
# BOURNEMOUTH UNIVERSITY

## An initial evaluation of the relationship between human pelvic size and shape and the distribution, type and severity of vertebral degenerative disease in archaeological material

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**Linda Ellen O'Connell**

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# A An initial evaluation of the relationship between human pelvic size and shape and the distribution, type and severity of vertebral degenerative disease in archaeological material

**(VOLUME 1)**

**Linda Ellen O'Connell**

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# Abstract

Keywords bipedal adaptation; pelvic shape; pelvic dimensions; vertebral degenerative disease

In order to adopt an efficient bipedal posture and method of locomotion, the human skeleton has evolved a curved vertebral column and a stable, compact male pelvic girdle. Adaptive vertebral curves and the force of gravity render it susceptible to injury and degenerative change.

This study examines if there is any association between pelvic size and shape and the distribution, type and severity of vertebral degenerative disease. Four documented North-west European, middle-class skeletal samples from the eighteenth and nineteenth century were examined. Pelvic shape and size were recorded, the latter of which necessitated the measurement of 93 dimensions. The severity and distribution of osteophytes, porosity and eburnation in the vertebral column were recorded.

Statistical analysis was undertaken of relationships between pelvic measurements and the sex and age at death of individuals as well as correlations between the measurements themselves. The relationship between pelvic shape and degenerative disease was also investigated. The correlation between measurements in the pelvis and disease were examined and a mechanism was created to display this relationship.

Results demonstrated that this sample exhibited significant dimorphic differences in pelvic measurements and pelvic shape between the sexes. Significant correlations were found between age and pelvic dimensions in five (33%) sacral, 29 (94%) innominate and four (25%) reconstructed pelvis measurements. Correlations were small but positive for both sexes in the sacrum and innominate. In the reconstructed pelvis, significant correlations were again small, but positive in females and negative in males, suggesting that although a larger pelvis may be selected for in older females, the opposite is occurring with males. This supports the theory of an evolutionary effect selecting for females with larger pelves and males with more compact pelves.

Statistical analyses of the relationship between pelvic shape and the severity or presence/absence of degenerative disease were limited and not deemed to have any statistical merit.

A 'signpost' configuration was created to graphically display results of correlations between individual measurements and disease. Results suggest that osteophytosis was the most common type of disease encountered and the superior and inferior body surfaces were the main areas affected, particularly in the lower half of the thoracic and lumbar regions. All, correlations, except one, were positive, implying a positive association between those measurements and the degree of degenerative change. Patterning of the correlations was identified and discussed and statistical differences between correlations at levels of maximum and minimum curvature were examined. Results suggest that particular pelvimetry plays a significant role in this at levels of maximum and minimum curvature.

Discriminant function analysis was employed to explore the predictive ability of combinations of measurements to predispose to the development and severity of osteophytosis on the superior vertebral body surface. Contrived data was then used to test this model and was successful in predicting an expected level of expression of pathological change.

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# CHAPTER 1 INTRODUCTION

In 1966, Riesenfeld documented that of all the evolutionary changes that transpired during human vertebrate history, the locomotional form of bipedalism and the acquisition of upright posture was considered the most significant (p. 449). His reference to this event, as one of dramatic and traumatic consequence, has been reiterated by many authors since, such as Campbell (1998:97), who refers to it as a "remarkable and unique evolutionary development".

However, far from being an isolated "improvement", bipedalism constitutes one of four cardinal events that, most anthropologists now concur, shaped our evolution. The other three episodes include terrestriality, encephalization and civilization (culture) (Lewin, 1998, 1999), but there has been much debate over the precise order in which each materialized, although it is now accepted that bipedalism preceded encephalization.

The term bipedal or bipedalism basically refers to the act of standing or moving using the hindlimbs (Campbell, 1998; Dorland, 2000; Jones *et al.*, 1992; Spraycar, 1995), but has come to represent the locomotional ability exhibited by humans in the upright position. Bipedal locomotion may, at first, appear simpler than quadripedal movement, but it requires a greater neuromuscular control to master this skill and produce the smooth, functioning movement that we all take for granted. Indeed command of the integration of numerous physiological systems to sequence the events needed to accomplish efficient walking, is a combination of both learning and instinct (Rose and Gamble, 1994).

In tandem with this interplay of complex systems, adaptations have developed within the skeletal structure and these have included a metamorphosis in, among other areas, the vertebral column, thoracic cage, pelvis and femur. This change does, however, confer its own definite disadvantages which include intervertebral herniation, dislocation of the hip, tibiofemoral pathology and fallen foot arches, not to mention a whole catalogue of associated problems (Riessenfeld, 1966; Tattersall, 1998).

Nowhere are the repercussions of this biomechanical modification felt more acutely than in the vertebral column, where the habitual force of gravity stretches this structure to its functional extreme. This renders it susceptible to extreme stresses and subsequent pathological manifestations (Nathan 1962), such as osteophytosis, osteoarthrosis, intervertebral disc degeneration (Schmorl's nodes) and necrosis of bone tissue (Scheuermann's disease).

Back pain is the most common orthopaedic complaint (Collier *et al.*, 1991). In Britain alone, around 375,000 people lose some time from work each year as a result. This amounts to an astounding annual loss of about 11.5 million working days (Kumar and Clark, 1987). In 1989, Hamerman reported similar effects of osteoarthritis in North America, in terms of its "prevalence and its costs", noting that the culmination of this condition was "billions of dollars in medication, surgery, and days lost from work" (p. 1322). Indeed, in the United States alone, osteoarthritis is second only to ischaemic heart disease as a cause of work disability in men aged over 50 years (Cooper, 1994). Not surprisingly, these statistics have generated immense interest in the deduction of the mechanisms that are responsible for the development of this disease – in an attempt to better manage the condition and thus diminish the serious drain on the resources of both clinicians and employers alike.

In the literature, incomplete adaptation to bipedal posture is frequently cited as the reason for development of particular patterns of 'arthritic' change (Cook *et al.*, 1983). However, as Cook and colleagues note, any successful organism is expected to be well adapted and if this tenet holds, then the maladaptation is not truly evolutionary in origin. This, in part, is supported by the fact that joint degeneration is seen in large land animals (*ibid.*) and the frequency and distribution arises as a consequence of body size, locomotor patterns and longevity (Fox, 1939; Harris, 1977). In non-human primates, various patterns of osteoarthritic change have been reported, but none of these exhibit a predilection for a specific region of the vertebral column (Cook *et al.*, 1983). Surprisingly, most general pathological texts only highlight demographic and physiological parameters as possible aetiological factors for differences in prevalence rates of joint disease. They rarely, if at all, intimate that bipedalism is an aetiological factor. However, it is known that a compromise has been reached between efficient upright posture/bipedal locomotion and the size and shape of the female pelvis in relation to its role in parturition (Aiello and Dean, 1990; Cox, 2000; Day, 1992; Scheuer and Black, 2000). If the bipedal theory of development is extant, then it would not be unreasonable to expect a difference between the rates of degenerative disease observed in the two sexes. What is uncertain, is whether the actual size and shape of the pelvis alone bears any relation to the distribution, type and severity of degenerative disease in the vertebral column.

## 1.1 PREVIOUS RESEARCH INTO THE ANATOMICAL BASIS OF VERTEBRAL DEGENERATIVE DISEASE

The pelvis has sustained a number of mechanical adaptations in order to facilitate bipedal posture. The sacral base rotates anteriorly about its middle transverse axis located at the second sacral segment and the pubic symphysis moves anteriorly as the innominates rotate posteriorly about a functional transverse axis located through the femoral heads. This counter-rotation occurs in all persons and exaggerated rotations of the bones induced by gravity lead to mechanical strain and injury to the spinal structures. Martin Jungmann, a radiologist who began practice in Vienna in the 1920s (Oldham 1998), delineated a measurement, which is known as the pelvic index, to allow calculation of this pelvic counter-rotation assumed under gravity's influence. This index reflects the relative position of the sacrum and innominates and has been recorded as gradually increasing with age (*ibid.*). However, the aforementioned work was not published in any anthropological journal and so in the absence of details it is not clear whether this change was morphologically progressive, or whether individuals who lived longer just had bigger pelves. In other words, did possession of a larger pelvis confer advantages?

Work conducted by Amonoo-Kuofi (1992) also investigated the relationship of age to the anatomical morphology of the vertebral column and found that the degree of lumbar lordosis, sacral inclination and lumbosacral angulation exhibited a tendency to vary steadily with age and that patterns of change differed in males and females (females possessed greater angles than males). The author attributed these differences to programmed growth changes affecting the vertebrae and intervertebral discs and a possible adaptation of the female lumbar spine to prepare for support of the weight of the uterus during pregnancy. All three of the parameters investigated tended to decrease after the sixth decade. Burton *et al.* (1996) investigated the relationship between intervertebral disc degeneration in the lumbar spine and overall sagittal flexibility and concluded that a reduction in disc height was significantly associated with reduced lumbar range of mobility. However, this flexibility is known to reduce with advancing age (Burton *et al.* 1989; Battié *et al.* 1991), and so should not be considered indicative of intervertebral disc degeneration.

Towards the end of the last century, Vanharanta *et al.* (1993) and Boden *et al.* (1996) investigated the association between degenerative disc disease and facet tropism and degenerative spondylolisthesis and the orientation of facet joints in the lumbar spine. No

correlation was recorded in the former category, but evidence of a relationship in the latter was suggested. In 1995, Swanpoel *et al.* examined the extent and location of apophyseal cartilage damage in an attempt to ascertain if the extent of damage was correlated with the degree of disc degeneration, age or both. Results indicated that a weak correlation existed between apophyseal joint damage and intervertebral disc degeneration grade, but this was considered inconclusive as both increased with age.

Most recently Mangione and Sénégas (1997) considered the relationship of morphological pelvic positioning in the development of sagittal spinal diseases. They examined 57 patients aged between 17 and 85 years (mean age 43 years) and consisting of 32 males and 25 females, in order to evaluate the relationship between sagittal shape and muscular functions in seven different vertebral diseases. These conditions comprised lumbar kyphosis (degenerative and post-operative), spondylolisthesis, spondylolyses, lumbar stenosis, backache and lumbar vertebral stenosis (*ibid.*). Muscular strength of the hamstrings, *quadriceps femoris* and flexors and extensors of the vertebral column were measured, together with muscular retractions (hamstrings, *rectus femoris* and *iliopsoas*). Joint mobility was also assessed in hip extension and lumbar flexion. Radiographic evaluation of pelvic and vertebral parameters was also undertaken. These were described as the pelvic incidence, sacral curvature and pelvic backward tilt for the former, and vertebral curvature (lordotic and kyphotic), sagittal orientation and pelvi-femoral angle for the latter. The authors found a significant correlation between the pelvi-femoral angle and pelvic backward tilting and thus considered this angle as fundamental in the assessment and evaluation of sagittal posture (*ibid.*). Mangione and Sénégas (1997) concluded that it is only when the balance between hip extension and lumbar lordosis is correct, that an optimal and economic upright posture can be achieved. In lumbar kyphosis, pelvic tilt-up and hip extension develop to compensate the anterior displacement of the centre of gravity. In the case of spondylolisthesis, the anterior displacement arises secondary to sacral obliquity. These two conditions are examples of failure of the mechanisms enabling upright posture (*ibid.*).

With all of the above mentioned work, no consideration of pelvic size and shape was made or even suggested. Indeed, pelvic dimensions and their relationship with other anthropological and palaeopathological parameters have received very little interest over the past ten to twelve years. Work conducted by Cox (1989) and Cox and Scott (1992) endeavoured to evaluate the significance of certain obstetric characteristics (preauricular sulcus, dorsal pitting of the pubis and pubic tubercle) in an 18th century British skeletal sample of known parity status. Results included a positive correlation between pelvic size

and the former two from the above list - thus concluding that these characteristics tend to reflect pelvic capaciousness. Other work in the field, primarily involving pelvimetry in living individuals, has really only tended to concentrate on the effects of certain activities, such as squatting, on the pelvic dimensions (Gupta *et al.* 1991; Lilford *et al.* 1989) or on the collection of "normal" pelvic measurements from certain female racial groups (English and Alcoair, 1995).

