and the results are summarised in the charts in Figure 2.3.5.

6a. Rates of degeneration at other bony surfaces in those cases with degenerative changes at the glenohumeral joint

6b. Rates of degeneration at other bony surfaces in those cases with degenerative changes at the inferior acromion

6c. Rates of degeneration at other bony surfaces in those cases with degenerative changes at the greater tuberosity

6d. Rates of degeneration at other bony surfaces in those cases with degenerative changes at the lesser tuberosity

6e. Rates of degeneration at other bony surfaces in those cases with degenerative changes at the bicipital sulcus

6f. Rates of degeneration at other bony surfaces in those cases with degenerative changes at the acromioclavicular joint

6g. Rates of degeneration at other bony surfaces in those cases with degenerative changes at the sternoclavicular joint

6h. Rates of degenerative changes at bony surfaces and joints

Fig. 2.3.5 Charts showing variation in rates of degenerative change at all surfaces with positive findings at each in turn; summary data shown in 6h. GHJ: glenohumeral fossa; IA: inferior acromion; GT: greater tuberosity; LT: lesser tuberosity; BS: bicipital sulcus; ACJ: acromioclavicular joint; SCJ: sternoclavicular joint

It can be seen from a cursory glance at the charts in Figure 2.3.5 that there was variation in the range of joint or bony surface involvement, as cases of degenerative changes in each particular area are considered in turn. On closer inspection, some patterns emerge. The rates of involvement of the acromioclavicular and sternoclavicular joints were high across the board, at between 88-100%, and not associated with any particular pattern. However, patterns emerged when other joints and surfaces were considered in turn, and appeared to indicate some association between glenohumeral, lesser tuberosity and bicipital sulcus involvement. The overall rate of degenerative change at the glenohumeral joint (29%; 23/79) rose to 55% (16/29) with positive findings at the lesser tuberosity, and 67% (8/12) with positive findings at the bicipital sulcus. The overall rate of positive findings at the lesser tuberosity was 38% (36/96), rising to 84% (16/19) in association with changes at the glenohumeral joint. With positive findings at the bicipital sulcus, the rate of lesser tuberosity involvement was 100% (13/13), *i.e.:* bicipital sulcus degeneration was only found in the presence of lesser tuberosity degenerative changes. At the bicipital sulcus, the overall rate was 14% (13/96), rising to 39% (13/33) in lesser tuberosity involvement, and 47% (8/17) in glenohumeral involvement.
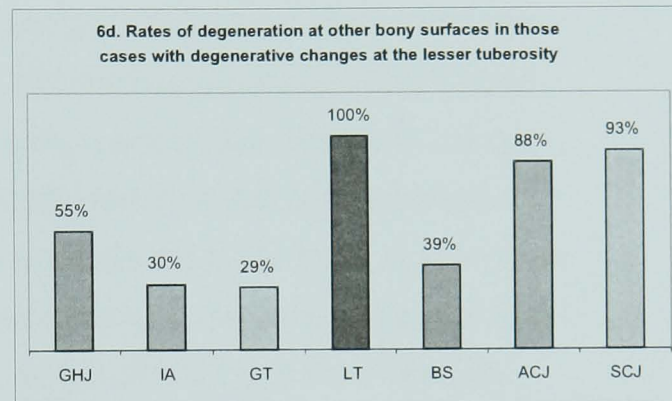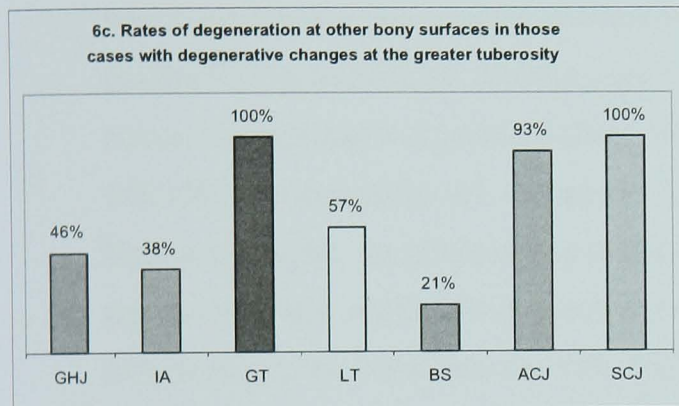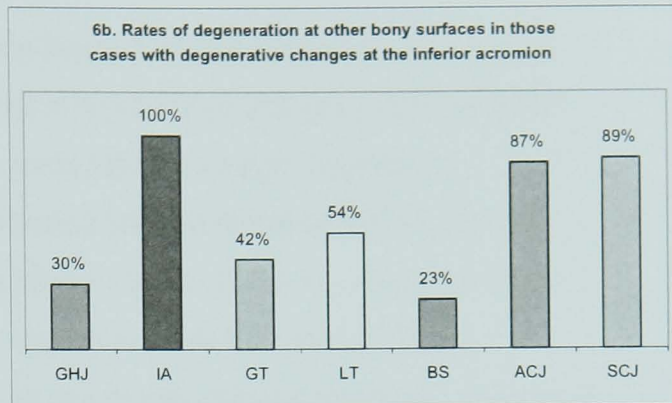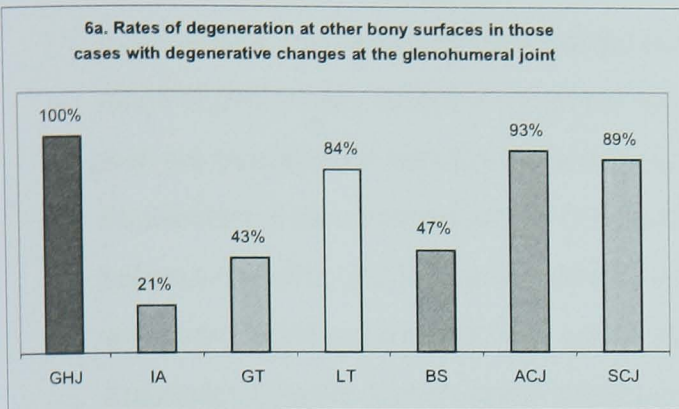
Factor analyses

Since the factor analysis required complete data on the joints and surfaces for each individual side, the sample size reduced to 45. In addition, the acromioclavicular and sternoclavicular data were removed, as these joints were so commonly affected as to obscure any other underlying patterns. The relationships between degenerative changes at the shoulder joint, inferior acromion, greater tuberosity, lesser tuberosity and bicipital sulcus were then investigated using factor analysis. As detailed in Table 2.3.3, a two-factor analysis was found to describe these five variables best; there was no loss of explanatory value compared with a three-factor solution, and in a one-factor analysis the inferior acromion and greater tuberosity were lost from the factor space. The uniqueness refers to the extent to which the variable is *not* represented by the factors. Table 2.3.3 reveals that glenohumeral joint, lesser tuberosity and bicipital sulcus formed an underlying variable, with greater tuberosity and inferior acromion being more modestly correlated but nonetheless forming a further underlying variable. In a further factor analysis excluding inferior acromion and greater tuberosity, the sample size increased to 96 and glenohumeral joint, lesser tuberosity and bicipital sulcus were still seen to be correlated and forming a single underlying variable.

	Rotated Factor Loadings		
Variable	1	2	Uniqueness
Glenohumeral joint	0.66	0.01	0.56
Inferior acromion	0.11	0.37	0.85
Greater tuberosity	0.31	0.30	0.82
Lesser tuberosity	0.77	0.13	0.39
Bicipital sulcus	0.60	0.04	0.64

Table 2.3.3 Results of factor analysis

2.4   Discussion

The results from this study concur with Miles' general observations of palaeopathological changes in the shoulder complex, confirming that changes consistent with a diagnosis of subacromial impingement syndrome may be identified in dry bones. But in addition, the results described here revealed rates and particular patterns of degenerative change in the shoulder complex, reflecting a wider range of rotator cuff pathology, including subcoracoid impingement.

2.4.1   Acromioclavicular and sternoclavicular DJD

High rates of DJD were found at the clavicular joints; 85% (58/68) of acromioclavicular joints and 85% (39/46) of sternoclavicular joints displayed degenerative bony changes at these joints. The acromioclavicular and sternoclavicular joints are recruited in every movement of the arm, and are amongst the most frequently utilised joints (Yood & Goldenberg, 1980). A high prevalence of clavicular DJD has been noted in previous osteological studies. Examinations of the Spitalfields collection and on a plague pit in London revealed the acromioclavicular joint to be amongst the principal sites of osteoarthritis, alongside spinal and hand DJD (Waldron, 1991; 1992). A separate study of the Spitalfields collection found sternoclavicular DJD to be almost ubiquitous in skeletons aged over 35 years (Miles, 1999b). The high frequency of DJD in the clavicular joints has been noted in a range of clinical and histological studies (Buttaci et al. 2004; Poncelet, 2003; Prescher 2000). It appears that enlargement of the acromioclavicular joint facet by marginal osteophyte occurs before definitive degenerative changes (Edelson, 1996; Miles, 1999b). Degeneration itself commences very early, evident even from the second decade, and then increases in frequency with age. Indeed, acromioclavicular DJD is indeed so common as to be considered a normal accompaniment of ageing by some investigators (Buttaci et al. 2004; Prescher, 2000). Sternoclavicular DJD shows a similar age-related increase; a histological study of 200 sternoclavicular joints documented a steady rise in DJD with age, from 18% of joints in the 3rd and 4th decades, to 70% in 5th, 83% in the 6th, and 94% in the 7th to 9th decades (Silberberg et al. 1959).

In this study, wherever sternoclavicular DJD was recorded, the acromioclavicular joint was always found to be affected as well, and the sternoclavicular joint was affected in 90% of cases of acromioclavicular DJD. Although there do not seem to have been any studies into an association between DJD at these two joints, the closely linked rates of DJD seen here may reflect the biomechanics of the shoulder girdle: the clavicle forms a strut connecting the scapula to the axial skeleton, and movement at one clavicular joint is accompanied by movement at the other (Soames, 1995). However, age is also likely to be a contributing factor here; both joints are more likely to be affected by DJD with increasing age. It lay without the remit of this study to investigate changes in rates of DJD with age; the principal aim of this study was to investigate the presence of patterns of degenerative changes in the shoulder complex in adult skeletal material.