It is generally accepted that the human's relatively unstable posture renders him/her (in comparison with the quadruped) more vulnerable to the effect of gravity. These pathophysiological manifestations, however, may be associated with pelvic size and not necessarily to age related phenomena. No research to date has been conducted in this specific area although it clearly requires academic attention in order to determine if the pelvis does indeed play a role in the development of degenerative disease in the spine. This study endeavours to redress this balance and to identify which, if any, factors are the greatest predilectional variables. It also hopes, through subsequent analysis of data, to either support or refute existing hypotheses as well as constructing new theories on the pathogenesis of degenerative disease in the spine. In order to realize these aims, a number of objectives were set and these have been detailed below.

## 1.2 AIMS AND OBJECTIVES OF THE STUDY

### 1.2.1 Aim

To evaluate the relationship between human pelvic size and shape and the distribution, type and severity of vertebral degenerative disease in archaeological material.

### 1.2.2 Objectives

A number of objectives have been identified and will incorporate the following:

- examination of the skeletal anatomy of the vertebral column and pelvis.
- consideration of the adaptations of human skeletal structure to bipedal posture and locomotion.
- discussion of pathological bases for degenerative disease in the vertebral column (including osteoarthritis and intervertebral disc disease).

- review of currently perceived relationships between anatomical structure and degenerative change in the vertebral column.
- identification and measurement of appropriate pelvic parameters.
- diagnosis and documentation of specific degenerative conditions in the spine (osteophytosis, porosity and eburnation).
- evaluation of data to identify any correlations that exist between each of the measurements obtained from the pelvis.
- analysis of data to determine if any correlation exists between measurements obtained from the pelvis and
  a) the sex of the individual.
  b) the age at death of the individual.
- creation of an appropriate mechanism to effectively display the relationship between individual pelvic measurements and specific pathological manifestations in both a comprehensible and interactive way.
- examination of data to ascertain if there is any relationship between measurements in the pelvis and
  a) distribution, site and severity of osteophytosis.
  b) distribution, site and severity of porosity.
  c) distribution and expression of eburnation.
- examination of the role of the important weight transmitting sacro-iliac joint. This would involve analysis of the relationship between various auricular surface measurements and five specific parameters: the sex and age of the individual; the size and shape of the pelvis; and the distribution of degenerative disease.

## 1.3 ORGANIZATION OF THE THESIS

This research will be documented in eight chapters. Chapter Two will examine the anatomy, sexual dimorphism and classificatory systems of the pelvis as well as briefly considering the biomechanical attributes of this structure. Chapter Three will similarly investigate the anatomy and biomechanical modelling of the vertebral column. The adaptations of the pelvis and spine to bipedal posture and locomotion will be discussed in Chapter Four. The fifth chapter will present an overview of the pathogenesis of osteophytosis, osteoarthritis and Schmorl's nodes and review the currently perceived relationships between anatomical structure and degenerative joint processes in the spine. Materials and methods are submitted in Chapter Six. The results, together with discussion, will comprise Chapter Seven and the conclusions and recommendations for further work will be tendered in Chapter Eight.

# CHAPTER 2 THE HUMAN PELVIS

The pelvis is a complex, rigid, hollow bony structure. The latin term *pelvis* literally translates as basin (Aiello and Dean, 1990; Snell, 1986) and this describes the basin-shaped morphology of the structure. This area of the human skeleton has a number of important functions:

1) To support and protect the pelvic viscera (Aiello and Dean, 1990; Palastanga *et al.*, 1994; Snell, 1986; White and Folkens, 1991.)

2) To support the abdominal organs (Aiello and Dean, 1990; Palastanga *et al.*, 1994; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991).

3) To provide a link between the trunk and lower limbs (Aiello and Dean, 1990; Gosling *et al.*, 1996).

4) To transmit weight from the vertebral column to the lower limbs (Palastanga *et al.*, 1994; Steele and Bramblett, 1988).

5) To provide an attachment site for muscles (Aiello and Dean, 1990; Gosling *et al.*, 1996; Palastanga *et al.*, 1994; Steele and Bramblett, 1988; White and Folkens, 1991).

6) To provide a bony support for the birth canal in females (Aiello and Dean, 1990; Palastanga *et al.*, 1994).

## 2.1 ANATOMY OF THE PELVIS

The bony pelvis comprises four elements: the right and left innominates, which form the anterior and lateral walls, and the sacrum and coccyx, which are positioned at the posterior limit (Gosling *et al.*, 1996; Gunn, 1996; McMinn and Hutchings, 1985; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991) (Figure 2.1). The continuous line joining the sacral promontory (posterior), the arcuate or iliopectineal lines (laterally) and the symphysis pubis (anteriorly) defines the pelvic inlet (or brim) (Bennett and Brown, 1999; Chamberlain, 1995; Cunningham *et al.*, 1997; McMinn and Hutchings, 1985; Scheuer and Black, 2000; Snell, 1986; Sweet and Tiran, 1999). Above this line lies

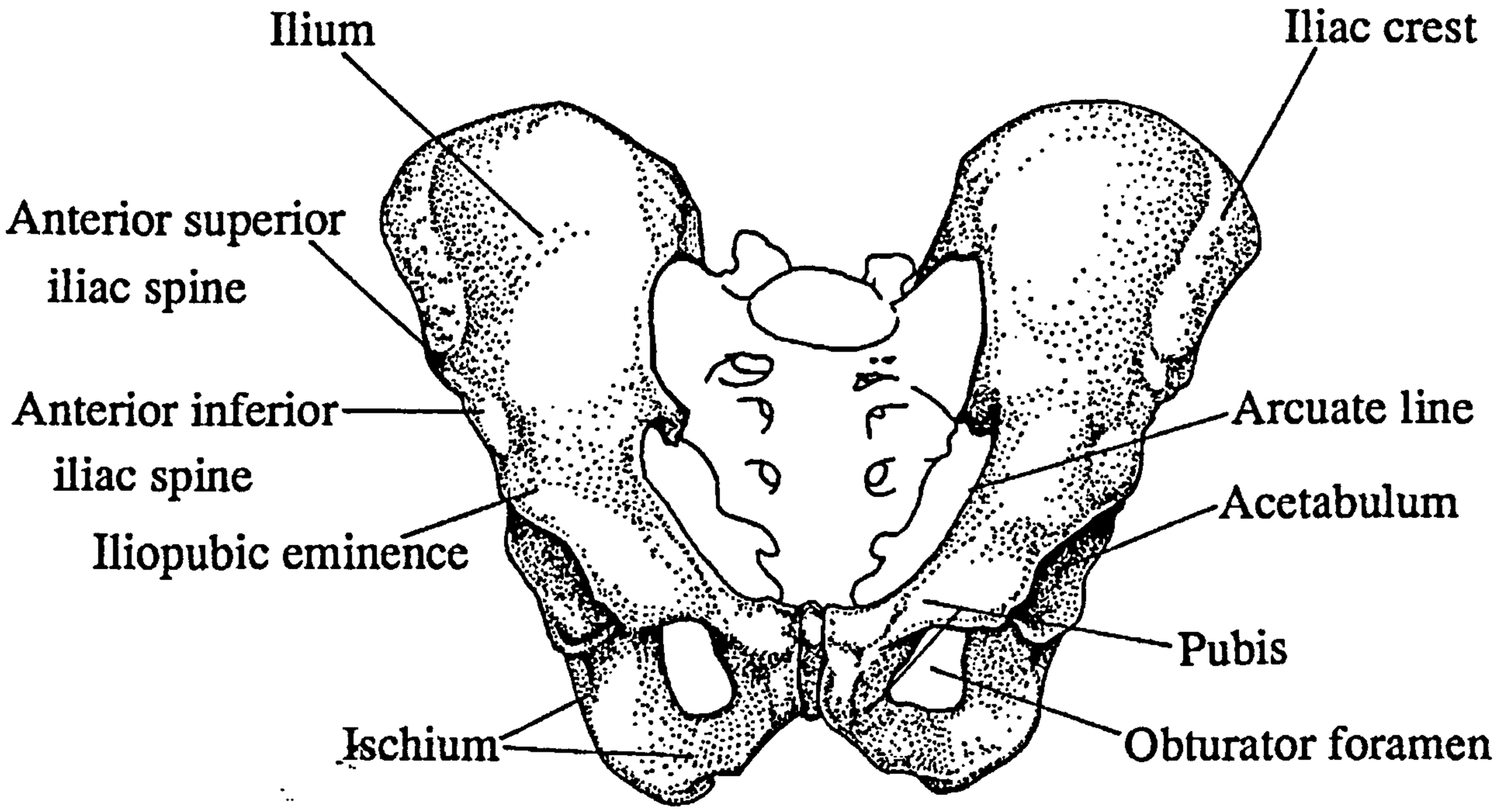



**Figure 2.1 The Human Pelvis**
**(From Schwartz, 1995: 125. Original Figure No. 5-1)**

the greater or false pelvis (which forms part of the abdominal cavity) and below it resides the lesser or true pelvis (Chamberlain, 1995; Gosling *et al.*, 1996; Gunn, 1996; Scheuer and Black, 2000; Snell, 1986; Steele and Bramblett, 1988).

The greater or false pelvis is delineated on its anterior aspect by the anterior abdominal wall, laterally by the iliac fossa and *iliacus* muscle and posteriorly by the lumbar vertebrae (Scheuer and Black, 2000; Snell, 1986). It flares at the uppermost aspect, where it accommodates part of the abdominal cavity.

The lesser or true pelvis possesses an inlet (or pelvic brim), an outlet and a cavity (Gunn, 1996; Snell, 1986) (Figure 2.2). The pelvic outlet is bounded anteriorly by the pubic arch, laterally by the ischial tuberosities and posteriorly by the coccyx (Bennett and Brown, 1999; Chamberlain, 1995; Cunningham *et al.*, 1997; Gunn, 1996; Scheuer and Black, 2000; Snell, 1986; Sweet and Tiran, 1999). This outlet comprises three wide notches: the pubic arch on the anterior aspect, and the greater sciatic notches on the postero-lateral boundary. The latter are divided by the sacrospinous and sacrotuberous ligaments (Gosling *et al.*, 1996; Snell, 1986) (Figure 2.2) into the greater and lesser sciatic foramina (Gosling *et al.*, 1996; McMinn and Hutchings, 1985; Snell, 1986).

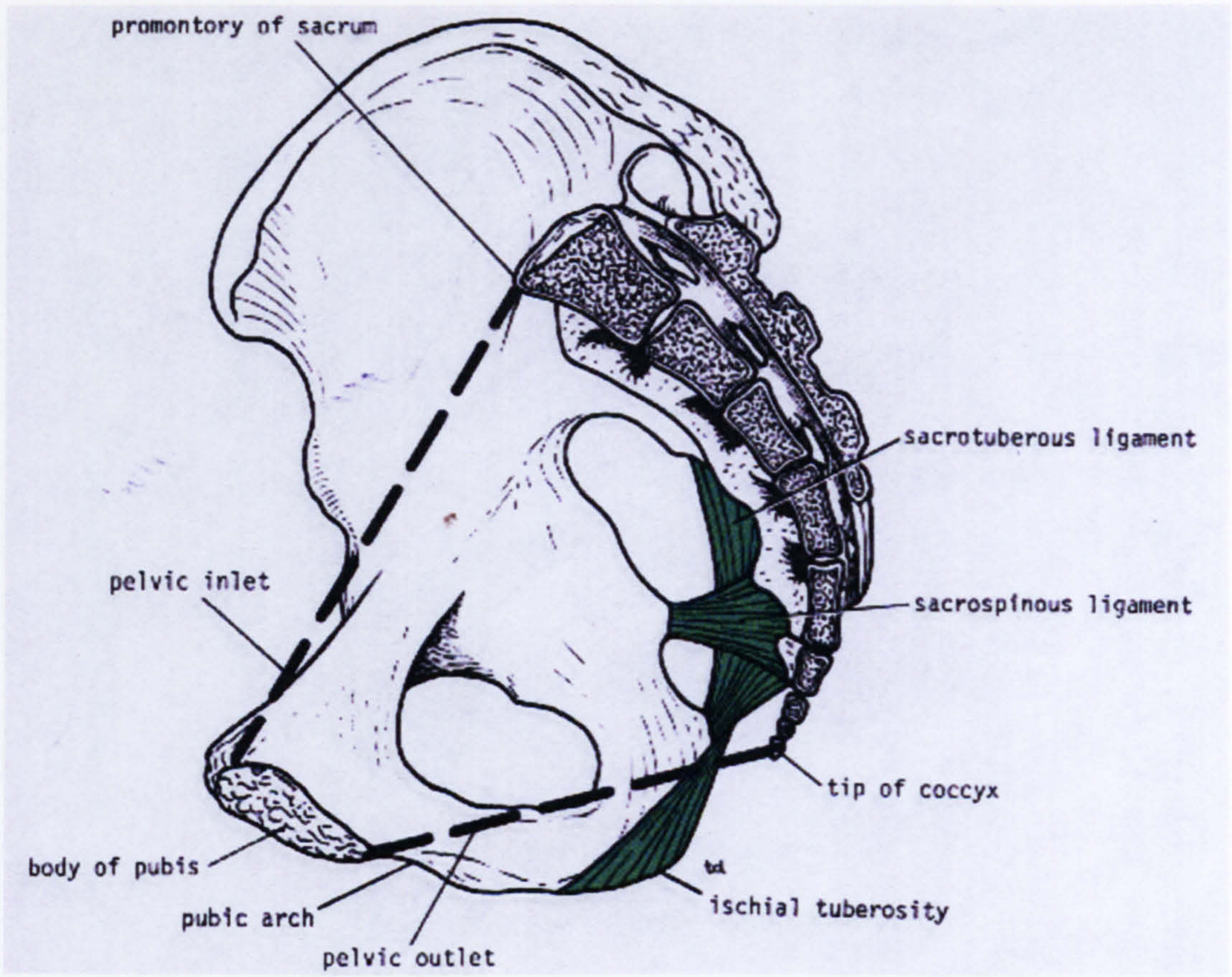
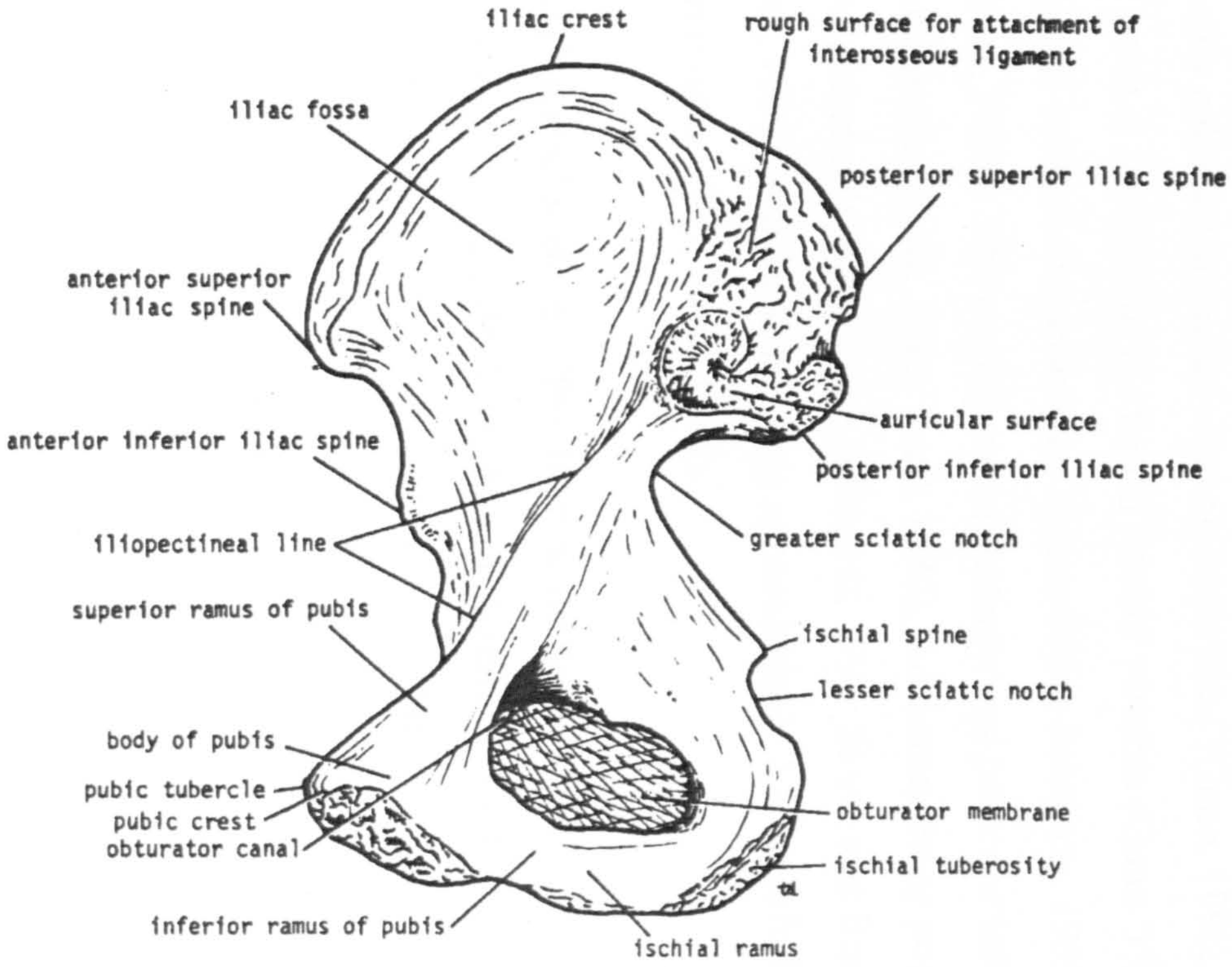



**Figure 2.2 The right half of the pelvis showing the position of the pelvic inlet, pelvic outlet and sacrospinous and sacrotuberous ligaments (From Snell, 1986: 305. Original Figure No. 6-6)**

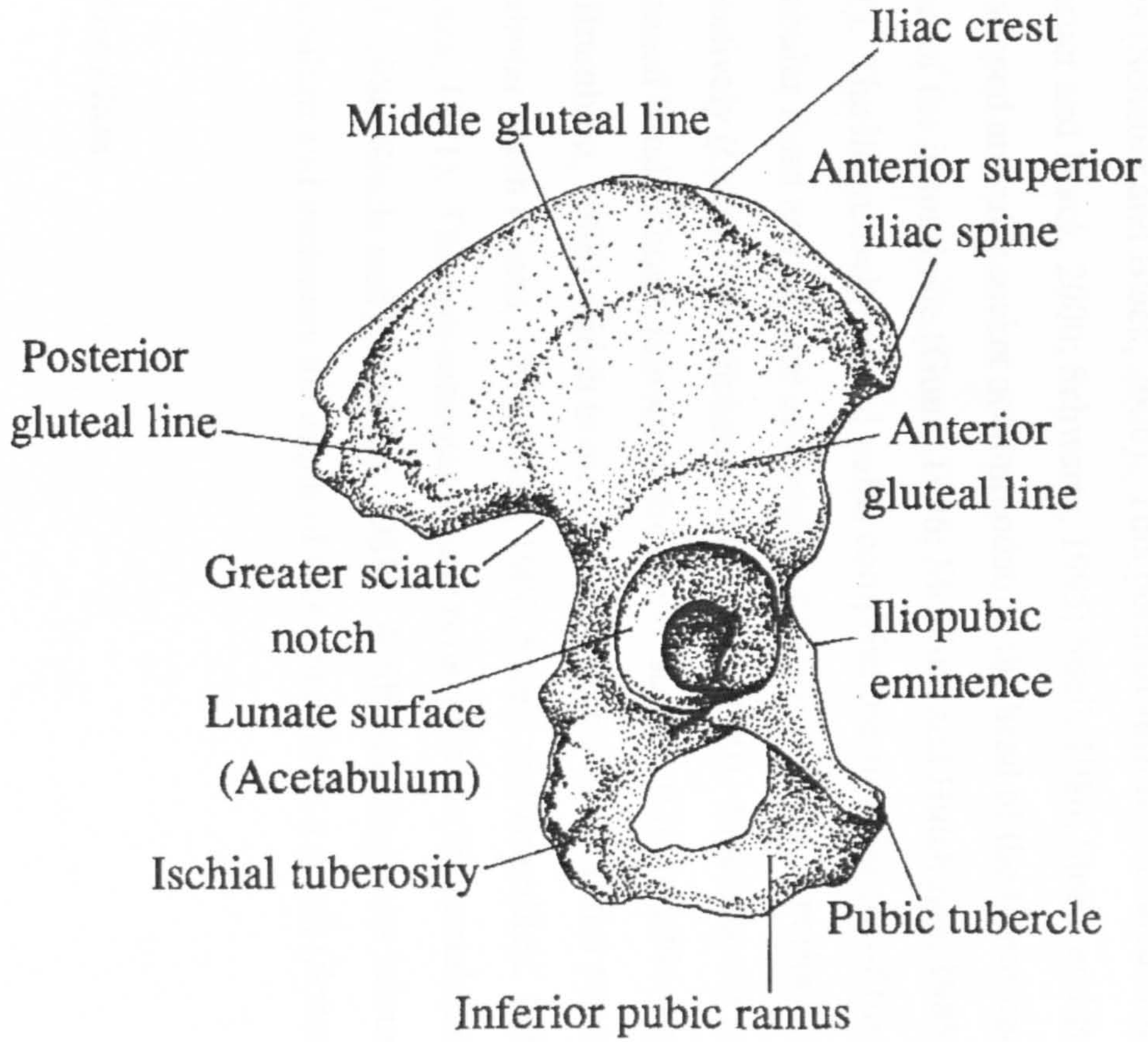
The sacrotuberous ligaments are particularly strong structures which can be considered to form part of the pelvic outlet. In this way, they render the opening diamond-shaped in appearance (Snell, 1986). The pelvic cavity lies between the pelvic inlet and outlet and during life (Bennett and Brown, 1999; Sweet and Tiran, 1999) consists of a curved canal with a shallow anterior wall and a deeper posterior one (Snell, 1986). It contains the internal reproductive organs, the urinary bladder and the most inferior part of the large intestine (rectum) (Gosling *et al.*, 1996; Scheuer and Black, 2000; Snell, 1986).

### 2.1.1 The Innominate Bone

This bone consists of three parts: the ilium, ischium and pubis (Gosling *et al.*, 1996; Gunn, 1996; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991) (Figure 2.3) which develop as separate entities *in utero*, and following initial fusion of the latter two elements, finally fuse to one component around 11-15 years in females and 14-17 years in




A




B

**Figure 2.3 The right innominate bone showing (A) the medial (visceral) surface and (B) the lateral (external) surface (Left image from Snell, 1986: 311. Original Figure No. 6-12A. Right image from Schwartz, 1995: 125. Original Figure No. 5-1)**

males (Scheuer and Black, 2000). This point of fusion is located within the acetabulum (Scheuer and Black, 2000; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988), a cup-shaped articular socket accommodating the head of the femur and lying on the lateral aspect of the innominate (Gunn, 1996; McMinn and Hutchings, 1985; White and Folkens, 1991). The ilium, ischium and pubis comprise the superior two-fifths; floor of the acetabular fossa and inferior and posterior two-fifths; and superior and anterior fifth respectively (Gunn, 1996; Scheuer and Black, 2000). In adults, the acetabulum exhibits a thickened band of bone, known as the lunate surface (Gunn, 1996; Schwartz, 1995; Steele and Bramblett, 1988), which is incomplete on the anteroinferior aspect forming the acetabular notch (Gunn, 1996; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991). The non-articular area is referred to as the acetabular fossa (Gunn, 1996; Snell, 1986; Steele and Bramblett, 1988). A fibrocartilaginous labrum attaches around the acetabulum and increases the depth of this structure as a result (Scheuer and Black, 2000).

**a) *The Ilium***

The ilium is described as a 'blade-like' structure, due to its anteroposteriorly deep morphology (Schwartz, 1995). The superior border consists of an S-shaped iliac crest, which is easily palpated in a relatively thin individual (Gunn, 1996; Snell, 1986) and forms its highest point at the level of the fourth lumbar vertebra (Gunn, 1996). It terminates in the anterior and posterior superior iliac spines (*ibid.*; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988). The corresponding anterior and posterior inferior iliac spines lie inferior to these (Schwartz, 1995; Snell, 1986), the former being positioned immediately above the acetabulum (Gunn, 1996; Schwartz, 1995; Steele and Bramblett, 1988; White and Folkens, 1991), and the latter lying approximately 2.5 cm inferior to its superior counterpart (Gunn, 1996; Snell, 1986).