Although the correspondence between DJD at the acromioclavicular and at the sternoclavicular joints could be explained through a shared, age-related increase, it is of note that the rates of degenerative changes at the other sites did not appear to be significantly affected by the presence of DJD at the clavicular joints (figure 2.3.5). Some clinical studies have suggested that acromioclavicular DJD is implicated in the pathogenesis of, RCD, biceps tendon lesions and glenohumeral DJD (Bigliani et al. 1991; Bigliani et al. 1997a; Brown et al. 2000). However, in the study by Brown et al. (2000) of 218 shoulders with acromioclavicular DJD, where he recorded co-existing rotator cuff degeneration in 81%, there was no control group. Cuomo et al. (1998) assessed 123 cadaveric shoulders for rotator cuff tears and acromioclavicular degeneration, and found a significant correlation between acromioclavicular DJD and cuff tears. However, the authors caution that this does not imply causation, as both acromioclavicular DJD and cuff tears increase in frequency with age. Pearsall et al (2003) found no association between acromioclavicular DJD and RCD.

Pathoaetiology of acromioclavicular DJD

Acromioclavicular DJD may follow traumatic injury to the joint, which is common amongst athletes, and in particular in sports involving overhead arm activity (Beim & Warner, 1997; Beim, 2000). Some sports also put the acromioclavicular joint, and clavicle, at risk from direct trauma: shoulder girdle injuries are common in mountain biking, hockey and judo (Jeys et al. 2001; Klassen et al. 1997). Whilst it is likely that some of the DJD recorded in this study may represent complications of trauma from strenuous overhead arm activity or blows to the shoulder, and other cases may be purely age-related degeneration, it is not possible to differentiate these two routes to DJD on the basis of bony changes. In addition, these 2 aetiologies probably lie at opposite

ends of a spectrum, and DJD in these skeletalised joints represents the reaction of a joint to a lifetime of activity, ranging between one or several major injuries to chronic microtrauma. This is one reason why it is extremely difficult to relate joint degeneration, especially that seen in skeletal remains, to specific occupations. This thorny issue will be further explored in Chapter 5.

Clavicular joints aside, the results for the other sites revealed surprising patterns, with implications for a wider appreciation of RCD and the interconnectedness of lesions in the shoulder system.

2.4.2 Rates and patterns of degenerative change relating to RCD

As RCD, and the specific form of subacromial impingement syndrome, is such a common modern clinical diagnosis, this may lead one to expect that bony changes in the inferior acromion and greater tuberosity may be the predominant pattern in archaeological skeletal material. In a study of modern, cadaveric skeletal material, Kerr et al (1985) reported an association between subacromial spurs and degenerative changes of the inferior acromion with greater tuberosity enthesopathy. In his investigations of archaeological acromia and humeri, Miles concentrated on these two areas, which seemed to correlate with the most common clinical pattern of RCD (Miles, 1996; 1999a; 2000).

The results of the study reported here revealed a preponderance of lesser tuberosity degenerative change, at a rate of 37% compared with 15% of greater tuberosities. This contrasts with the study undertaken by Kerr et al (1985), where enthesopathic changes around the humeral neck were found in 54 of 74 (73%) of humeri, with the greater tuberosity being most commonly affected (although precise numbers were not given). However, these results are not strictly comparable with the present study, as Kerr used the presence of osteophyte or enthesophyte only as an indicator of degenerative change; this study employed the standard palaeopathological criteria, where osteophyte alone is not sufficient as an indicator of degeneration.

In terms of patterns of lesions, the factor analysis in this study revealed that, whilst the greater tuberosity and inferior acromion changes were modestly correlated, they formed only a lesser, underlying variable. The main underlying variable in the data appeared to be an association between glenohumeral, lesser tuberosity and bicipital sulcus degenerative changes. This observation remained in the sensitivity analyses, with fewer variables in the factor analysis, but a

much larger sample size. In these factor analyses left and right sides were considered as independent data points even if they were from the same individual, and therefore the factor analyses ignore intra-individual correlations. However, this should not have influenced the findings as it is unlikely that there are substantial systemic influences on the relationships between degenerative changes at different sites.

Although much of the clinical literature on RCD focuses on the supraspinatus tendon, and its insertion on the greater tuberosity, the millennium seemed to mark a turning point. Recent publications have explored the complex nature of RCD, and the involvement of other rotator cuff muscles and stabilisers of the glenohumeral joint. Some have highlighted the secondary involvement of other rotator cuff tendons, with primary supraspinatus tendon tears may extend posteriorly into infraspinatus or anteriorly into subscapularis (Boon et al., 2004; Halder et al., 2001). Other papers have drawn attention to the presence of primary partial tears in subscapularis, caused either by internal or external (subcoracoid) impingement. Gerber & Sebesta (2000), while accepting that full-thickness tears are much less common in subscapularis tendon compared with supraspinatus tendon, asserted that partial tears of subscapularis are 'surprisingly frequent' and may be caused by internal impingement. Radas and Pieper (2004) drew attention to subcoracoid impingement of subscapularis tendon, and of LHB tendon. In an MRI study of the throwing shoulders of professional handball players, where rates of different tendon involvements were recorded, supraspinatus abnormalities, including partial tears, were found in 83% of shoulders, infraspinatus abnormalities in 60% and subscapularis abnormalities in 50% (Jost et al. 2005).

As subscapularis tendon forms part of the biceps pulley, retaining the tendon of LHB in its groove, lesions of subscapularis are often associated with subluxation and lesions of the LHB tendon, and with damage to the superior glenoid labrum, to which the LHB tendon attaches (Bencardino et al. 2000; Bey et al. 1998; Habermeyer et al. 2004). The other components of the biceps pulley, *i.e.:* the coracohumeral ligament, superior glenohumeral ligament and supraspinatus tendon, may also be involved in or implicated in the development of these lesions (Gerber & Sebesta, 2000; Habermeyer et al. 2004). Damage to the biceps pulley allows the LHB tendon to sublux medially out of the bicipital sulcus, which may cause further damage to the insertion of the subscapularis tendon (Habermeyer et al. 2004). A clinical study of LHB subluxation and dislocation showed that subluxation of the LHB (onto the medial lip of the bicipital groove) sometimes occurred in the presence of an intact biceps pulley, but that the pulley was always torn in dislocation, defined as

the situation when the tendon slips beyond the medial lip and completely out of the sulcus (Walch et al. 1998). Lesions of the LHB tendon, including complete rupture, may also be caused by subacromial impingement, as the tendon is one of the structures interposed between the head of the humerus and the coracoacromial arch (Bigliani & Levine, 1997a; Burns & Whipple, 1993; Prescher, 2000). Conversely, damage to the LHB may destabilise the glenohumeral joint, leading to subacromial impingement (Habermeyer et al. 2004).

Whilst it is recognised that RCD may lead to glenohumeral DJD, the rates of glenohumeral arthropathy associated with evidence of rotator cuff pathology in this investigation (67% of shoulders with bicipital sulcus changes; 55% of those with lesser tuberosity changes; 46% of those with greater tuberosity changes and 30% of those with inferior acromial changes) are high compared with clinical studies. Neer et al. (1983) estimated that only 4% of patients with a complete rotator cuff tear would go on to develop arthropathy. However, recent cadaver studies have suggested that the incidence of DJD associated with rotator cuff tears may be much higher: Hsu et al. (2003) found evidence of cartilage damage to the glenoid and humeral head in around a third of cadaveric shoulders with rotator cuff tears; Feeney et al. (2003) found that 100% (10 out of 10) of shoulders with rotator cuff tears also had glenohumeral articular cartilage degeneration, compared with 13/23 of shoulders without tears.

The findings of this study cannot be taken as proof of pathoaetiological progression, and cannot reveal any cause-effect relationships. However, the association between lesser tuberosity, bicipital sulcus and glenohumeral degenerative changes in this study is biomechanically explicable, and correlates with an accepted concept of progressive degeneration in the shoulder complex. At its simplest, this progression involves damage to the insertion of subscapularis tendon, represented in this study by degenerative changes at the lesser tuberosity, weakening of the biceps pulley, followed by subluxation and dislocation of the LHB tendon, represented here by degenerative changes in the bicipital sulcus itself. Damage to the subscapularis and LHB tendons destabilises the glenohumeral joint, leading to DJD (Gerber & Sebesta, 2000; Radas & Pieper, 2004; Sakurai et al. 1998). The results of this study support this pathoaetiological progression. Degenerative change at the glenohumeral joint, lesser tuberosity or bicipital sulcus was associated with a significant increase in frequency of degenerative change at the other two sites. The overall rate of degenerative change at the glenohumeral joint (29%; 23/79) rose to 55% (16/29) with positive findings at the lesser tuberosity, and 67% (8/12) with positive findings at the bicipital sulcus. The overall rate of positive findings at the lesser tuberosity was 38% (36/96),

rising to 84% (16/19) in association with changes at the glenohumeral joint. With positive findings at the bicipital sulcus, the rate of lesser tuberosity involvement was 100% (13/13); *i.e.:* bicipital sulcus degeneration was only found in the presence of lesser tuberosity degenerative changes. At the bicipital sulcus, the overall rate was 14% (13/96), rising to 39% (13/33%) in lesser tuberosity involvement, and 47% (8/17) in glenohumeral involvement.

The wider scope of RCD, beyond just subacromial impingement, as attested in the more recent clinical literature and evidenced by the bony changes documented in this study, was anticipated by Miles in his 1996 paper – the first definite mention of RCD in the palaeopathological literature. Although Miles, quite correctly at the time, concentrated on the contemporary clinical model of RCD, which was dominated by subacromial impingement and supraspinatus involvement, he did not fail to notice that the lesser tuberosity was often affected, and even noted several cases where the lesser tuberosity was 'virtually destroyed'. He wrote: 'Changes in the lesser tubercle are rarely referred to in the clinical descriptions of acromion impingement disorder; hence no further comment is possible'. This seems like an almost prescient comment in the light of the broader approach to RCD reflected in the more recent clinical literature. Miles also remarked on changes to the bicipital sulcus which he considered to be evidence of LHB tendon damage and re-attachment to the floor of the sulcus (Miles, 1996).

The discrepancies between the current study's findings and previous work on bony specimens, in particular the particularly relatively high rates of lesser tuberosity involvement, suggest that this is an area which would benefit from more study. Work on larger numbers of specimens, across a variety of ages and populations, is needed to make sense of this complex and disparate, yet related, range of pathologies.

Pathoaetiology of RCD

Clinically, RCD is the most common pathology affecting the shoulder complex (Michener et al. 2003). In its most inclusive interpretation, it represents an overlapping collection of different pathologies, involving various tissues and tendons around the shoulder, and a palimpsest of traumatic and degenerative aetiologies.

The development of subacromial impingement syndrome depends on anatomical, age-related and activity-related factors (Bigliani & Levine, 1997; Cohen & Williams, 1998; Michener et al. 2003; Tytherleigh-Strong et al. 2001). Anatomical factors relate to the boundaries of the

supraspinatus outlet. Bigliani and other researchers draw attention to the shape of the acromion, arguing that a 'hooked' acromion or acromial 'spurs' may exacerbate compression of the supraspinatus tendon (Bigliani & Levine, 1997a; Hyvonen et al. 2001; Lee et al. 2001). Other structures have also been implicated in impingement: inferiorly directed osteophyte at a degenerate ACJ (Cuomo et al. 1998; Habermeyer et al. 2004), the CAL itself (Burns & Whipple, 1993; Fremerey et al. 2000), and os acromiale (Sammarco, 2000). Less commonly, the coracoid process may impinge on the outlet anteriorly (Bigliani & Levine, 1997a; Burns & Whipple, 1993). Glenohumeral instability may allow subluxation of the head of the humerus, compressing the space from below (Jensen et al. 1999).

Age-related factors include hypovascularity of the cuff, which may lead to degenerative tendinopathy (Miller et al. 1998), whilst calcifying tendinitis may cause a non-degenerative tendon tear (Gotoh et al. 2002).

Activities likely to cause subacromial impingement include repetitive forceful movements in the overhead position, which can overload the supraspinatus tendon and this lead to the pathology typically seen in young athletes engaged in racquet or throwing sports such as baseball or handball (Bigliani et al. 1997a,b; Jost et al. 2005). The throwing position, with the arm extended, abducted and laterally rotated, may cause posterosuperior impingement (Bigliani & Levine, 1997; Schickendantz et al. 1999). Although RCD is often discussed in the context of athletes engaging in repetitive overhead activity, its effect in the more general population is not insubstantial. For instance, whilst Jost et al (2005) discovered abnormal MRI findings in 93% of the throwing shoulders of professional handball players (although only 37% were symptomatic), 80% of the dominant shoulders in a volunteer 'control group' also gave abnormal findings. Manual workers have increased prevalence of shoulder disorders, and whilst overhead use of the arm is certainly a factor, any physical exertion of the upper extremity, especially if sustained and repetitive, as well as awkward postures, may cause damage to shoulder tissues (Frost et al. 2002). Miles (1996) discusses particular activities that would be conducive to RCD, including overhead activities such as throwing, but also lifting and supporting weights on the back, and carrying loads with a pendent arm, where deltoid may pull the humeral head superiorly and cause impingement. He also mentions leaning on a stick – where the humerus would be passively forced superiorly.

Several factors may interact with each other to cause a cascade of pathological changes. For example, the throwing position in baseball can cause impingement directly, but repetitive throwing

movements may also lead to glenohumeral instability and therefore predispose to impingement; the coracoacromial arch may even change shape in the athletic throwing shoulder over time (Arroyo et al.1997; Bigliani et al. 1997b; Falla et al. 2003; Park et al. 2002). Overhead athletes are particularly susceptible to ACJ pathology, which may in turn lead to impingement (Beim & Warner, 1997). Once a rotator cuff tear has been initiated, the resulting glenohumeral instability predisposes to glenohumeral arthropathy, worsening the instability further and thus exaggerating the subacromial impingement (Jensen et al. 1999). Abduction and rotation of the arm also twists the supraspinatus tendon and this could impair perfusion, contributing to hypovascular tendon degeneration (Nakajima et al. 2004). An increased level of apoptosis has been detected in torn rotator cuff tendons compared with normal tendons; this may reflect a response to repetitive stress in the tendon, leading to degeneration and tendon tears (Murrell, 2002). Activity-related factors could be viewed as accelerators of normal age-dependent degeneration (Frost et al. 2002).

Like supraspinatus lesions, glenoid labrum and LHB tendon lesions are common in overhead athletes (Kuhn et al. 2003), but also likely to be caused by a variety of activities. Lesions of the biceps pulley may be caused by trauma, e.g.: a fall onto an outstretched hand or repetitive microtrauma, or degeneration (Walch et al. 1998; Habermeyer et al. 2004).

It is notoriously difficult to ascribe various types of DJD to particular occupations or activities. Indeed, Jurmain and Kilgore (1995) go as far as to call any attempt to make any connections between rates of osteoarthritis and specific activities 'an extremely hazardous intellectual venture.' In the case of RCD, Kerr et al (1985) note that it is difficult to ascribe the condition to a particular cause, especially when studies of living patients do not provide evidence for occupational factors. Although there is evidence that, for instance, manual workers engaged in repetitive tasks are more likely to suffer shoulder disorders, and that risk increases with force requirements, specific biomechanical risk factors have not been pinned down (Frost et al. 2005). In a dynamic system, and over a lifetime of use, it may be very difficult to distinguish between various contributing factors – especially specific activity-related factors - in terms of the resulting pathology.

This study was designed to investigate general patterns of pathology around the shoulder, rather than to make any comparison between different populations. However, within-individual comparisons could be made, and this study did not find any convincing difference in rates of DJD

between right and left shoulders or between the sexes. Miles found a higher proportion of his 12 impingement cases to be female, but noted that this could be simply reflecting the age-related nature of the condition, as the female sample contained a higher proportion of older individuals. In his studies of the Ensay and Spitalfields skeletons, Miles (1999b) did compare rates of DJD between the two populations, but only in order to make very general comparisons. He concluded that the earlier appearance of degenerative changes in the Ensay population reflected their more physically arduous lifestyle.

As always with the physical signs of pathology, it is difficult to draw inferences about the effect of these changes on individuals. Although rotator cuff tears may cause pain, and difficulty in abducting the shoulder, they may also be symptomless. Sher et al. (1995) used MR to investigate the shoulders of 96 asymptomatic individuals, and discovered that a third of these individuals actually had painless rotator cuff tears.

2.4.3 Types of bony change: 'normal' and pathological

Miles (1996) examined scapulae and humeri from 116 adults from the post-Medieval burial site on Ensay. He found evidence of bilateral subacromial impingement in 12 individuals; as these were selected specifically because they displayed changes on both the inferior acromial surfaces and on the greater tuberosity, these numbers do not represent the actual frequency of bony changes at different sites within the population. Miles also included specimens with signs restricted to proliferative changes such as osteophyte, lipping and enthesophyte. The bony changes in each specimen were carefully described, with the majority taking the form of combined destructive (e.g.: erosion, pitting) and proliferative (e.g.: new bone formation, 'nodular osteophyte', lipping and enthesophyte) changes. This concurs with the results of the study described here, where pitting and osteophyte were the most common signs of degenerative change (Figure 2.3.1). Amongst Miles' 12 cases of subacromial impingement, there were 4 examples of eburnation on the inferior acromion and on the corresponding greater tuberosity, all affecting the right side unilaterally, and one example of an area of eburnation on the greater tuberosity alone. There were 2 cases of eburnation at the glenoid margin with corresponding eburnation on the margin of the humeral head, both affecting the left side; Miles sought evidence of left-handedness in these individuals but found no convincing signs. In all these specimens that Miles selected as showing signs of subacromial impingement, there were accompanying changes

at the glenoid, lesser tuberosity and bicipital sulcus, although as noted, the recorded changes included osteophyte alone.

It can be difficult to distinguish 'normal' bony changes in a joint from pathological; Miles (1999b) discusses this in regard to osteophytic lipping around the acromioclavicular joint, where he makes a distinction between 'adaptive enlargement of the articular surfaces in response to use' and degenerative lipping, which he describes as more 'gross and nodular'. Differentiation between these normal and pathological forms of osteophyte is difficult and highly subjective; the Rogers & Waldron (1995) criteria for diagnosis of degenerative change, as used in this study, avoid this potential minefield by only admitting osteophyte as an indicator of DJD when it is accompanied by either pitting or altered bony contour. However, the clarity and standardisation that can thus be achieved in diagnosis should not colour the appreciation of osteoarthritis as a complex pathology, produced by 'normal' reactions of bone to abnormal stresses.

The bony changes recorded in this study are similar to the degenerative changes reported by Miles around the shoulder (Miles, 1996; 1999a,b; 2000), and also relate to degenerative changes seen in radiography of clinical cases of RCD (Bigliani & Levine, 1997a; Jiang et al. 2002; Pearsall et al. 2003; Umans et al. 2001). It is particularly interesting that these degenerative changes are not restricted to the subchondral bone of articular surfaces. Radiographic changes such as subchondral cysts and sclerosis are typical of osteoarthritis in subchondral bone; in subacromial impingement, similar changes have been noted at the non-articular greater tuberosity (Bigliani & Levine, 1997a; Jiang et al. 2002; Pearsall et al. 2003; Umans et al. 2001).

Miles argues that the dominant features of degeneration around the shoulder involve the rotator cuff tissues and capsule, rather than the articular cartilage and subchondral bone of the humeral head (Miles, 1996). A narrow definition of shoulder osteoarthritis, referring to degeneration at the glenohumeral joint only, ignores the complexity of the joint mechanism. However, it is useful to make the distinction when recording bony changes, and when considering mechanisms of pathoaetiology. The paucity of specific mention of RCD in the palaeopathological literature could relate either to cases being ignored when only 'glenohumeral osteoarthritis' *sensu stricto* was recorded, or to cases being recorded but hidden within 'shoulder osteoarthritis/osis' *sensu lato*.

Palaeopathologically, pitting and osteophyte, altered bony contour and eburnation of articular surfaces characterise osteoarthritis. In both this study and in Miles' studies, these same changes

have been recorded at non-articular surfaces, namely the inferior acromion, greater and lesser tuberosities, and in the bicipital sulcus (Miles, 1996; 1999a,b; 2000). In this study, pitting and osteophyte together represented the most frequent indicator of degenerative change, whilst eburnation was relatively rare (Fig. 2.3.1 & 2.3.2). Whilst there is debate in the literature over the merits of osteophyte, and pitting in particular, as indicators of degenerative change, eburnation is less controversial. Eburnation represents an unequivocal indication of degenerative change, to the point at which bony surfaces have been stripped of intervening tissues, allowing 'direct bone-to-bone frictional contact' (Miles, 1996). The reliability of these bony signs, and their relationships to soft tissue changes, will be discussed in Chapter 3.