The medial (internal) surface of the ilium is divided into the concave iliac fossa and the sacropelvic surface (Gunn, 1996; Steele and Bramblett, 1988). The former is continuous up to the area of articulation with the sacrum. The latter is situated between the medial and posterior borders of the ilium and is divided into three areas: the iliac tuberosity (for the attachment of ligaments), the auricular surface (for articulation with the sacrum [Snell, 1986; Steele and Bramblett, 1988]), and the pelvic surface (which forms the wall of the lesser pelvis) (Gunn, 1996).

The auricular surface lies on the posteromedial aspect (Gosling *et al.*, 1996; Steele and Bramblett, 1988; White and Folkens, 1991) and consists of two distinct components (superior and inferior), which exhibit differing appearances in respect of morphology (Schwartz, 1995). The shorter, superior aspect is orientated postero-superiorly, while the longer, inferior part faces postero-inferiorly (Scheuer and Black, 2000). The former articulates with the first sacral vertebra and the latter with the second, and occasionally third, sacral vertebrae. This forms the very strong sacro-iliac synovial joint (Figure 2.4). The posterior sacro-iliac and interosseous sacro-iliac ligaments suspend the sacrum between the two ilia (Gosling *et al.*, 1996; Snell, 1986; Steele and Bramblett, 1988) and the anterior sacro-iliac ligament, together with the iliolumbar, sacrospinous and sacrotuberous counterparts, further support this structure (Gosling *et al.*, 1996). The weight of the trunk tends to push the upper aspect of the sacrum anteriorly and inferiorly, and the lower aspect, posteriorly and superiorly. This rotatory movement, however, is resisted by the strong sacrospinous and sacrotuberous ligaments (*ibid.*; Snell, 1986).

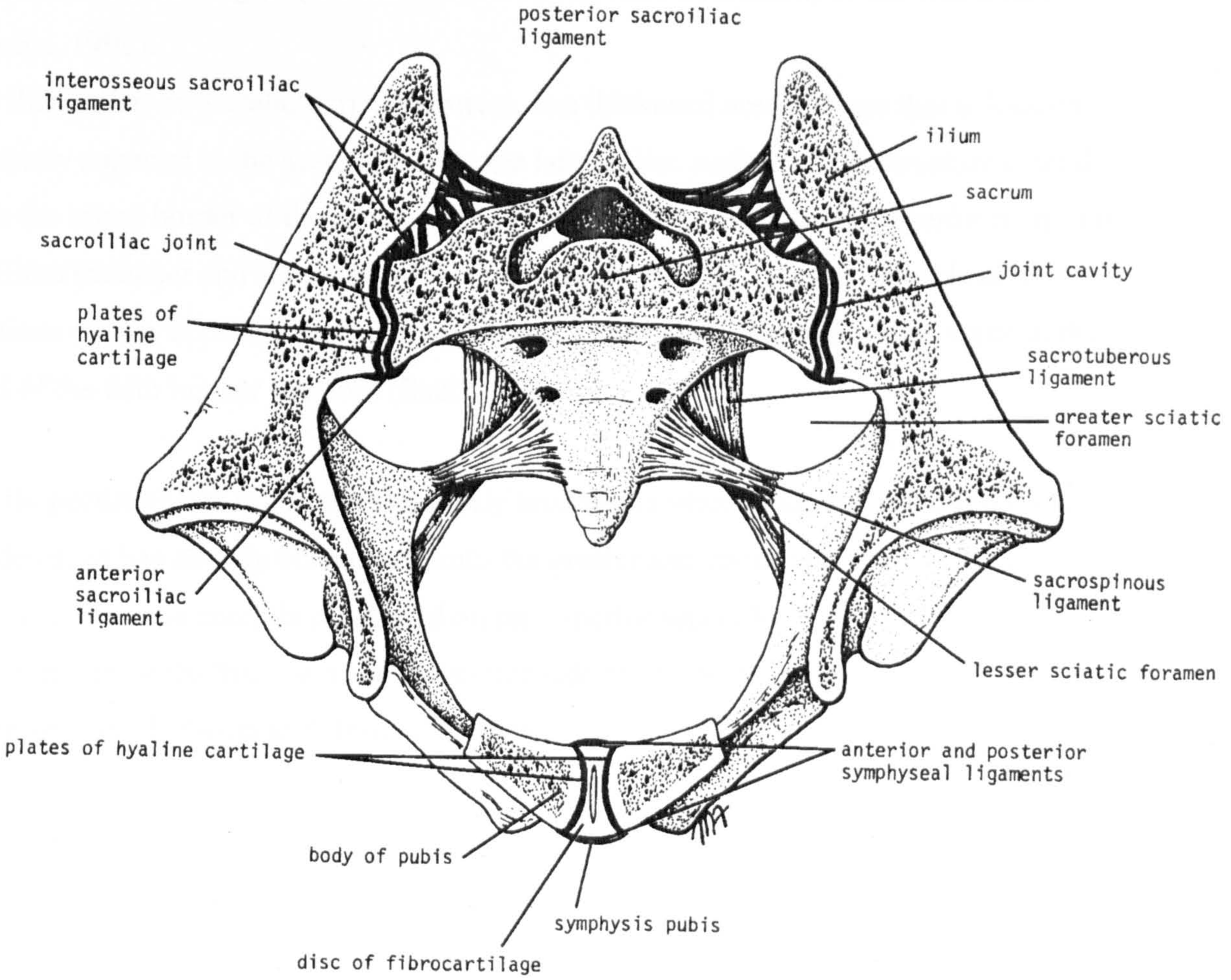



**Figure 2.4 Horizontal section through the pelvis showing the sacro-iliac joint and symphysis pubis.**
**(From Snell, 1986: 321. Original Figure No. 6-19)**

Immediately below the inferior edge of the auricular surface lies the preauricular sulcus (Schwartz, 1995; White and Folkens, 1991). In some individuals this may be absent or fairly shallow, but in others it may be deep, with a large surface area. Some authors (Houghton, 1974; Kelley, 1979; Ullrich, 1975) have documented how the morphological characteristics of this feature can be utilized to determine parity status. This suggestion, however, has now been discredited by subsequent work (Cox, 1989; Cox and Scott, 1992; MacLaughlin and Cox, 1989) which has shown that the preauricular sulcus is not an obstetric phenomenon, but rather an indicator that is positively correlated with pelvic capaciousness.

The lateral (external) surface of the ilium comprises two areas. The first consists of a small inferior region which forms part of the acetabulum (Gunn, 1996). The second consists of a larger superior gluteal surface which is transversed by three anteroposteriorly running roughened ridges. These three eminences are known as the gluteal lines (superior or posterior; middle; inferior or anterior) and demarcate the region in which the gluteal muscles take their origins (Schwartz, 1995; Steele and Bramblett, 1988; White and Folkens, 1991).

The iliac pillar, or acetabulocristal buttress, is a thickened area of bone that is located vertically superior to the acetabulum on the lateral iliac surface. This structure extends from the upper border of the acetabulum on the inferior aspect, to the superior margin of the ilium (Scheuer and Black, 2000). Here it forms the iliac (cristal) tubercle at its terminus (*ibid.*), approximately 5 cm posterior to the anterior superior iliac spine at the level of the fifth lumbar vertebra (Snell, 1986).

The iliopectineal line runs anteroinferiorly around the visceral aspect of the ilium and divides it, as has already been noted, into the greater and lesser pelves on the lateral aspect. The greater sciatic notch is subtended on the superior aspect by the inferior border of the posterior part of the ilium and on its anterior side by the posterosuperior part of the ischium (Schwartz, 1995; Steele and Bramblett, 1988).

The iliopubic eminence marks the junction of the ilium and pubis and is situated on the anterior aspect of the medial border (Gosling *et al.*, 1996; Gunn, 1996; Steele and Bramblett, 1988; White and Folkens, 1991) just below the anterior inferior iliac spine (Schwartz, 1995).

**b)** ***The Ischium***

The ischium forms the inferior and posterior part of the innominate (Gunn, 1996; Snell, 1986) and consists of a body and ramus (Scheuer and Black, 2000). The body comprises part of the acetabulum and the greater sciatic notch. The latter has the ischial spine situated at its inferior end and this structure provides attachment for the sacrospinous ligament (Gunn, 1996; Steele and Bramblett, 1988; White and Folkens, 1991). Inferior to this spine is another notch, the lesser sciatic notch (Gunn, 1996; Steele and Bramblett, 1988; White and Folkens, 1991). Inferior to the acetabulum, the ischium continues as a short ramus which terminates on its inferior-most aspect at the ischial tuberosity (Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991) - a roughened area which provides attachment for the hamstring muscles in the posterior compartment of the thigh. The smooth pelvic surface forms the lateral wall of the ischiorectal fossa (Scheuer and Black, 2000). Fusion between the ischium and pubis in the area of the rami generally occurs between five and eight years of age, although it can occur as early as three years (Scheuer and Black, 2000; Schwartz, 1995).

**c)** ***The Pubis***

This element forms the inferior and medial part of the innominate and part of the acetabulum (Gunn, 1996). It comprises a flattened, trapezoid-like body and superior and inferior rami (Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991). The body forms the anterior wall of the lesser pelvis and bears the pubic crest (Snell, 1986) and pubic tubercle (Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988) and articulates with the opposite side at the symphysis pubis (Gosling *et al.*, 1996; McMinn and Hutchings, 1985; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991) (Figure 2.4). This joint is secondary cartilaginous in nature - the articular surfaces are covered by a layer of hyaline cartilage and connected by a fibrocartilaginous disc (Gosling *et al.*, 1996; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991). The whole joint is surrounded by ligaments that extend between the opposing pubic bones (Gosling *et al.*, 1996; Snell, 1986).

The external surface of the body is roughened and forms the attachment site for muscles, while the visceral surface is comparatively smooth and slightly convex (Steele and Bramblett, 1988). The margins of the pubic body close to the symphysis pubis may appear pitted and although this has been attributed to parturitional processes (Angel, 1969; Kelley,

1979; Suchey *et al.*, 1979), they have also been identified in males and nulliparous females (Cox, 1989; Cox and Scott, 1992; Kelley, 1979; Suchey *et al.*, 1979). The most recent studies attribute this phenomenon to pelvic capaciousness (Cox, 1989; Cox and Scott, 1992; MacLaughlin and Cox, 1989).

The superior ramus of the pubis forms that part of the acetabulum which lies anterior to the anterior inferior iliac spine (Gunn, 1996; Schwartz, 1995) and the inferior ramus extends inferolaterally to join the ascending ischial ramus (Gosling *et al.*, 1996; Gunn, 1996; McMinn and Hutchings, 1985; Schwartz, 1995; Steele and Bramblett, 1988; White and Folkens, 1991).

The obturator foramen is a large opening which is bounded by the body and rami of the ischium, and the superior and inferior rami of the pubis (Steele and Bramblett, 1988; White and Folkens, 1991).

### 2.1.2 The Sacrum

The sacrum (Figure 2.5) consists usually, in the adult, of five fused vertebrae which form an anteriorly concave, wedge-shaped bone (Gosling *et al.*, 1996; Gunn, 1996; McMinn and Hutchings, 1985; Schwartz, 1995; Snell, 1986; White and Folkens, 1991). The pedicles are short and face posteriorly and laterally, and the laminae are inclined inferiorly, medially and posteriorly (Gunn, 1996). The fused pedicles and laminae enclose the sacral canal (Gosling *et al.*, 1996; Gunn, 1996; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988), which contains part of the cauda equina, filium terminale and meninges as far as the lower border of the second sacral vertebra (Scheuer and Black, 2000; Snell, 1986). This canal terminates in the sacral hiatus (Gosling *et al.*, 1996; McMinn and Hutchings, 1985; Steele and Bramblett, 1988), a structure situated on the posterior aspect of the inferior-most part of the bone and lying approximately 5 cm above the tip of the coccyx. It is subtended by the sacral cornua, structures that form the terminal aspect of the intermediate crests, created by fusion of the articular processes. The visceral surface of the sacrum extends inferiorly beyond the mouth of the hiatus, to form the sacral apex (Gosling *et al.*, 1996; Gunn, 1996; Schwartz, 1995; Steele and Bramblett, 1988).

Extensions project from the lateral aspects of the first sacral vertebra and form the large flaring lateral masses known as the alae (Centeno, 1999; Scheuer and Black, 2000; Schwartz, 1995; Steele and Bramblett, 1988).