It is of note that the bony changes recorded here are not limited to articular subchondral bone, and thus appear to represent a more general reaction of bone to compressive forces. This does not, however, rule out a pathoaetiological role for cartilage in these particular degenerative changes, as the non-articular surfaces under consideration are effectively lined with cartilage. The tendons of the rotator cuff muscles inserting into the tuberosities of the humerus possess fibrocartilaginous entheses, which is a typical characteristic of tendons inserting into or near the epiphyses of long bones. Such tendons pass through a large change in angle as the joint is moved, and it has been proposed that the specific function of the fibrocartilage at these entheses is to resist the compression and dissipate the stress generated at the hard-soft tissue interface (Benjamin & Ralphs, 1998). Histologically, fibrocartilaginous entheses involve 4 zones of tissue: dense fibrous connective tissue, uncalcified fibrocartilage, calcified fibrocartilage and bone. The histological tidemark seen between the calcified and uncalcified fibrocartilage represents the plane at which soft tissues separate from macerated bone. In the absence of degenerative changes, the macerated area presents a smooth, circumscribed area with no vascular foramina, and thus similar in appearance to the articular surfaces of normal synovial joints on dry bones (Benjamin & Ralphs, 1998); see Figure 2.3.2a.

As this study has demonstrated, concurring with Miles' (1996) observations, the appearance of these non-articular areas when subject to degenerative change is also similar to the bony surfaces of degenerate synovial joints (see Figure 2.3.2b). The bicipital groove is also lined with fibrocartilage (Benjamin & Ralphs, 1998; Prescher 2000), and this fibrocartilage disappears when the LHB tendon ruptures (Benjamin & Ralphs, 1998). Miles (1996) suggests a sequence of events in DJD of the shoulder where the first degenerative changes would occur at the fibrocartilaginous attachments of the rotator cuff muscles, where compressive forces, as the

tendons turn over the humeral head, are higher than those in the articular cartilage surfaces. In other words, the fibrocartilaginous nature of these entheses is itself an adaptation to compressive loads; when these compressive loads become extreme, they produce the bony responses described here and in Miles' work. Miles (1999) categorised changes on the undersurface of the acromion, attributing the periosteal reactions seen in younger specimens to 'pressure that develops in the subacromial tissues during normal function', whilst relating the degenerative changes predominant in older age groups to impingement, but suggests that the periosteal changes are 'but an early stage of the other'. This approach to pathology, and to degenerative changes in bone in particular – where instead of black and white, archetypal 'normal' and 'pathological' conditions, tissues are seen as reacting to largely normal or abnormal or disrupted patterns of use, will be discussed further in the synthesis of Chapter 5.

Acromial spurs

Osteophyte was recorded as present, whether alone or accompanied by other bony changes, on 25 of 84 (30%) acromia in this study. This is very close to the rate reported by Mahakkanukrauh & Surin (2003), where osteophytes were found on 200 of 692 (28.9%) skeletal acromia; the majority (174, 87%) of these were categorised as 'traction type' with the remainder classified as 'claw type'. In Miles' case study of 12 shoulders showing signs of RCD, he records the presence of raised, osteophytic plaques on the undersurface of the acromion ('subacromial facets') and comments that almost all such facets were 'associated with enthesophytes projecting from the lateral edge of the acromial tip.' He relates these enthesophytes to traction exerted on the CAL and deltoid attachments (Miles, 1996). Osteophyte around the glenoid margin and humeral margin has also been interpreted as a bony reaction to capsular traction (Kerr et al. 1985). In the current study, no distinction was made between 'traction' or 'claw' type osteophyte, or between osteophyte and enthesophyte, as these were considered to be fairly subtle variations in the same phenomenon, and that any attempt to distinguish them would necessarily involve a high level of subjectivity. However, it is clear that the response of bone to its mechanical environment is complex; in some areas, such as the tip of the acromion and the capsular attachments, traction appears to stimulate bony proliferation, whereas in others, such as the inferior acromion and humeral tuberosities, compression is the stimulus.

2.4.4　Conclusion

In conclusion, this study has added to the work of Miles and confirmed that changes consistent with a diagnosis of subacromial impingement syndrome may be indentifed in dry bones. However, the classic combination of greater tuberosity and inferior acromion degeneration was only a minor pattern in the data; the major association was that between glenohumeral, lesser tuberosity and bicipital sulcus degeneration. The latter pattern reflects a growing awareness of the multifaceted nature of RCD, including recognition that subscapularis tendon may be involved more often than had previously been suspected. The clavicular joints were commonly affected by degenerative disease, but degeneration at the acromioclavicular joint was not associated with a significant increase in degeneration at other joints and surfaces around the shoulder. Finally, it is of note that the degenerative changes seen at the non-articular but fibrocartilaginous entheses at the humeral tuberosities are similar to those seen in subchondral bone in osteoarthritis.

This study has focussed on identifying general patterns of degeneration in the shoulder complex, and has not attempted to identify how these patterns relate to specific activities or occupations, develop with age, or vary between populations,. The first issue is difficult to approach using archaeological material, where the specific identities and occupations of individuals are usually unknown, apart from the occasional serendipitous finding such as the association of coffin plates with skeletons, as at Spitalfields. However, it may be possible to differentiate between the traumatic pattern of RCD seen clinically in younger individuals, and the primary degenerative disease afflicting the elderly. The latter two concerns lie within the field of palaeopathological investigation, and could be studied using aged individuals from various populations. In biologically older skeletons, it is impossible to say whether bony changes represent injuries incurred in youth, or repetitive microtrauma producing degeneration. However, if such changes were found in younger adults, they could be ascribed to acute injury rather than chronic age-related degeneration.

This study also adds weight to Miles' interpretations of bony changes in skeletal shoulders, which emphasised the appearance of bony changes on non-articular surfaces of the shoulder, such as the inferior surface of the acromion, and on the tuberosities of the humerus (Miles 1996; 1999a,b; 2000). It is important that, when assessing skeletal material, the palaeopathologist does not limit themselves to recording only those changes on the articular surfaces themselves. The interpretation of such degenerative signs requires more study, and depends on a continuing conversation between the clinical, osteological and palaeoanthropological worlds.

3. Anatomical, osteological and radiographic appearance of arthropathy and enthesopathy in the shoulder system

'The human anatomist who presumes to ignore the field of function adopts an unenviable role. To be sure, the day is long past when anatomists can-or presume to-cover the field of physiology as well as their own, but structure and function are as intimately related as ever.'

'If attrition actually occurs in the articular cartilages, we should, to be sure, expect to find evidences of it also in other soft parts, such as bursae, articular capsules, and tendons about diarthroses.'

Arthur William Meyer
Department of Anatomy, Stanford University (1924)

3.1   Introduction

3.1.1   Diagnosis in palaeopathology

The palaeopathological diagnoses presented in Chapter 2 are based on bony changes in the shoulder complex that relate to the degenerative changes seen in radiography of clinical cases of rotator cuff disease (RCD).

It is important that palaeopathological diagnosis is linked as closely as possible to clinical diagnosis, and that general agreement on diagnostic criteria is achieved, so that data may be comparable (Miller, 1996; Roberts, 2007). Radiography provides a useful link between palaeopathological and clinical settings, although some criteria, such as joint space narrowing, will always be lost to the palaeopathologist. In the clinical setting, the diagnosis of RCD is based on a range of clinical signs and symptoms, and on the results of investigations including arthroscopy, radiography, MRI and ultrasound scans. There are many published clinical studies investigating the correlation between pathological findings in these different investigative modalities with findings at surgery or arthroscopy, aimed at providing validation for diagnostic criteria (Umans et al. 2001).

In 1935, Keyes made a study of 'senile changes' in cadaveric shoulders, at the Washington University School of Medicine. He did not make observations from dry bones, as he dissected but did not macerate the specimens. However, he nevertheless remarked on bony changes around

the shoulder, including 'surface irregularities and knobbing... [varying] from small protuberances to extensive piling up of new bone, often soft and pitted, sometimes with plateau formation and lipping'. He remarked that these changes were most often found on the greater tuberosity and were most pronounced in association with large tears in the tendon of supraspinatus, and also mentions that irregularities were seen on the surface of the lesser tuberosity in a few cases. Although most cases of bony change were associated with a tear in supraspinatus, some bony changes were noted in the absence of a tendon tear. Keyes recorded these lesions in cadaveric specimens long before they were recognised as part of the clinical syndrome that comprises RCD. The soft and hard tissue lesions he describes are now well recognised by clinicians through the use of arthroscopy, and modern imaging techniques such as MRI. Keyes noted that the lesions he observed lacked inflammatory changes, and suggested that they were the result of attrition, or degeneration, following Meyer's (1924) hypothesis.

More recent studies have involved anatomical observations on shoulder pathology in cadaveric specimens, comparisons of anatomical and radiographic findings, and comparisons of different imaging modalities with surgical findings in living patients (Bonsell et al. 2003; Panni et al. 1996; Pearsall et al. 2003; Umans et al. 2001). Studies have been made looking at archaeological bones (Miles 1996, 1999a, 2000), but no study has been made where observations on macerated bones are compared with anatomical or radiographic findings.

3.1.2 Aims

This part of the project was designed to test the palaeopathological criteria for diagnosis of RCD, by investigating the relationship between pathological changes in soft and hard tissue (at dissection) and pathological changes in dry, macerated bones.

Clinical studies often rate the diagnostic power of various modalities against findings at arthroscopy or open surgery, as the 'gold standard' (Umans et al. 2001). In the present cadaveric study, anatomical dissection was proposed to provide a similar benchmark, allowing for direct visualisation of all tissues.

3.2   Material and Methods

3.2.1   Materials

Cadaveric shoulders were dissected in the Department of Anatomy, University of Bristol. All bodies had been donated to the Department under the Anatomy Act (1984), for the purposes of teaching and morphological research. An application to dissect, macerate and radiograph 10-12 shoulders, in order to explore anatomy and pathology in the shoulder complex, was submitted and approved by the Departmental Ethics Committee. The average age across the 12 specimens was 77 years (range 62-97 years).

Specimen	DR code	side	age (years)	sex
H1	10.03	R	66	M
H2	10.03	L	66	M
H3	13.04	R	66	F
H4	13.04	L	66	F
H5	05.01	R	97	F
H6	28.03	L	91	F
H7	12.03	R	76	M
H8	12.03	L	76	M
H9	6.03	R	82	M
H10	4.02	R	85	M
H11	24.02	L	62	M
H12	3.03	L	91	F

Table 3.2.1 Details of shoulder specimens

3.2.2   Data collection

The shoulders included in the study were ex-teaching specimens and were dissected as they became available, between 2004 and 2007. Pathological findings were recorded at various stages: during dissection of the specimens, after staining of the articular cartilage with Indian ink, following maceration of the bones, and from radiographs of the macerated bones, as described below. Findings were described and scored: a four grade scoring system was devised for each method of pathological investigation (anatomical, cartilage staining, dry bone and radiographic). Although the researcher was not blind to the identity of the specimens, each investigation (anatomical dissection, cartilage staining, dry bone and radiography) was separated temporally by at least one month, and the results recorded separately before being collated for this report.

1. Anatomical dissection
Each specimen was dissected, using a standard dissection kit (forceps, disposable-blade scalpel, and scissors) in a systematic way:

- the skin and superficial fascia were removed;
- trapezius and deltoid muscles were dissected away from the clavicle and scapular spine and removed from the specimen, in order to expose the rotator cuff muscles and shoulder joint;
- the coracoacromial ligament was dissected clean of fascia;
- the coracoacromial ligament was divided and removed from the specimen to reveal the tendon of supraspinatus; any pathological changes were recorded;
- the shoulder capsule was incised, from the biceps pulley to the glenoid rim, and detached from the tuberosities; the internal surface of the shoulder capsule and the tendon of the long head of biceps were inspected;
- the shoulder capsule was removed; the humerus was detached from the specimen and the glenohumeral articular surfaces inspected;
- the clavicular joint capsules were exposed and opened; the articular discs and clavicular articular surfaces were inspected; the clavicle was detached;
- The bones were dissected clean of muscle and ligament attachments.

Pathological changes were recorded at each stage of the dissection, and graded according to the scheme below. This grading scheme was formulated to correspond with the general level of degeneration seen in the other methods, but also based on the grading of glenoid labrum lesions

as seen on arthroscopy in patients; grading of superior labrum, anterior and posterior (SLAP) lesions includes grade I, where the labrum is frayed, grade 2, where the labrum and long head of biceps tendon are detached (Bey et al. 1998). Digital photos were taken, using a Nikon D70 digital camera and ring flash.

Grade	Description
0	No appreciable signs of arthritis
1	Cartilage damage (partial thickness) and/or small marginal osteophyte (mild degenerative changes) and/or attenuation or fraying of tendons/glenoid labrum
2	Full thickness cartilage loss and/or large marginal osteophytes and/or ruptured tendons (moderate changes)
3	Joint surface destruction/bone exposed/altered bony contour

Table 3.2.1 Grading of pathological changes observed at dissection

2. Cartilage staining and grading

Meachim (1972) originated the method of staining joint surfaces with Indian ink, and it has since been used widely to reveal areas of cartilage fibrillation that are otherwise difficult to detect macroscopically (Brommer et al. 2003; Chang, Iverson et al. 1997; Kerin et al. 2003; Yoshioka et al. 1996). Indian ink particles do not stain intact cartilage, but are taken up in fibrillated, proteoglycan depleted areas (Brommer et al. 2003; Spriet et al. 2005). In a study of cartilage damage on rabbit femora, Chang, Iverson et al (1997) reported the Indian ink technique to have 80% sensitivity for fibrillation and 90.9% for ulceration (full thickness cartilage defects), and a specificity of 96.4% for fibrillation and 90.5% for ulceration.

The technique of applying the Indian ink to the joint surface was based on that described by Brommer et al (2003):

- The bones (and articular cartilage) were rehydrated in a normal (0.9%) saline solution for 2 days before staining;
- each articular surface was submerged in Indian ink for 5 minutes, using a retort stand and clamp;
- excess ink was then removed by gentle washing with saline solution;
- the bone was placed in a clamp to facilitate digital photography of the stained articular surface, and the surface was graded.

Studies of glenohumeral cartilage damage in RCD have shown no consistent pattern of cartilage loss (Umans et al. 2001): in this study, cartilage loss was scored for the joint surface as a whole. The 4-point grading system used to assess the cartilage damage at each articular surface was based on the systems used by other researchers using an Indian ink staining technique in both human and animal models (Chang, Iverson et al, 1997; Guyette et al. 2002; Koepp et al. 1999; Spriet et al. 2005).

Grade	Description
0	Normal cartilage (no staining)
1	Limited fibrillation (small focal areas of light ink uptake)
2	Widespread damage/fibrillation over articular surface (large intense patch of ink uptake)
3	Exposed subchondral bone (exposed subchondral bone)

Table 3.2.2 Grading of cartilage damage

The lesions were also recorded using a digital camera.

3. Maceration of bones and osteological assessment

The bones, with the majority of soft tissue removed by dissection, were then macerated by boiling and scrubbing. The bones were then assessed in the same way as the archaeological specimens in Chapter 2, with the same set of metric, non-metric and pathological data collected for each scapula, humerus and clavicle. (The metric and non-metric data were used as part of the human sample for the intra- and interspecific comparisons in Chapter 4). Degenerative changes were graded as per Table 3.2.3. The grades were based on Rogers' diagnostic criteria, (Rogers et al. 1987; Rogers & Waldron, 1995), and designed to correspond with the general level of degeneration indicated by equivalent grades in the other methods.

Grade	Description
0	No changes
1	Pitting or osteophyte
2	2 of pitting, osteophyte, altered bony contour
3	Eburnation (with or without other signs)

Table 3.2.3 Grading of bone changes

4. Radiography

Radiographs commonly used to assess the shoulder clinically include an anteroposterior view of the glenohumeral joint, with the humerus in 30° external rotation, a supraspinatus outlet view and an active abduction view (Bonsell et al. 2000; Guyette et al. 2002; Pearsall et al. 2003; Umans et al. 2001). Changes in the acromion and greater tuberosity may be assessed on anteroposterior radiographs (Bigliani & Levine, 1997a).

An initial set of anteroposterior radiographs were taken of each specimen, prior to dissection. However, due to the stiffness of tissues through embalming, it was difficult to achieve a similar view in all specimens, the image was often obscured by densification of soft tissues, and abduction of the humerus was not possible. Consequently, a set of radiographs were taken of the individual bones, after maceration, and these were used to assess bony changes (as they would be in palaeopathological studies of archaeological specimens). The scapula and humerus were positioned on the x-ray plate in an anteroposterior plane, and the clavicle was placed flat, in a

craniocaudal plane. The voltage and exposure was adjusted to achieve optimum resolution of bony architecture for each set of bones.

Radiographic changes associated with RCD include narrowing of the distance between the inferior surface of the acromion and the superior surface of the humeral head, osteophytes, sclerosis, subchondral cysts and osteolysis in the greater tuberosity, and sclerosis, concavity and irregularity of the inferior surface of the acromion (Pearsall et al. 2003; Umans et al. 2001). The radiographic films were viewed on a light box and pathological changes recorded, using a modified scheme based on the grading system used by Guyette et al. (2002) to assess subacromial impingement and glenohumeral DJD in living patients. Joint space narrowing could not be included as a criterion for these macerated bones.

Grade	Description
0	No appreciable signs of arthritis
1	Mild sclerosis and/or small marginal osteophyte less than 2mm on one side of joint (mild degenerative changes)
2	Large marginal osteophytes or osteophytes on more than one side or surface of the joint (superior, inferior humeral or glenoid), sclerosis and/or presence of cysts (moderate changes)
3	Evidence of joint surface destruction (altered bony contour)

Table 3.2.4 Grading of radiographic changes

3.2.3   Statistical analysis

Descriptive statistics were compiled, summarising the anatomic, osteologic and radiographic data.

Statistical analysis was carried out using Microsoft Excel and GraphPad Prism 4 for Windows (version 4.02). The mean scores across all specimens, at each joint surface, were compared graphically, and a one-way ANOVA used to test the difference between the means; Tukey's Multiple Comparison Test was then applied to discover where the differences lay.

After tests for normality of distribution within the raw scores, Spearman and Pearson tests were used to assess the correlation between pairs of scores across all anatomical sites in all specimens.

When considering the reliability of various methods in comparison with each other, a key concern is whether there is agreement on the basis of no change vs change; the scores were converted into binary: 0 (no change) or 1 (any change, *i.e.:* a score of 1-3). Paired T tests were applied to pairs of scores to determine whether there was any significant difference between the means. The binary scores were also organised into a table to illustrate correspondence between positive and negative scores for each pair of scoring methods.

A palaeopathological diagnosis of degenerative change corresponds, in this study, with bone scores of 2 or more (representing at least 2 signs out of: osteophyte, pitting or altered bony contour, or eburnation alone). The bone scores were therefore converted into palaeopathological (P) scores, and tabulated for comparison with the other methods. Finally, individual instances ('cases') of bony degenerative change at specific sites in particular specimens were described in relation to findings in the other methods.

3.3   Results

3.3.1 Descriptive results

Descriptions of observed pathological changes, together with scores for each method are
presented in Table 3.3.1. Examples of cartilage damage scores and bone scores are shown in
Figure 3.3.1, with examples of pathological changes and abnormalities observed at dissection in
photographs and lab sketches in Figures 3.3.2 to 3.3.7.