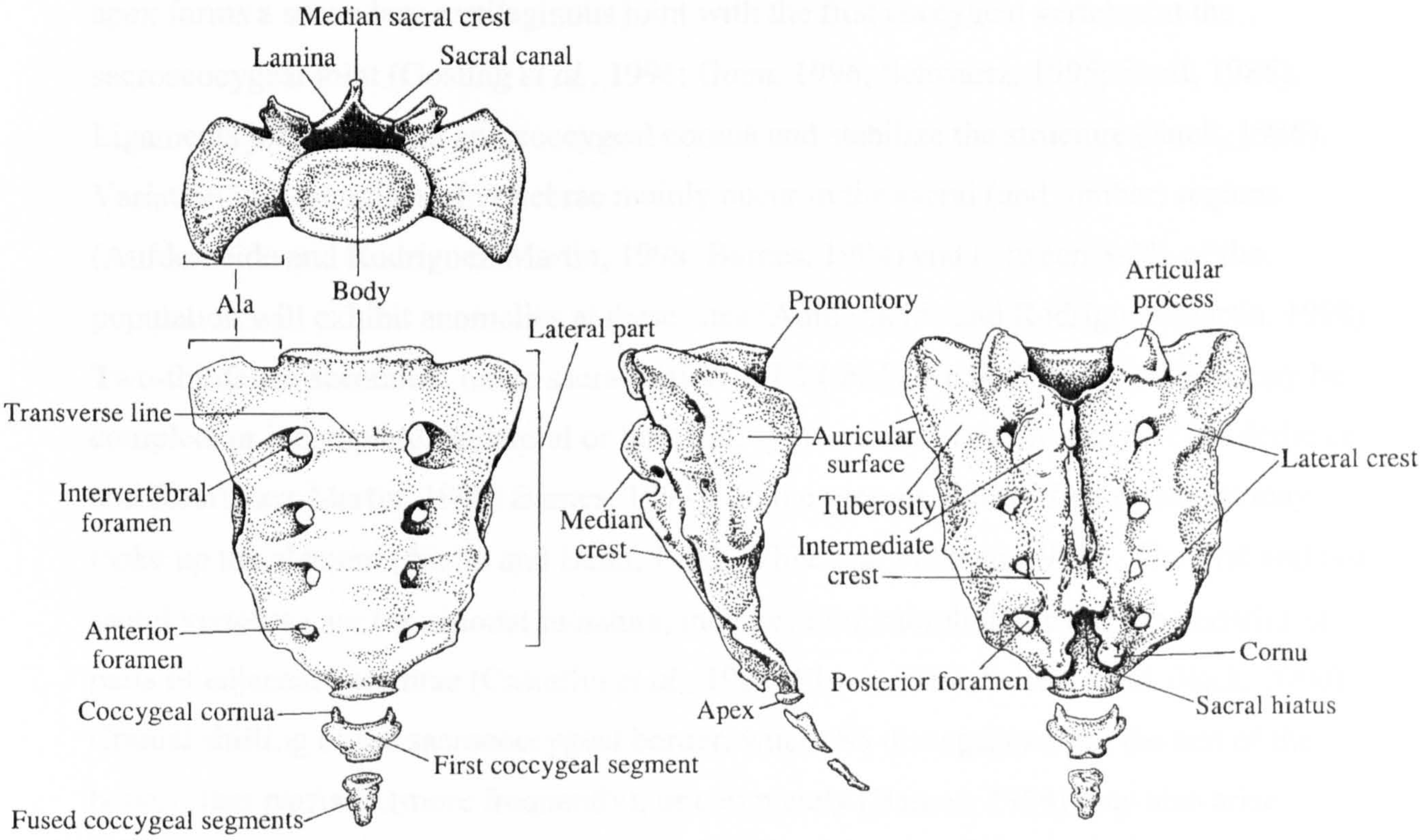



**Figure 2.5 The sacrum and coccyx in superior (*top left*), anterior (*bottom left*), right lateral (*middle*) and posterior (*right*) view (From Schwartz, 1995: 91. Original Figure No. 3-9)**

The transverse processes fuse with the costal elements to form the lateral crest (Gunn, 1996; McMinn and Hutchings, 1985; Steele and Bramblett, 1988) and the median sacral crest is generated due to the midline fusion of the spinous processes (Gunn, 1996; McMinn and Hutchings, 1985; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991) and this can be palpated subcutaneously in the uppermost part of the natal cleft between the buttocks (Snell, 1986).

There are four foramina identifiable on the anterior and posterior aspects of the bone and these transmit the anterior and posterior rami of the upper four sacral nerves (Gosling *et al.*, 1996; Gunn, 1996; Scheuer and Black, 2000; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988).

The anterior margin of the sacrum projects forward to form the sacral promontory (Gunn, 1996; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991) and the angulation formed between this and the fifth lumbar vertebra is defined as the lumbosacral angle (Snell, 1986).

Laterally, the sacrum articulates with the innominate at the sacro-iliac joint. This structure has already been discussed in consideration of the pelvic anatomy. Inferiorly, the sacral

apex forms a secondary cartilaginous joint with the first coccygeal vertebra at the sacroccocygeal joint (Gosling *et al.*, 1996; Gunn, 1996; Schwartz, 1995; Snell, 1986). Ligaments join the sacral and coccygeal cornua and stabilize the structure (Snell, 1986). Variation in the number of vertebrae mainly occur in the sacral (and lumbar) regions (Aufderheide and Rodriguez-Martin, 1998; Barnes, 1994) and between 3-5% of the population will exhibit anomalies at these sites (Aufderheide and Rodriguez-Martin, 1998). Two-thirds are accounted for as sacralization of L5 (*ibid.*). In both cases, defects may be complete or incomplete, unilateral or bilateral, symmetrical or asymmetrical (Aufderheide and Rodriguez-Martin, 1998; Barnes, 1994). In the sacrum, four or five segments may make up the element (Aiello and Dean, 1990; White and Folkens, 1991). The first and last sacral vertebrae are transitional in nature, incorporating morphological characteristics of parts of adjacent vertebrae (Castellvi *et al.*, 1984; Elster, 1989; Scheuer and Black, 2000). Cranial shifting of the sacrococcygeal border, where S5 disengages from the rest of the bone, either partially (more frequently), or completely (Barnes, 1994) may also arise. When sacralization of L5 occurs, the latter is usually completely fused with the sacrum (Aufderheide and Rodriguez-Martin, 1998; McMinn and Hutchings, 1985; Scheuer and Black, 2000) and this anomaly is found in 3-6% of the population (Centeno, 1999). Some authorities have even suggested that this normal variation confers additional height and strength to the sacrum as a consequence (Shore, 1930). Lumbarization of S1 is relatively rare (around 0.7% [Trotter and Lanier, 1945]), although females tend to exhibit a greater predilection (Aufderheide and Rodriguez-Martin, 1998). In this variant form, the first part of S1 is incompletely fused with the rest of the sacrum (Aufderheide and Rodriguez-Martin, 1998; McMinn and Hutchings, 1985) and becomes partially or completely independent of the sacral body (Barnes, 1994). Hemi-lumbarization, where S1 demonstrates lumbar characteristics on one side, but a sacral appearance on the other, may also occur. The occurrence of this, however, is unrecorded.

### 2.1.3 The Coccyx

The four (sometimes three or five [McMinn and Hutchings, 1985; Schwartz, 1995; White and Folkens, 1991]) vertebrae that constitute the coccyx (Figure 2.5) are usually fused to form a triangular-shaped bone (Gunn, 1996; McMinn and Hutchings, 1985; Schwartz, 1995; Snell, 1986). In a majority of cases, however, the first coccygeal element remains unfused or incompletely fused (Snell, 1986; Steele and Bramblett, 1988). The inferior surface of the tip of this structure may be palpated in the natal cleft, approximately 2.5 cm behind the anus, or anteriorly *per rectum* (Snell, 1986).

These rudimentary vertebrae, which demonstrate articular and transverse processes superiorly, lack pedicles, laminae and spinous processes (Steele and Bramblett, 1988; White and Folkens, 1991). The cornua of the first coccygeal segment represent the remains of the pedicles and
superior articular facets (Snell, 1986; Steele and Bramblett, 1988) and articulate with the sacrum, together with the superior aspect of the body. The coccyx, which forms an anchor for pelvic muscles and ligaments (White and Folkens, 1991), may eventually fuse to the sacrum (Schwartz, 1995; White and Folkens, 1991).

Sacrilization of the coccyx may be complete or incomplete (Aufderheide and Rodríguez-Martin, 1998; Bass, 1994) and is more commonly observed than separation of the terminal sacral segment (Aufderheide and Rodríguez-Martin, 1998).

In the correct anatomical orientation, the symphysis pubis and the anterior superior iliac spines should lie in the same vertical plane, so that the pelvic (or visceral) surface of the symphysis pubis faces posterosuperiorly and the anterior surface of the sacrum is directed anteroinferiorly (Chamberlain, 1995; Snell, 1986) (Figure 2.6).

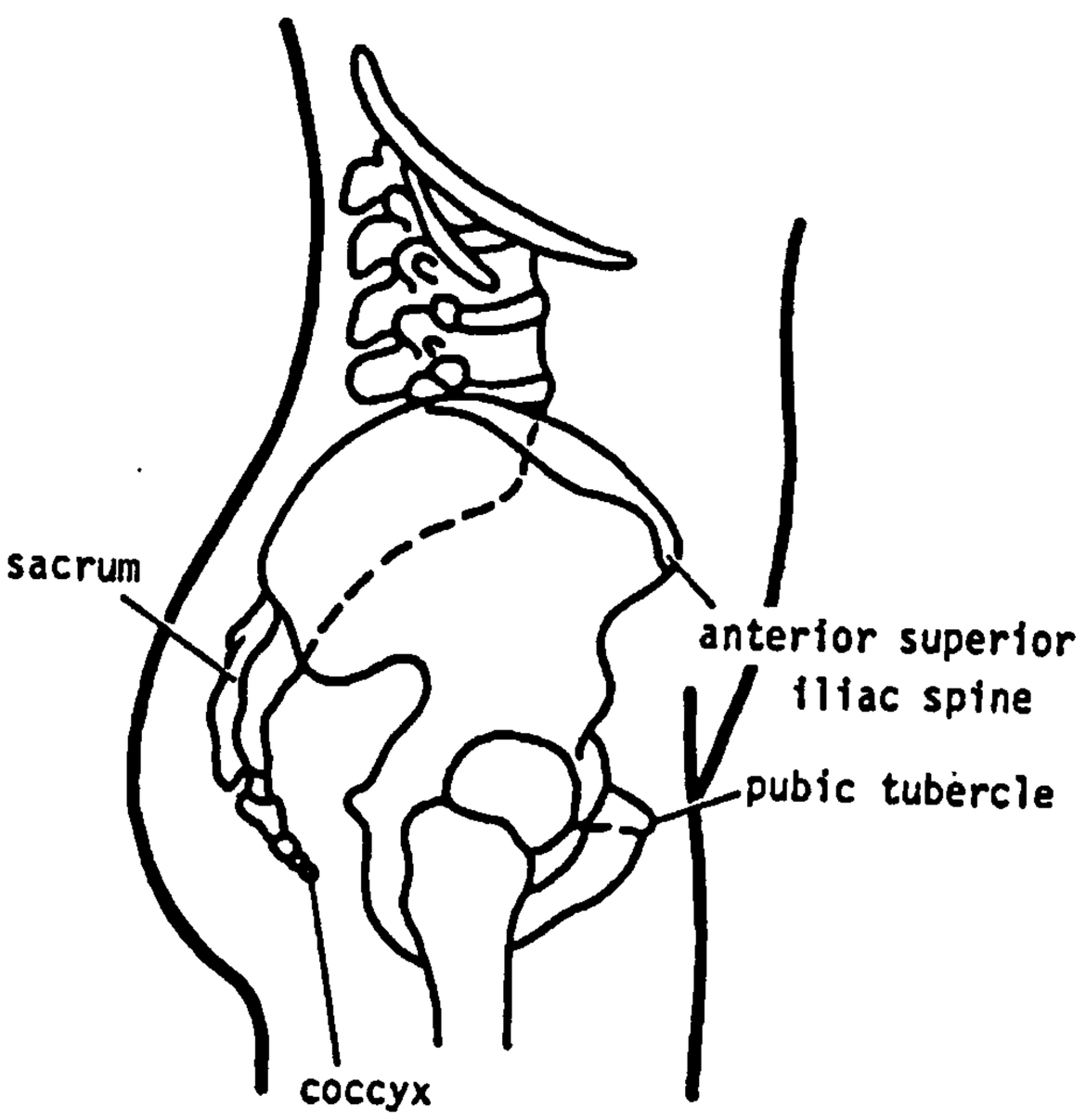



**Figure 2.6 Lateral view showing the anatomical position of the pelvis (From Snell, 1986: 302. Original Figure No. 6-3)**