Table 3.3.1 Descriptive results and scores for each shoulder:

Specimen: H1 (R)	Pathological changes			
	Changes observed at dissection	Cartilage score	Macerated bones	Radiographic score
glenohumeral joint	No changes (0;0)	Glenoid: 0	glenoid: marginal osteophyte (1)	glenoid: 0
		humeral head: 0	humeral head: 0	humeral head: 0
inferior acromion	No changes (0)		no changes (0)	0
greater tuberosity	No changes (0)		no changes (0)	0
lesser tuberosity	No changes (0)		no changes (0)	sclerosis (1)
bicipital sulcus	No changes (0)		no changes (0)	
acromioclavicular joint	cartilage fibrillated on both surfaces (1;1)	acromial facet: 2	acromial facet: marginal osteophyte & pitting (2)	acromial facet: 0
		lateral clavicle: 1	lateral clavicle: articular osteophyte & pitting (2)	lateral clavicle: 0
sternoclavicular joint	No changes (0)	medial clavicle: 0	medial clavicle: pitting superiorly (1)	medial clavicle: 0

Specimen: H2 (L)	Pathological changes			
	Changes observed at dissection	Cartilage score	Macerated bones	Radiographic score
glenohumeral joint	Loss of depth of cartilage on LHB trajectory, near bicipital sulcus; loss of cartilage depth centrally on glenoid; labrum slightly flattened and frayed anterosuperiorly (1;1)	glenoid: 1	glenoid: slight marginal osteophyte (1)	glenoid: 0
		humeral head: 0	humeral head: 0	humeral head: 0
inferior acromion	No changes (0)		no changes (0)	0
greater tuberosity	No changes (0)		no changes (0)	0
lesser tuberosity	No changes (0)		no changes (0)	0
bicipital sulcus	No changes (0)		Marginal osteophyte (1)	
acromioclavicular joint	Fibrillated cartilage over lateral clavicle and acromion (1;1)	acromial facet: 2	acromial facet: pitting and marginal osteophyte (2)	acromial facet: 0
		lateral clavicle: 2	lateral clavicle: pitting and marginal osteophyte (2)	lateral clavicle: 0
Sternoclavicular joint	Fibrillation on medial clavicle; ragged disc adherent to clavicle (1)	medial clavicle: 2	medial clavicle: marginal osteophyte (1)	medial clavicle: 0

Specimen: H3 (R)	Pathological changes			
	Changes observed at dissection	Cartilage score	Macerated bones	Radiographic score
glenohumeral joint	area of loss of depth in cartilage anteriorly, close to margin on humeral head; LHB tendon within capsule slightly flattened and frayed at edges; slight fraying of inner margin of glenoid labrum (1;1)	glenoid: 0	glenoid: slight marginal osteophyte (1)	glenoid: 0
		humeral head: 1	humeral head: 0	humeral head: 0
inferior acromion	No changes (0)		Osteophyte, spur (1)	0
greater tuberosity	No changes (0)		Pitting and osteophyte (2)	0
lesser tuberosity	No changes (0)		Osteophyte (1)	0
bicipital sulcus	No changes (0)		Marginal osteophyte (1)	
acromioclavicular joint	Fissuring and fibrillation of cartilage on lateral clavicle and acromial facet; ragged articular disc (1;1)	acromial facet: 2	acromial facet: pitting and osteophyte (2)	acromial facet: 0
		lateral clavicle: 2	lateral clavicle: pitting and osteophyte (2)	lateral clavicle: 0
Sternoclavicular joint	(Medial clavicle damaged)	medial clavicle: -	medial clavicle: -	medial clavicle: -

Specimen: H4 (L)	Pathological changes			
	Changes observed at dissection	Cartilage score	Macerated bones	Radiographic score
glenohumeral joint	LHB tendon slightly frayed near attachment; small area of roughened cartilage near inferior margin of glenoid; thinning of cartilage on humeral head along LHB trajectory and fibrillation near posterior margin (1;1)	**glenoid:** 1 (faint speckling inferiorly)	**glenoid:** slight marginal osteophyte (1)	**glenoid:** small inferior osteophyte (1)
		humeral head: 1 (speckling over LHB trajectory & margins)	**humeral head:** 0	**humeral head:** 0
inferior acromion	No changes (0)		Flattened osteophyte (1)	0
greater tuberosity	No changes (0)		Pitting and osteophyte (2)	0
lesser tuberosity	No changes (0)		Osteophyte (1)	0
bicipital sulcus	No changes (0)		no changes (0)	
acromioclavicular joint	Fissuring and fibrillation of cartilage on lateral clavicle and acromial facet; ragged articular disc (1;1)	**acromial facet:** 2	**acromial facet:** osteophyte and pitting (2)	**acromial facet:** 0
		lateral clavicle: 2	**lateral clavicle:** osteophyte and pitting (2)	**lateral clavicle:** 0
Sternoclavicular joint	Medial clavicle damaged; ragged articular disc adherent (1)	**medial clavicle:** 2	**medial clavicle:** osteophyte (1)	**medial clavicle:** 0

Specimen: H5 (R)	Pathological changes			
	Changes observed at dissection	Cartilage score	Macerated bones	Radiographic score
glenohumeral joint	Fibrillation superiorly on humeral head, full thickness pit on LHB trajectory, loss of depth inferiorly; fine fibrillation over glenoid, moderate fibrillation near inferior margin (1;2)	glenoid: 1 (inferiorly)	glenoid: No changes (0)	glenoid: small inferior osteophyte (1)
		humeral head: 1	humeral head: No changes (0)	humeral head: 0
inferior acromion	No changes (0)		No changes (0)	0
greater tuberosity	No changes (0)		No changes (0)	0
lesser tuberosity	Irregular surface (no obvious changes in tendons) (1)		Florid osteophyte (1)	Sclerosis & lucent area (1)
bicipital sulcus	No changes (0)		Osteophyte (1)	
acromioclavicular joint	Ragged articular disc adherent to lateral clavicle; fibrillation anteriorly on acromial facet (1;1)	acromial facet: 1	acromial facet: marginal osteophyte (1)	acromial facet: osteophyte (1)
		lateral clavicle: 1	lateral clavicle: pitting and osteophyte (2)	lateral clavicle: 0
Sternoclavicular joint	Fibrillation of cartilage on medial clavicle (1)	medial clavicle: 1	medial clavicle: pitting and osteophyte (2)	medial clavicle: subchondral sclerosis & anterior lip (2)

Specimen: H6 (L)	Pathological changes			
	Changes observed at dissection	Cartilage score	Macerated bones	Radiographic score
glenohumeral joint	Fibrillation of capsule posteriorly, close to labrum; fraying of glenoid labrum posteriorly; LHB tendon adherent to capsule distally, becomes discrete again proximally, close to insertion; bare bone at anterior margin of humeral head, close to lesser tuberosity; focal area of cartilage loss on LHB trajectory; area of loss of depth of cartilage inferiorly on medial aspect and posteriorly, close to margin (1; 2).	glenoid: 2	glenoid: pit in centre; pitting on supraglenoid tubercle (1)	glenoid: 0
		humeral head: 2	humeral head: marginal osteophyte (1)	humeral head: 0
inferior acromion	No changes (0)		no changes (0)	0
greater tuberosity	Supraspinatus insertion intact; no changes (0)		no changes (0)	0
lesser tuberosity	Subscapularis insertion intact; LHB fibres inserting onto lateral surface; irregular osteophyte (1)		Irregular osteophyte and pitting (2)	Sclerosis& lucent area (1)
bicipital sulcus	LHB in sulcus, but fibres inserting into lesser tuberosity, base of bicipital sulcus (1)		no changes (0)	
acromioclavicular joint	Fibrillation and cartilage loss on acromial facet; articular cartilage of lateral clavicle fibrillated; disc ragged (1;1)	acromial facet: 2	acromial facet: osteophyte & pitting (2)	acromial facet: 0
		lateral clavicle: 2	lateral clavicle: osteophyte and pitting (2)	lateral clavicle: 0
Sternoclavicular joint	Crescentic area of cartilage loss (~30%) anteroinferiorly on medial clavicle (1)	medial clavicle: 1	Medial clavicle: Marginal osteophyte (1)	medial clavicle: small marginal osteophyte (1)

| Specimen: H7 (R)	Pathological changes			
	Changes observed at dissection	Cartilage score	Macerated bones	Radiographic score
glenohumeral joint	Biceps tendon flattened and frayed; slight fibrillation inferiorly on glenoid; anterior labrum frayed; slight loss of cartilage depth on humeral head superiorly, near LHB trajectory (1;1)	glenoid: 1	glenoid: marginal osteophyte (1)	glenoid: 0
		humeral head: 1	humeral head: slight marginal osteophyte (1)	humeral head: small marginal osteophyte superiorly (1)
inferior acromion	Spur extending into CAL (1)		Anterior osteophyte/spur (1)	Sclerosis on anterior inferior acromion (1)
greater tuberosity	No changes (0)		Osteophyte (1)	0
lesser tuberosity	Third head of biceps sending fibres to blend with capsule and biceps pulley, attaching to lesser tuberosity and medial lip of bicipital sulcus; LHB attaching to LT (1)		Moderate osteophyte (1)	Sclerosis& lucent area (1)
bicipital sulcus	No changes (0)		Osteophyte (1)	
acromioclavicular joint	Fibrillation on lateral clavicle superiorly; fibrillation on acromial facet anteriorly; disc degenerate (1;1)	acromial facet: 2	Acromial facet: pitting and osteophyte (2)	acromial facet: subchondral sclerosis (1)
		lateral clavicle: 1	lateral clavicle: osteophyte and pitting (2)	lateral clavicle: 0
Sternoclavicular joint	Fibrillation on medial clavicle (1)	medial clavicle: 1	medial clavicle: osteophyte (1)	medial clavicle: small marginal osteophyte (1)

Specimen: H8 (L)	Pathological changes			
	Changes observed at dissection	Cartilage score	Macerated bones	Radiographic score
glenohumeral joint	Biceps tendon flattened and frayed; humeral cartilage scored along LHB trajectory; fine fibrillation in inferior half of glenoid (1;1)	glenoid: 1	glenoid: slight marginal osteophyte (1)	glenoid: 0
		humeral head: 1	humeral head: slight marginal osteophyte (1)	humeral head: 0
inferior acromion	Roughened; sutures in CAL (1)		Small spur (1)	Mild sclerosis on anterior inferior acromion (1)
greater tuberosity	No obvious degenerative changes (but evidence of rotator cuff repair) (0)		Osteophyte, erosion and pitting (2)	Irregular surface, sclerotic (1)
lesser tuberosity	No changes (0)		Osteophyte (1)	Sclerosis (1)
bicipital sulcus	No changes (0)		No changes (0)	
acromioclavicular joint	Ragged disc, adherent to articular surfaces; fibrillation on cartilage (1;1)	acromial facet: 1	acromial facet: osteophyte (1)	acromial facet: osteophyte (1)
		lateral clavicle: 1	Lateral clavicle: osteophyte (1)	lateral clavicle: 0
Sternoclavicular joint	Fibrillation on medial clavicle (1)	medial clavicle: 1	medial clavicle: moderate marginal osteophyte (1)	medial clavicle: 0

Specimen: H9 (R)	Pathological changes			
	Changes observed at dissection	Cartilage score	Macerated bones	Radiographic score
glenohumeral joint	Glenoid labrum flattened and spreading onto glenoid cavity; pit in cartilage in centre of glenoid and crescential arc of fibrillation around margins in inferior half; intracapsular LHB severely frayed but still attaching to superior labrum; pit of cartilage loss near humeral margin, on new LHB trajectory; well-circumscribed area of partial loss of cartilage depth inferiorly, medially (1;1)	**glenoid: 2** **humeral head: 1**	**glenoid:** marginal osteophyte (1) **humeral head:** marginal osteophyte (1)	**glenoid: 0** **humeral head:** slight osteophyte inferiorly (1)
inferior acromion	Roughened area; split in inserting fibres of CAL (1)		Pitting and osteophyte (2)	Mild sclerosis (1)
greater tuberosity	Supraspinatus tendon attenuated/partial thickness rupture; florid osteophyte on supraspinatus facet (1)		Pitting and osteophyte (2)	Irregular surface, sclerosis (1)
lesser tuberosity	Subscapularis tendon attenuated/partial thickness rupture; fibres dragged over tuberosity by dislocated LHB; florid osteophyte at anatomical neck (2)		Osteophyte (1)	Sclerosis (1)
bicipital sulcus	LHB dislocated medial to lesser tuberosity; some frayed fibres attaching to the base of the sulcus; osteophyte close at anatomical neck(2)		Osteophyte (1)	
acromioclavicular joint	Heavily fibrillated cartilage on lateral clavicle and acromial facet; disc degenerate and attached to clavicle; articular osteophyte on clavicle (1; 2)	**acromial facet: 2**	**acromial facet:** slight marginal osteophyte (1)	**acromial facet:** marginal osteophyte, sclerosis (1)
		lateral clavicle: 2	**Lateral clavicle:** slight marginal osteophyte anteriorly & slight pitting (2)	**lateral clavicle: 0**
Sternoclavicular joint	Fibrillation on medial clavicle; disc degenerate, attached to clavicle (1)	**medial clavicle: 2**	**medial clavicle:** marginal and articular osteophyte, pitting and eburnation in anterior third (3)	**medial clavicle:** dense sclerosis and marginal osteophyte (2)

Specimen: H10 (R)	Pathological changes			
	Changes observed at dissection	Cartilage score	Macerated bones	Radiographic score
glenohumeral joint	Area of fibrillation anteroinferiorly on glenoid cavity; mild fibrillation near bicipital sulcus on humeral head (1;1)	glenoid: 2	glenoid: marginal osteophyte (1)	glenoid: marginal osteophyte (1)
		humeral head: 1	humeral head: no changes (0)	humeral head: No changes (0)
inferior acromion	No changes (0)		No changes (0)	Sclerosis (1)
greater tuberosity	No changes (0)		Slight pitting (1)	No changes (0)
lesser tuberosity	No changes (0)		Osteophyte and pitting (2)	No changes (0)
bicipital sulcus	No changes (0)		Lipping (1)	
acromioclavicular joint	Fibrillated cartilage on both surfaces; disc degenerate (1;1)	acromial facet: 2	acromial facet: Severe pitting and osteophyte (2)	acromial facet: marginal osteophyte, altered contour (2)
		lateral clavicle: 2	Lateral clavicle: pitting and osteophyte (2)	lateral clavicle: 0
Sternoclavicular joint	No changes (0)	medial clavicle: 1	medial clavicle: osteophyte (1)	medial clavicle: sclerosis (1)

Specimen: H11 (L)	Pathological changes			
	Changes observed at dissection	Cartilage score	Macerated bones	Radiographic score
glenohumeral joint	2 small (<10mm diameter) areas of mild fibrillation posteriorly and anterosuperiorly on glenoid cavity; humeral head normal (1; 0)	glenoid: 2	glenoid: marginal osteophyte (1)	glenoid: No changes (0)
		humeral head: 1	humeral head: no changes (0)	humeral head: No changes (0)
inferior acromion	No changes (0)		No changes (0)	No changes (0)
greater tuberosity	No changes (0)		Slight osteophyte (1)	No changes (0)
lesser tuberosity	No changes (0)		Osteophyte and pitting (2)	No changes (0)
bicipital sulcus	No changes (0)		No changes (0)	
acromioclavicular joint	Cartilage fibrillated and bone exposed on lateral clavicle; cartilage heavily fibrillated on acromial facet; disc degenerate (1; 3)	acromial facet: 2	acromial facet: Flattened articular osteophyte and altered contour (2)	acromial facet: No changes (0)
		lateral clavicle: 3	Lateral clavicle: Flattened articular osteophyte and altered contour (2)	lateral clavicle: No changes (0)
Sternoclavicular joint	(missing)	medial clavicle: -	medial clavicle: -	medial clavicle: -