## 2.2 SEXUAL DIMORPHISM IN THE PELVIS

Historically, studies of human sexual dimorphic traits have tended to categorize effectors into either genetic or environmental origins. In practice, however, these two parameters are closely entwined. The secondary sexual characteristics do not manifest themselves until puberty, even though sexual differentiation begins very early in fetal life, around the tenth week (Weaver, 1980). Despite the wealth of literature devoted to possible indicators of sexual dimorphism in the fetal and juvenile pelvis, it is widely accepted that these do not reach a sufficiently high level to allow reliable differentiation between the sexes until extensive skeletal modifications of puberty have manifested (Scheuer and Black, 2000). Hormones mediate the development of sexual differences in both soft and hard tissues. In the male fetus, levels of testosterone begin to rise around eight weeks of gestation and remain elevated until birth. After this period, they fall into decline and remain low until puberty is reached (Wilson *et al.*, 1981). At this point they become responsible for the subsequent development of physical features associated with the male. In females, however, hormonal secretion by the ovaries *in utero* is not mandatory for transition to this sex. Rather, it is the absence of male hormones which stimulate this path of development. From about 20 weeks gestation the female fetus is approximately 10% more mature than male counterparts and this persists until the attainment of full maturity (Stini, 1985). Such a difference in maturational rate is presumably influenced by a complex of factors, including diet, environment and genetics. At puberty, female hormones then elicit their effects over a fairly short period (usually less than two years) and promote pelvic growth in those areas involved in the development of the birth canal (Wood and Chamberlain, 1986). The adult pelvis has always been considered as the most sexually dimorphic part of the human skeleton (Figure 2.7) and the most reliable component to examine for sex identifiers. As early as 1948 and 1951, Stewart documented that an adult pelvis could be correctly assigned sex in 90-95% of cases, and Krogman and Isçan (1986) also maintain that the percentage accuracy afforded by examination of the pelvis alone reaches 95%.

However, it must be remembered that absolute differences seldom exist between the sexes and many intermediate forms are found as a measure of the variation in sexual dimorphism between, and within, samples and populations. Having expressed these words of caution generalizations can be made regarding these dimorphic characteristics. The criteria adopted for most forms of skeletal analysis are presented in Table 2.1. These twenty-one traits have been described by Bass (1987), Buikstra and Ubelaker (1994), Krogman and

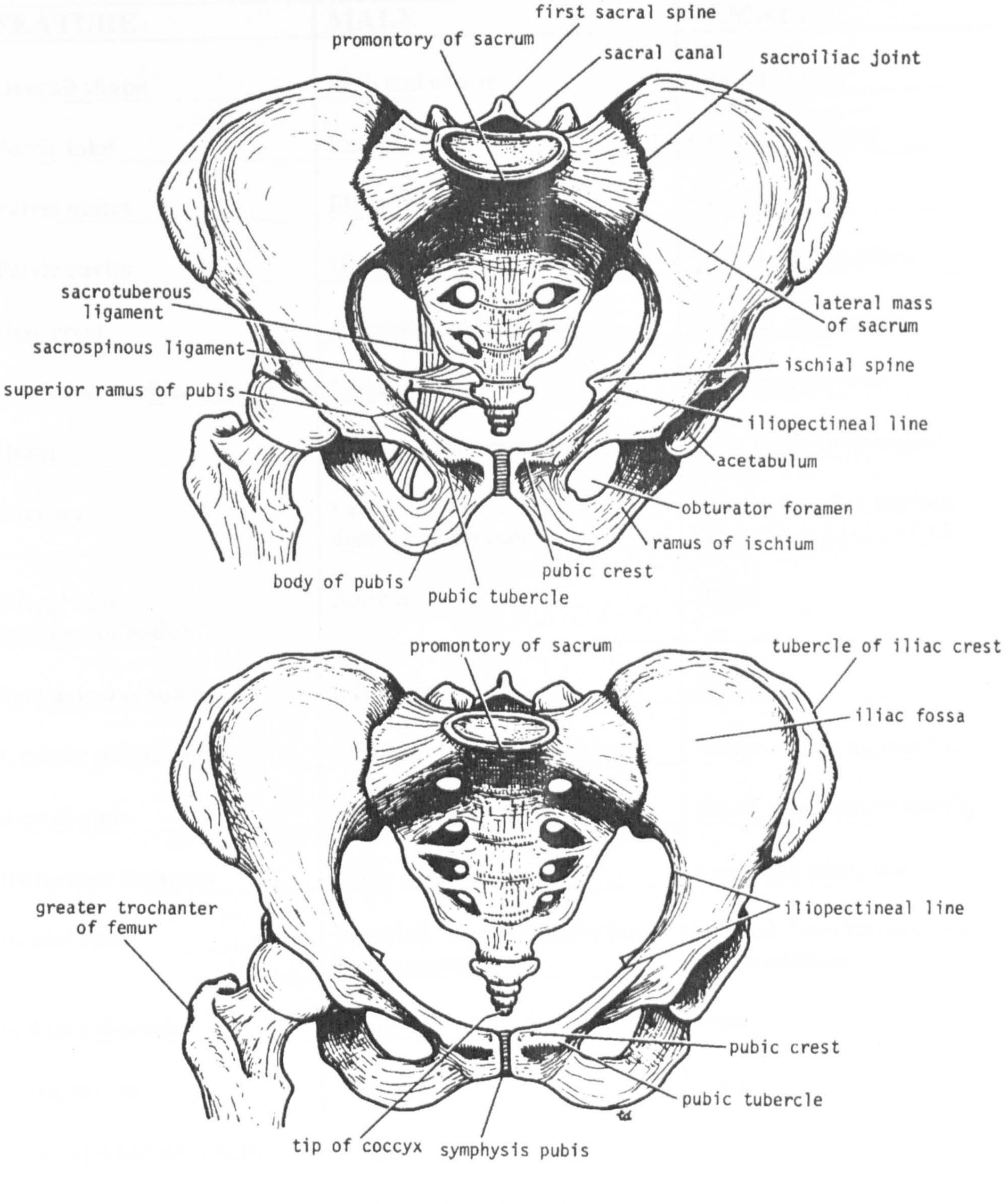



**Figure 2.7** **Anterior view of male pelvis (*above*) and female pelvis (*below*) (From Snell, 1986: 304. Original Figure No. 6-5)**

**Table 2.1 Skeletal differences between the male and female pelvis**

| FEATURE | MALE | FEMALE |
|---|---|---|
| **Overall shape** | High and narrow | Low and broad |
| **Pelvic inlet** | Heart shaped | Circular, elliptical |
| **Pelvic outlet** | Elliptical | Circular |
| **Pelvic cavity** | Deep and small | Shallow and spacious |
| **Iliac crest** | Angulated and uneven | Sinuous and smooth |
| **Auricular surface** | Large and flat | Small and elevated |
| **Ilium** | High, tends to be vertical | Low, laterally divergent |
| **Sacrum** | Larger, narrower, evenly distributed curvature | Shorter, broader, marked curvature at S1-2 and S3-5 |
| **Sacral alae (relative to body)** | Narrow | Broad |
| **Preauricular sulcus** | Infrequent | Frequent |
| **Greater sciatic notch** | Smaller, narrower, acute angle | Larger, wider, approaching 90° |
| **Acetabulum** | Large, faces laterally | Small, faces anterolaterally |
| **Obturator foramen** | Large and ovoid | Small and triangular |
| **Ischial spine** | Rounded. More intrusive into pelvic aperture | Pointed. Less intrusive into pelvic aperture |
| **Ischial tuberosity** | Large | Small |
| **Pubic ramus** | Shorter | Longer |
| **Pubic symphysis length** | Long | Short |
| **Ishiopubic ramus** | Wide, slightly everted | Narrow, strongly everted |
| **Subpubic angle** | V-shaped, narrow, sharp | U-shaped, wide, rounded |
| **Ventral arc** | Absent/rare | Usually present |
| **Subpubic concavity** | Absent/rare | Present |

Iscan (1986), Mays (1998), St. Hoyme and Iscan (1989), Schwartz (1995), Steele and Bramblett (1988), Ubelaker (1989) and White and Folkens (1991). In summary, the majority of these characteristics, which are employed to distinguish between the sexes, are features that serve to increase the capaciousness of the female birth canal. As a result, the female pelvis presents a circular pelvic inlet and outlet and a shallow pelvic cavity, thus forming an overall shape that is both low and broad. In contrast, the male pelvis retains a heart shaped inlet, elliptical outlet and a small, deep cavity that produces an overall high, but narrow, structure.

The ilium is more laterally divergent in the female and the iliac crest (forming the upper extremity of this region) tends to exhibit a more sinuous and smooth appearance, compared to the more rugged form of the male. The greater sciatic notch is more obtuse and shallower in the female and the iliac spine, situated at the inferior terminus of this structure, is more pointed and less intrusive into the pelvic aperture than in the male. The female ischial tuberosities are also smaller and less rugged and the acetabula face anterolaterally, rather than laterally as noted in the male. The preauricular sulcus (together with pubic pitting) are now considered as overall markers of pelvic capaciousness, rather that exact identifiers of male and female sex. Thus, they are found to occur more frequently in the obstetrically efficient gynaecoid pelvis while being absent from the android male counterpart. In the pubic region, the pubic ramus and pubic symphysis are longer and shorter respectively in the female. Furthermore, females also demonstrate a narrower and strongly everted ischiopubic ramus and a wide, rounded, subpubic angle. The ventral arc and subpubic concavities are also more developed in the female pelvis.

The sacrum also displays sexually dimorphic differences. In the female it is shorter and broader and the alae exhibit a greater relative width to that of the body. The male sacrum is larger, narrower, and demonstrates an evenly distributed curvature. The width of the sacral alae (relative to the body) is also much narrower.

## 2.3 CLASSIFICATION OF THE PELVIS

Classificatory systems of pelvic morphology have been defined according to architectural features observed by the naked eye, and anthropometric approaches. Anthropologists had first explored the application of pelvimetry (together with craniometry), for classification of the 'races' during the first half of the nineteenth century (Moscucci, 1990) and for the

most part had considered the European woman more superior in development, than her "primitive sister" (*ibid.*) due to the greater capaciousness of her pelvis. These studies have subsequently expanded to include the elucidation of certain demographic parameters, such as racial affinity (Turner, 1886), sex (Brinckmann *et al.*, 1981a; Flander, 1978; Pellico and Camacho, 1992; Tague, 1989) and age (Hulth *et al.*, 1995). Some authors have even commented on the benefits conferred by this area of study to the field of obstetrics.

A diverse range of methods have been employed to metrically assess the human pelvis. Both living subjects and skeletal remains (Iscan and Cotton, 1985; Sibley *et al.*, 1992; Tague, 1989) have each constituted the materials utilized in this research, and radiographic techniques were commonly employed (as evidenced by the extensive articles that exist) in studies that were undertaken at a time when the potential hazards of diagnostic radiography had not been fully appreciated (Caldwell *et al.*, 1939; Greulich and Thoms, 1938; Greulich *et al.*, 1939; Hanson and Calif, 1938; Heyns, 1947; Moloy, 1933; Reynolds and Hooton, 1936; Thoms and Greulich, 1940; Weitzner, 1935; Young and Ince, 1940).
The following section discusses these applications and the role that they have played in formulating a classificatory system for the human pelvis.