Specimen: H12 (L)	Pathological changes			
	Changes observed at dissection	Cartilage score	Macerated bones	Radiographic score
glenohumeral joint	Capsule attenuated posterosuperiorly, with fatty tissue in deficits; capsule disintegrated superiorly: bare surface of acromion; deltoid adherent to capsule (bursa degenerated); LHB tendon badly frayed and attached to inner surface of capsule; blood clots in fibrous tissue in capsule anterior to tendon; glenoid labrum frayed; humeral head – reticular osteophyte, fibrillated cartilage and exposed subchondral bone (1;3)	glenoid: 2	glenoid: slight marginal osteophyte (1)	glenoid: No changes (0)
		humeral head: 3	humeral head: moderate marginal osteophyte (0)	humeral head: Subchondral sclerosis (1)
inferior acromion	Bursa and capsule lost; bare undersurface of acromion revealed (3)		Osteophyte at apex and area (7x5mm) of eburnation inferiorly (3)	Sclerosis (1)
greater tuberosity	Florid osteophyte; supraspinatus tendon ruptured (2)		Osteophyte on supraspinatus facet and area (5x3mm) of eburnation (3)	Sclerosis, irregular (2)
lesser tuberosity	Florid osteophyte (2)		Osteophyte (1)	Sclerosis, irregular (2)
bicipital sulcus	Osteophyte lips (1)		Osteophyte, pitting and altered contour (2)	
acromioclavicular joint	Cartilage fibrillated and florid osteophyte on lateral clavicle; cartilage heavily fibrillated on acromial facet; disc degenerate (1; 3)	acromial facet: 2	acromial facet: pitting and osteophyte (2)	acromial facet: No changes (0)
		lateral clavicle: 2	Lateral clavicle: Osteophyte and altered contour (2)	lateral clavicle: irregular contour and osteophyte (2)
Sternoclavicular joint	cartilage heavily fibrillated on medial clavicle (2)	medial clavicle: 2	medial clavicle: Marginal osteophyte (1)	medial clavicle: irregular contour and osteophyte (2)
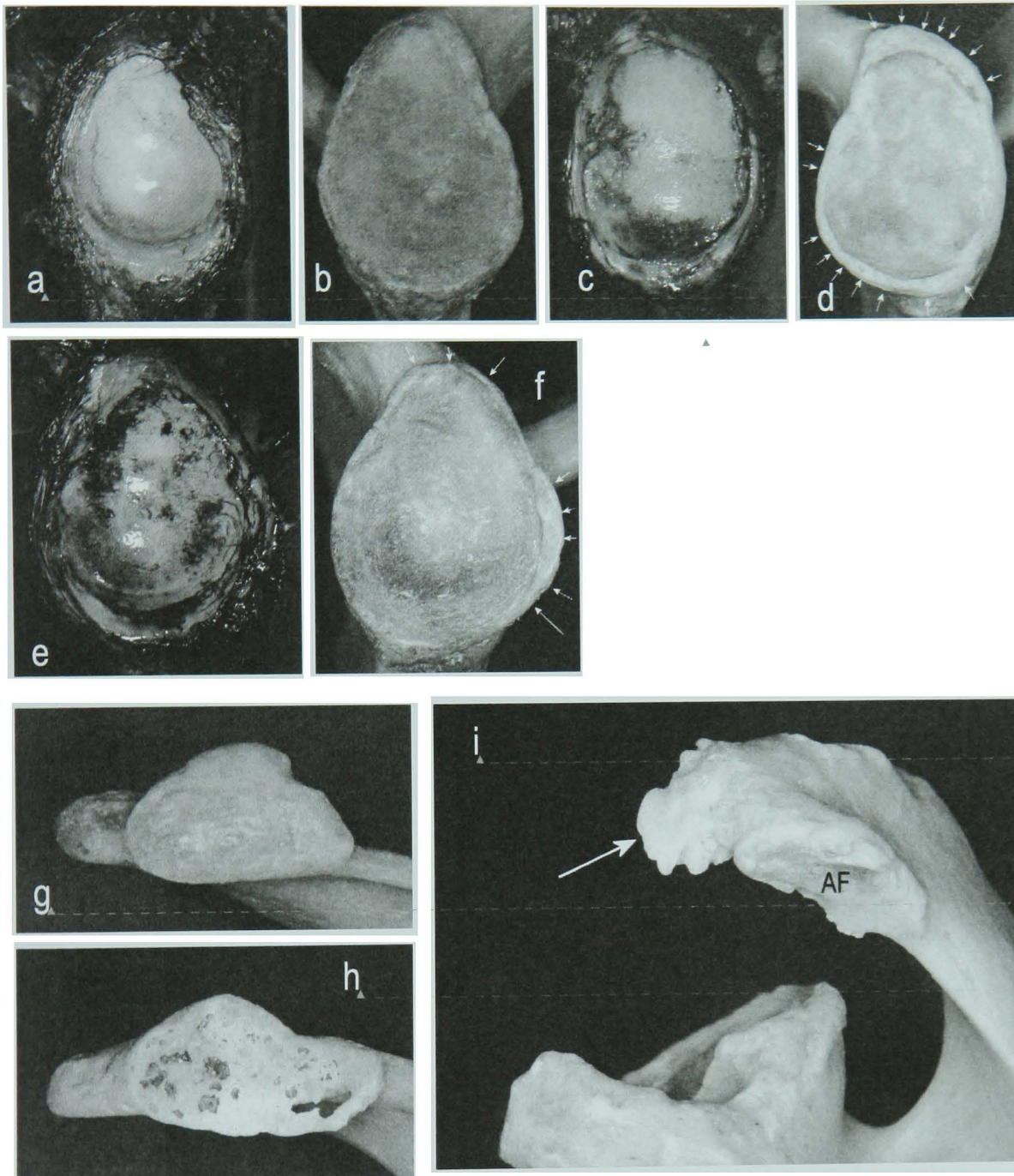
Figure 3.3.1 Examples of cartilage staining and bone scores: a. glenoid fossa of H1 with cartilage stained (cartilage score 0); b. macerated glenoid fossa of H1, bone score 0; c. glenoid fossa of H8, cartilage score 1; d. macerated glenoid fossa of H8 with marginal osteophyte arrowed, bone score 1; e. glenoid fossa of H11, cartilage score 2; f. glenoid fossa of H11 with marginal osteophyte arrowed, bone score 1; g. acromial facet of H5, with marginal osteophyte around periphery, bone score 1; h. acromial facet of H10, with pitting and marginal osteophyte, bone score 2; i. acromion of H7 with pitting and osteophyte on the acromial facet (AF), bone score 2, and osteophyte spur on anterior acromion, extending into CAL (white arrow), bone score 1.
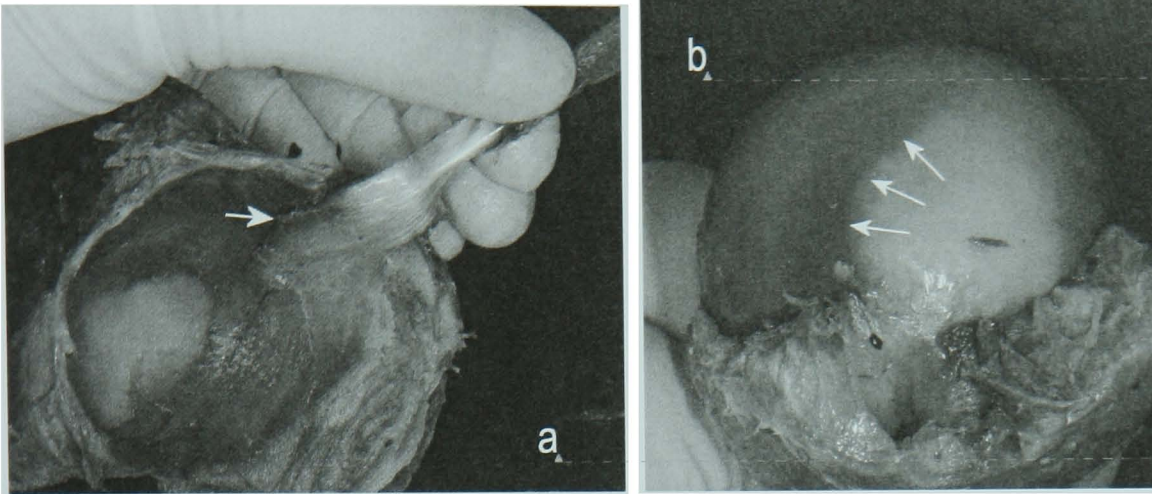
Figure 3.3.2 Shoulder H4: a. frayed LHB tendon within glenohumeral capsule (white arrow); b. cartilage loss and discolouration along the trajectory of the LHB tendon on the humeral head (white arrows).
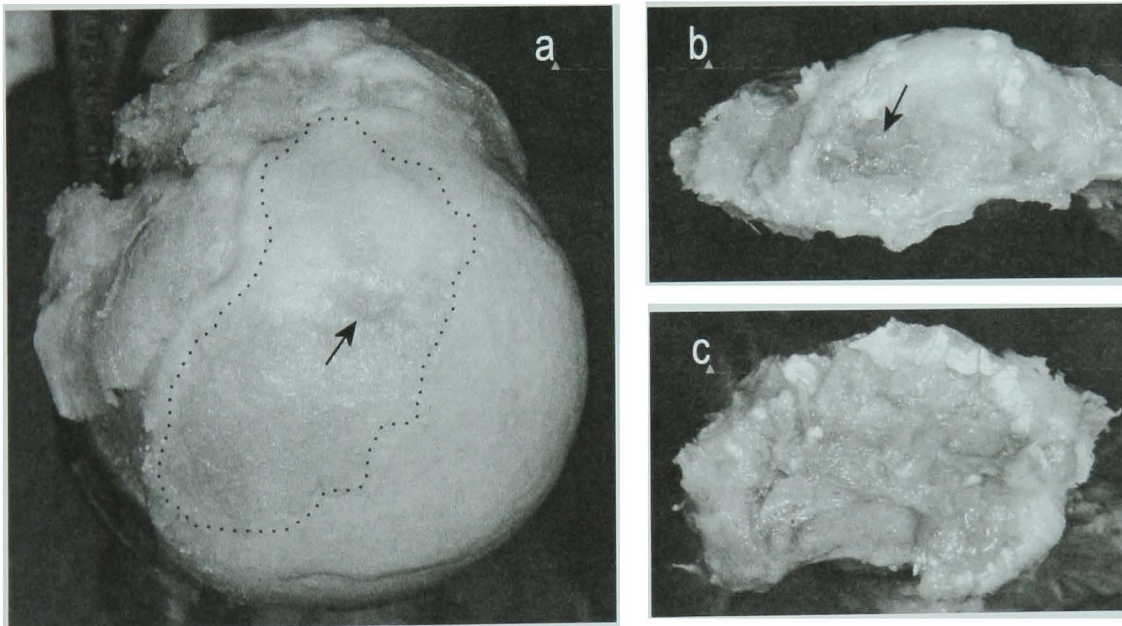

Figure 3.3.3 Shoulder H5: a. large area of fibrillated cartilage on the superolateral surface of the humeral head, unstained (area enclosed by dotted line); pit of full thickness cartilage loss on LHB trajectory (black arrow); b. fissuring and fibrillation of cartilage anteriorly on acromial facet (black arrow); c. fissuring and fibrillation of cartilage on lateral clavicle.
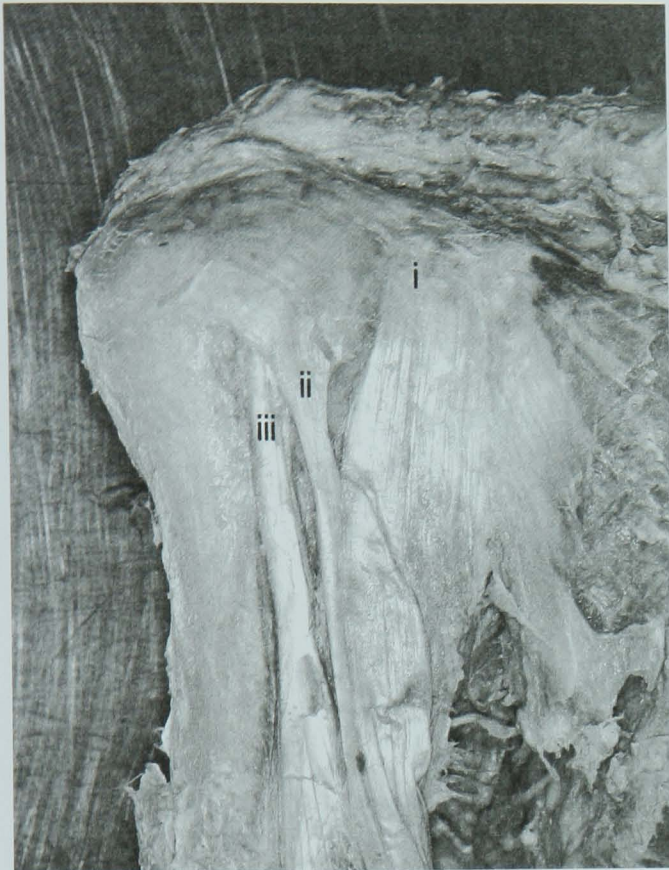
Figure 3.3.4 Shoulder H7: an abnormal tricipital biceps brachii; i. tendon of short head of biceps attaching to tip of coracoid process; ii. aberrant additional tendon attaching to lesser tuberosity and medial lip of bicipital sulcus, and sending fibres to blend with glenohumeral capsule and biceps pulley; iii. tendon of long head of biceps entering shoulder capsule.
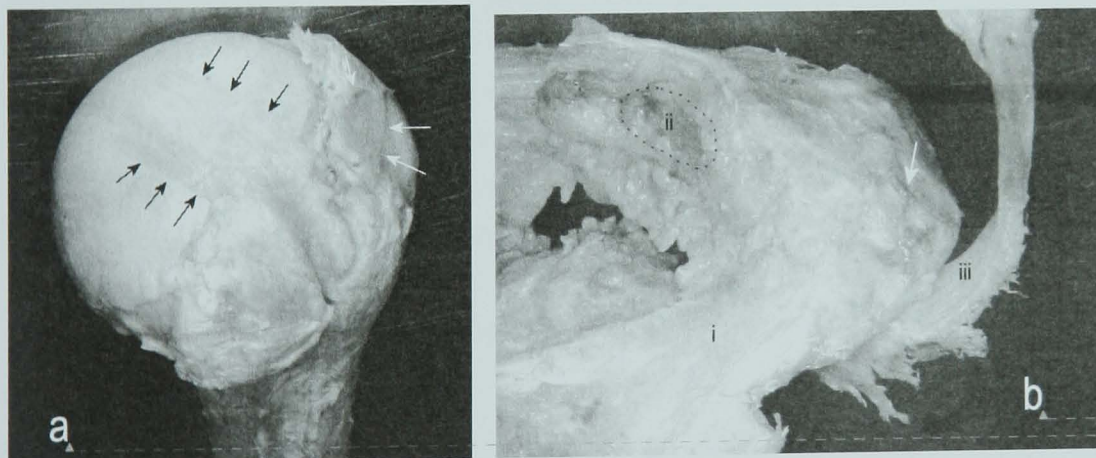

Figure 3.3.5 Shoulder H8: a. humeral articular cartilage widely scored along LHB trajectory (black arrows); sutures in the attachment of supraspinatus tendon to the greater tuberosity; b. superior aspect of acromion and coracoacromial ligament (i), showing fibrillated cartilage on acromial facet (ii), extensive fraying of the intracapsular portion of LHB tendon (iii), and sutures in the acromial attachment of the deltoid muscle (white arrow).