### 2.3.1 Anthropometric approaches to pelvic classification

Of all the approaches employed to calibrate the pelvic form, it would appear that the dimension that has received the most scrutiny is that of the pelvic inlet. Greulich and Thoms (1938) noted that, in 1762, William Smellie had described the female human pelvis and this specific dimension in his treatise on the theory and practice of midwifery. They further observed that 27 years later, in 1789, Baudelocque followed with his own discussion of the pelvic inlet. Numerous obstetrical works that were published in the following century gave similar reports on the dimensions of this parameter and are presented in Table 2.2. Unfortunately no sample sizes were reported for these studies.
At the same time, researchers were also attempting to classify pelvic shape according to this and other measurements. Both Caldwell and Moloy (1933) and Turner (1886) referred to Weber's work conducted in 1830 on female skeletal pelves, in which the latter had described four forms:

a) Oval, where the pelvic inlet was a transverse ovoid and the transverse diameter of the inlet exceeded the conjugate.

b) Round, where the pelvic inlet was circular in appearance and the transverse and conjugate diameters were equal.

c) Four-sided, where the anterior and posterior limits of the inlet were flattened and conferred a quadrangular configuration and where the transverse diameter was in excess of the conjugate.

d) Wedge-shaped, where the inlet was laterally compressed and cuneiform, with the transverse diameter being less than the conjugate.

**Table 2.2 Dimensions of the female pelvic inlet (determined on cadavers or dried pelves) according to twelve authors (Adapted from Table 1 and text descriptions in Greulich and Thoms, 1938: 46)**

| AUTHOR | DATE | ANTERO-POSTERIOR DIAMETER | TRANSVERSE DIAMETER |
|---|---|---|---|
| **Smellie** | 1762 | 4.25" | 5.25" |
| **Baudelocque** | 1789 | 4" | 5" |
| **Bard** | 1812 | 4-4.25" | 5-5.25" |
| **DeWees** | 1828 | "rather more than 4 inches" | "a little exceed 5 inches" |
| **Meigs** | 1849 | 10.6 cm (4.2") | 12.9 cm (5.0") |
| **Luschka** | 1864 | 11.0 cm | 13.5 cm |
| **Hodge** | 1866 | 10.1 cm (4.0") | 13.3 cm (5.23") |
| **Martin** | 1866 | 10.7 cm | 13.6 cm |
| **Verneau** | 1875 | 10.6 cm | 13.5 cm |
| **King *et al.*** | 1905 | 11.0 cm | 13.5 cm |
| **Litten** | 1925 | 10.4 cm | 14.0 cm |
| **Jarcho** | 1933 | 10.9 cm | 13.5 cm |

Some fourteen years later, Stein (1844, cited in Caldwell and Moloy, 1933, Steer, 1975 and Turner, 1886) presented his classification, based on work with skeletal female pelves. He characterized his observations into one of four categories: a) Elliptical in the transverse diameter; b) Elliptical in the conjugate diameter; c) Round and d) Truncated-cordate (blunt heart-shaped).

Both of the previous authors had employed observational, rather than metrical, approaches to aid their classifications. Turner (1886) reported how Zaaijer (working in Leyden in 1866) published the results of his metrical approach to considerations of the Javanese female pelvis. He presented information on how the pelvic (or brim) index was calculated, by multiplying the conjugate diameter by 100 and dividing by the transverse diameter. In

specimens where the conjugate diameter exceeded the transverse, the descriptive term longish-oval was applied. When each of these parameters approximated one another, the pelvis was labelled round.

Turner (1866) further noted how, in the same year, Martin (1866), who was working largely with female pelves, proposed a two group classificatory system, based upon the appearance of the pelvic inlet. Specimens which exhibited roughly equal transverse and conjugate diameters were accorded the title round, and those where the transverse diameter was in excess of the conjugate, were termed transversely oval.

Turner (1886) also based his classification on metrical evaluation. Although he basically assigned the terms long, wide and intermediate to his three groups, he also introduced three new terms to describe these attributes:

a) Dolichopellic (where the pelvic index is greater than 95).
b) Platypellic (where the pelvic index is less than 90).
c) Mesatipellic (where the pelvic index lies between 90-95).

Turner was basically attempting to anthropometrically define racial variations in pelvic morphology, and in order to achieve this objective, combined his observations with those of other authors who had examined a diverse range of geographical specimens. One important point that Turner was able to appreciate, was the limits imposed by the material under study, and as a consequence, he stated that although numerical ranges had been accorded to his pelvic types, these values could not be definitely fixed due to the samples examined. This information has been summarized and presented in Table 2.3 and clearly shows that sample size, in terms of statistical viability, does indeed leave much to be desired. However, there are a number of other omissions, which he did not elaborate upon. For instance, it is not documented whether the racial affinity and sex of material under observation was known or biologically assessed. Likewise, the age at death is not recorded, nor is parity status (in the females) or the presence of any pathological condition. Interobserver and intraobserver error are not mentioned, and in some cases, mean values have been calculated from as little as two specimens. Given the paucity of information on these aspects, it is quite surprising that Turner (1886) should be so resolute is ascribing pelvic types at all. However, in addition to doing this, he also commented on the fact that "in each race the brim index is, as a rule, distinctly higher in the male than in the female" (*ibid.*: 139). Further observations noted that the pelvic index in females "assists one in arriving at a conclusion as to the group in which the pelvis of each race should be placed"

## Table 2.3 Classification of pelvic types by geographical location and pelvic index

| Geographic origin/ Ancestry | Sample size | Sex | Transverse diameter | Conjugate diameter | Pelvic index | Classification according to Turner (1886) | Reference |
|---|---|---|---|---|---|---|---|
| Britain | ? | M | 116 | 102 | 87.9 | Male Platypellic | Watt (ND) cp.129 |
| | ? | F | 142 | 124 | 87.3 | | |
| | ? | M | 120 | 103 | 85 | | Wood (1859) cp.129 |
| | ? | F | 132 | 114 | 86 | | |
| | 6 | M | 127 | 98 | 77 | | Turner (1886) |
| | 11 | F | 137 | 109 | 79 | | |
| France? | ? | M | | | 80 | | Verneau (1875) cp.129 |
| | ? | F | | | 78 | | |
| Germany? | ? | M | 128 | 108 | 84 | Female Platypellic | Gegenbaur (1883) cp.129 |
| | ? | F | 135 | 116 | 85.9 | | |
| Europe | 11 | M | | | 81 | | Flower (ND) cp.129 |
| | 14 | F | | | 78 | | |
| Europe | ? | F | | | 80 | | Garson (1881) cp.129 |
| Spain | ? | F | | | 81 | | Navas (ND) cp.129 |
| Ireland | ? | F | | | 69 | | Martin (ND) cp.130 |
| Australia | 5 | M | | | 101 | Male Dolichopellic | Huxley (1866) cp.130 |
| | 1 | F | | | 37 | | |
| | ? | M | | | 100 | | Ecker (ND) cp.130 |
| | ? | M | | | 95 | | Keferstein (ND) cp.130 |
| | 5 | M | | | 92 | | Spengel (ND) cp.130 |
| | 1 | M | | | 98 | | Verneau (1875) cp.129 |
| | 2 | F | | | 80 | Female Platypellic/ Mesatipellic | |
| | 10 | M | | | 98 | | Flower (1879) cp.130 |
| | 5 | F | | | 91 | | Garson (1881) cp.131 |
| | 6 | M | | | 97 | | Turner (1886) |
| | 1 | F | | | 96 | | |
| Bush people | 5 | M | | | 99.5 (m) | Male Dolichopellic | Fritsch (1822), Huxley (1866), Müller (1834) cp. 131. Turner (1886) |
| | 8 | F | | | 89 (m) | Female Platypellic | Fritsch (1822), Görtz (1868), Huxley (1866), Müller (1834), Verneau (1875), Vrolik (ND) cp. 131 |
| Kaffir | 6 | M | | | 95-108 100.6 (m) | Male Dolichopellic | Fritsch (1822) cp.132 |
| | 1 | F | 107 | 96 | 89.7 | | |
| | 1 | M | | | 102.6 | | Weber (ND) cp.133 |

**Key:**

| | | | |
|---|---|---|---|
| ? | Sample size not stated | m | Mean |
| M | Male | ND | No date specified |
| F | Female | cp. | Citation page from Turner (1886) |

Blank cells indicate that no data was available for that parameter.

## Table 2.3 Classification of pelvic types by geographical location and pelvic index (contd)

| Geographic origin/ Ancestry | Sample size | Sex | Transverse diameter | Conjugate diameter | Pelvic index | Classification according to Turner (1886) | Reference |
|---|---|---|---|---|---|---|---|
| Negroid | 31[1] | F | | | 75.7-106 88.3 (m) | Male Mesatipellic | Fritsch (1822), Martin (ND), Verneau (1875), Vrolik (ND), Weber (ND), Wood (ND) cp. 133. Turner (1886) |
| | 35[1] | M | | | 72-105 92.7 (m) | Female Platypellic | Davis, (ND), Huxley (1866), Spengel (ND), Verneau (1875), von Sömmerring (ND), Vrolik (ND), Wood (ND) cp. 133. Turner (1886) |
| Andaman Islands | 13[2] | F | | | 96.4 (m) | Male Dolichopellic | Flower (1879/1884) |
| | 12 | M | | | 98.8 (m) | | cp.134 |
| | 13[2] | F | | | 96.4 (m) | | Garson (1881) cp.134 |
| | 3 | F | | | 87 (m) | Female Mesatipellic | Turner (1886) |
| | 1 | M | | | 97 | | |
| Tasmania | 3 | M | | | 93.3 (m) | | Davis (ND) cp.134 |
| | 1 | F | | | 83 | Male/Female Mesatipellic | |
| | 1 | M | 108 | 95 | 88 | | Verneau (1875) cp.134 |
| New Caledonia | 12 | M | 114 (m) | 104 (m) | 91 | | Verneau (1875) cp.134 |
| | 3 | F | 127 (m) | 110 (m) | 89 | | |
| Lifu | 1 | M | 116 | 124 | 107 | | Verneau (1875) cp.134-5 |
| New Guinea | 1 | M | 136 | 113 | 83 | General classification of[3] Polynesians Dolichopellic | Verneau (1875) cp.135 |
| Sandwich Island | 2 | M | 114(m) | 92 (m) | 81 | | Verneau (1875) cp.135 |
| | 3 | F | | | 83 | | Turner (1886) |
| Tonga | 1 | M | 126 | 121 | 96 | | Verneau (1875) cp.135 |
| Mangareva | 1 | M | 119 | 118 | 99 | | |
| Noukahiva | 1 | M | 108 | 94 | 89 | | |
| New Zealand | 2 | ? | | | 96 (m) | | Turner (1886) |
| Loyalty Is. | 1 | M | 114 | 106 | 92 | Melanesians Mesatipellic | Davis (ND) cp.135 |
| Tannese | 1 | M | 121 | 110 | 81 | | |
| Papuan | 1 | F | 115 | 110 | 95.6 | | von Franque (ND) cp. 135 |
| Guanche | 1 | M | | | 91 | Male PI (m) 88 ?Platypellic | Verneau (1875) cp.136 |
| | 1 | F | 132 | 120 | 91 | | |
| | 1 | M | | | 85 | | Turner (1886) |

**Key:**

| | |
|---|---|
| ? | Sample size not stated |
| M | Male |
| F | Female |
| m | Mean |
| PI | Pelvic index |
| ND | No date specified |
| cp. | Citation page from Turner (1886) |

[1] Some specimens may have been measured by more than one observer

[2] Same sample

[3] Variability in Pelvic Index attributed to diversity of populating islanders, including Polynesians, Melanesians and the Mahori

Blank cells indicate that no data was available for that parameter.

## Table 2.3 Classification of pelvic types by geographical location and pelvic index (contd)

| Geographic origin/ Ancestry | Sample size | Sex | Transverse diameter | Conjugate diameter | Pelvic index | Classification according to Turner (1886) | Reference |
|---|---|---|---|---|---|---|---|
| Eskimo | 1 | F | 153 | 117 | 76 | Male/Female ?Platypellic | Struthers (1854) cp.137 |
| | 1 | M | 124 | damaged | - | | Verneau (1875) cp.137 |
| | 1 | M | | | 88 | | Turner (1886) |
| | 1 | F | | | 84 | | |
| Lapland | 2 | M | 122 (m) | 101 (m) | 83 | Male/Female ?Platypellic | Verneau (1875) cp.137 |
| | 1 | M | | | 93 | | Turner (1886) |
| | 1 | F | | | 72.5 | | |
| Chinese | 1 | F | 133 | 104 | 78 | Male/Female ?Platypellic | von Franque (ND) cp. 137-8 |
| | 1 | M | 115 | 93 | 81 | | Verneau (1875) cp.137-8 |
| | 1 | F | 140 | 89 | 64 | | |
| | 1 | M | 112 | 95 | 85 | | Spengel (ND) cp.138 |
| | 1 | U[4] | | | 85 | | Turner (1886) |
| Aïnos | 1 | M | 113 | 115 | 102 | Male/Female ?Dolichopellic | Scheube (ND) cp.138 |
| | 1 | F | 102 | 117 | 97 | | Davis (ND) cp.139 |
| Java | 2 | M | | | 83 and 81 | | Davis (ND) cp.139 |
| | 1 | F | | | 90 | | Verneau (1875) cp.139 |
| | 1 | F | | | 92 | | von Franque (ND) cp. 135 |
| | 26 | F | | | <100/90 >100/90 | | Zaaijer (ND) cp. 139 |
| Malay | 1 | ? | 119 (m) | 109 (m) | 91.6 | ? Mesatipellic | Fritsch (1872), Martin (ND), Zaaijer (ND) cp. 139 |
| North American Indian | 1 | F | | | 84.5 | Male (m) 81 ?Platypellic | von Franque (ND) cp. 139-40 |
| | 1 | M | | | 76 | | |
| | 1 | M | | | 86 | | Davis (ND) cp.140 |
| South American Indian | 1 | M | | | 85 | Male PI (m) 80 Platypellic<br>Female PI (m) 83 Platypellic | Weber (ND) cp.140 |
| | 1 | F | | | 107 | | |
| | 1 | M | 116 | 116 | 100 | | Davis (ND) cp.140 |
| | 1 | M | | | 81 | | |
| | 1 | M | 122 | 115 | 94 | | Verneau (1875) cp.140 |
| | 1 | M | 123 | 91 | 74 | | |
| | 1 | M | 119 | 89 | 75 | | |
| | 1 | F | | | 86 | | |
| | 2 | M | 135 (m) | 91 (m) | 67 (m) | | |
| | 3 | F | | | 83 (m) | | |
| | 1 | M | 116 | 105 | 90.5 | | |
| | 1 | F | 130 | 104 | 80 | | |

**Key:**

| | | | |
|---|---|---|---|
| ? | Sample size not stated | ND | No date specified |
| M | Male | cp. | Citation page from Turner (1886) |
| F | Female | [4] | Label on specimen recorded male but Turner (1886) noted female characteristics |
| m | Mean | | |
| PI | Pelvic index | | |

Blank cells indicate that no data was available for that parameter.

(*ibid.*: 141). His overall conclusion was that the transverse diameter of the pelvic brim and cavity, together with the pelvic outlet was, for the most part, absolutely wider in females. Turner also calculated the sacral index for the specimens that he had observed, by multiplying the sacral breadth by 100 and dividing by the sacral length. By this calculation, indices in excess of 100 indicated a greater length of the element, and values less than 100, a wider breadth. His values have been presented in Table 2.4.

**Table 2.4 Turner's (1886) calculated sacral indices by ancestry (Adapted from an un-numbered table in Turner, 1886: 142)**

| Ancestry | Sacral index | Inference |
|---|---|---|
| Australian | 98 | Sacrum longer than broad |
| Bushmen/women | 94 | |
| Kaffir | 92.8 | |
| Andamese | 94 | |
| Negroid | 105.5 | Sacrum broader than long |
| European | 112 | |

Turner (1886) concluded that the first four listed groups, shown in Table 2.4, which exhibited a long, narrow sacrum and a generally dolichopellic character, displayed a similar morphology to that observed in the pelves of apes. He summarized these findings by stating that the pelvis in these groups manifests "a more degraded character - a less departure from the usual mammalian form" (*ibid.*: 143). These comments, although abhorrent to the modern reader, must be considered within the socio-cultural context of this period. Historically speaking, during the latter half of the last millennium and particularly during the eighteenth and nineteenth centuries, there existed the belief in the supremacy and equality of all whites, and this inevitably led to populations of other racial ancestries being treated with contempt and derision. To reinforce this "hierachial rank in a society dependent on inequality" (Jackson, 1997: 184), the dominant culture exploited many fields of human endeavour, as a means of socially controlling what they believed to be an inferior segment of society. Anthropology became one of many such "institutionalised mechanisms for exploiting and subjugating" (*ibid.*: 184) certain races during this time.

Hart (1916) noted two variations in, what he termed "inverted" pelves, and he denoted these as the more frequently occurring iliosacral, and the rarer, ischiopubic. Caldwell and Moloy (1933) engaged two approaches with their study on female pelves: direct observation (of dry specimens) and radiographic analysis (of living subjects). They

divided the pelvis into five categories, although attention was drawn to the fact that overlapping morphology occurs and thus renders it almost impossible to produce a simplistic classification. This aspect will be discussed in more detail later in this section.

The five basic types were called gynaecoid, android, anthropoid, platypelloid and asymmetrical. The gynaecoid (from the Greek - *gyne* - woman) pelvis displayed the accepted female sexual characteristics which included a round pelvic inlet, a wide, well-rounded anterior and posterior segment[1], an average sacral curvature and inclination, a wide subpubic angle, a medium sciatic notch, wide interspinous and intertuberous diameters and straight side walls.

The android (from the Greek - *andros* - man) form of the pelvis had been recognized for some time and documented by researchers such as Derry (1909), Hart (1916) and Straus (1927-8) and was described as a female pelvis which exhibited major male characteristics, particularly on the posterior aspect. This type of pelvis was seen to possess a wedge-shaped inlet, a narrow anterior segment, a flat, wide posterior segment, a forward inclining sacrum, a narrow subpubic angle, a narrow sciatic notch, narrow interspinous and intertuberous diameters and converging side walls.

The anthropoid (from the Greek - anthropos - human) pelvis was seen as a transversely contracted, or assimilation, pelvis and was the configuration that Turner (1886) had described as exhibiting "a more degraded character" (p. 143). Caldwell and Moloy (1933) present a detailed description in their paper of the similarities between this shape and that of the anthropoid apes. Characteristics of this pelvis include a long, narrow, oval pelvic inlet, a long and narrow anterior and posterior segment, a long, narrow, averagely curved and inclined sacrum, a narrow subpubic angle, a very wide and shallow sciatic notch, narrow interspinous and intertuberous diameters and straight side walls.

The platypelloid (from the Greek - *platy* - flat, pellis - pelvis) configuration is a rarer broad and flat form and this term had previously been proposed by Turner (1886) to describe it. It exhibits a transverse oval inlet, a very wide anterior and posterior segment, average sacral inclination, a very wide subpubic angle, a narrow sciatic notch, very wide interspinous and intertuberous diameters and straight side walls.

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[1] The anterior and posterior segments are defined by a line drawn through the greatest transverse diameter of the pelvic inlet (Cunningham *et al.*, 1997)

The final classificatory type of pelvis was referred to as an asymmetrical pelvis and usually conformed to one of the four previously described forms, but possessed an asymmetrical appearance.

It was noted that each of the first four main configurations were not associated with, or related to, any form of pathological process. Indeed, Steer (1975) records that 98% of all the pelvic forms which were radiographically studied by researchers (including himself) in the 26 year period from 1932-1958 represented normal variants. Of the remaining 2%, approximately half (1%) were affected by rickets (*ibid.*).

It would now be appropriate to return to the "mixed" forms of pelvic shape which occur (Cunningham *et al.*, 1997) and which Caldwell and Moloy referred to in their 1933 publication. Figure 2.8 displays the graduation of change in pelvic form which can be employed for most practical purposes, but this representation does not account for all of the mixed types encountered. Figure 2.9 presents these forms in more detail. Each of the mixed inlet types are classified first by the appearance of the posterior segment, and secondly by the shape of the anterior segment (Steer, 1975). Theoretically then, in the mixed configuration, the posterior segment of one of the four pure types may be combined with the anterior segment from any of the other three types, producing 12 variants. In practice, however, certain combinations appear to occur more frequently than others and these mixed types have been displayed in Table 2.5. Unfortunately, a review of the literature has not revealed actual percentages for these associations and thus the degree of occurrence remains unclear.

**Table 2.5 Commonly occurring combinations of pelvic segments**

| | | Posterior segment classificatory shape | | | |
|---|---|---|---|---|---|
| | | Gynecoid | Android | Anthropoid | Platypelloid |
| Anterior segment classificatory shape | Gynecoid | Pure | X | X | X |
| | Android | X | Pure | X | X |
| | Anthropoid | X | X | Pure | |
| | Platypelloid | X | X | | Pure |

**Key:**

Pure Pure form of classificatory shape
X Mixed types of classificatory shape

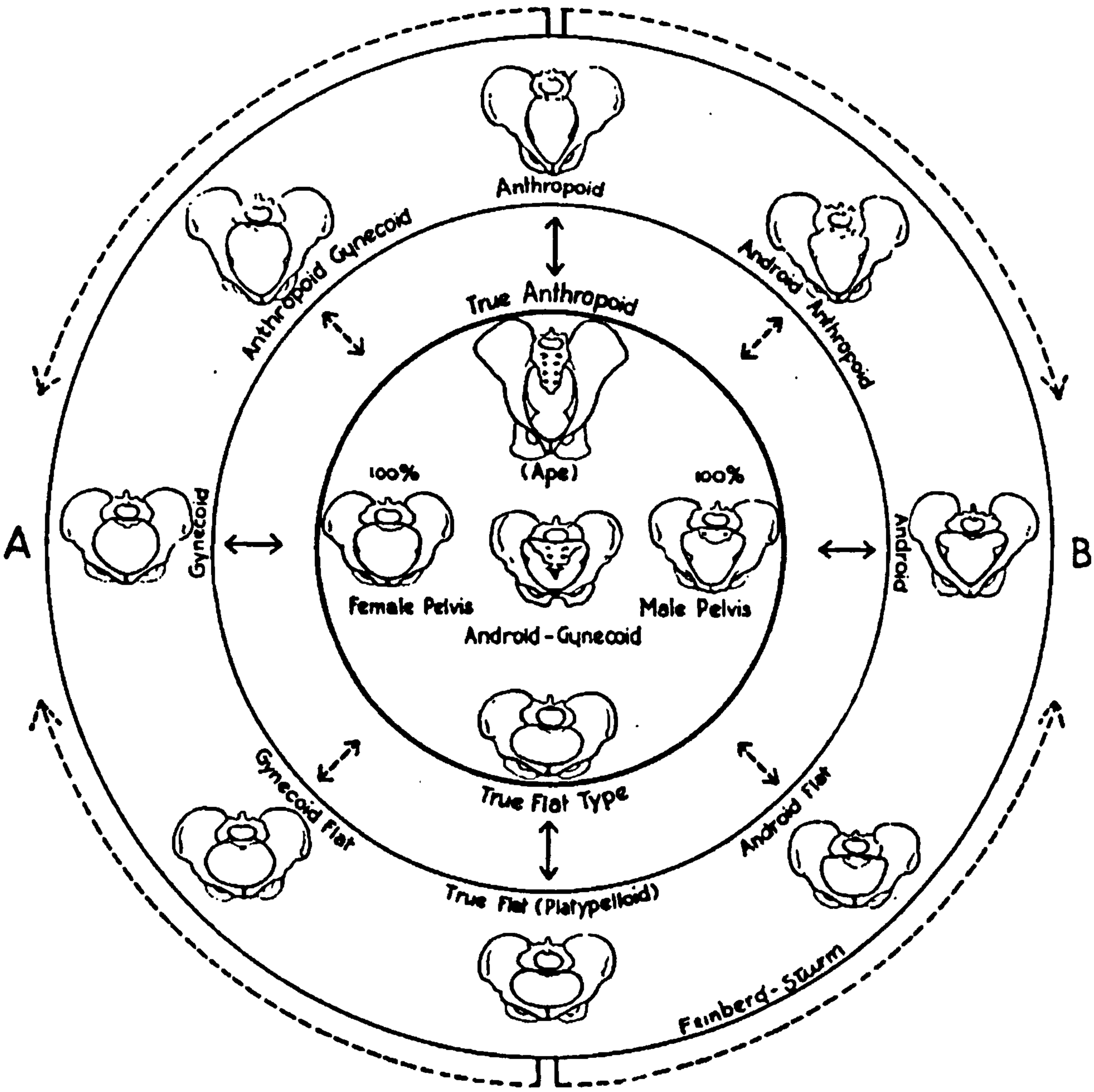



**Figure 2.8 Graduation in metamorphosis of pelvic morphology (From Steer, 1975: 22. Original Figure No. 12)**

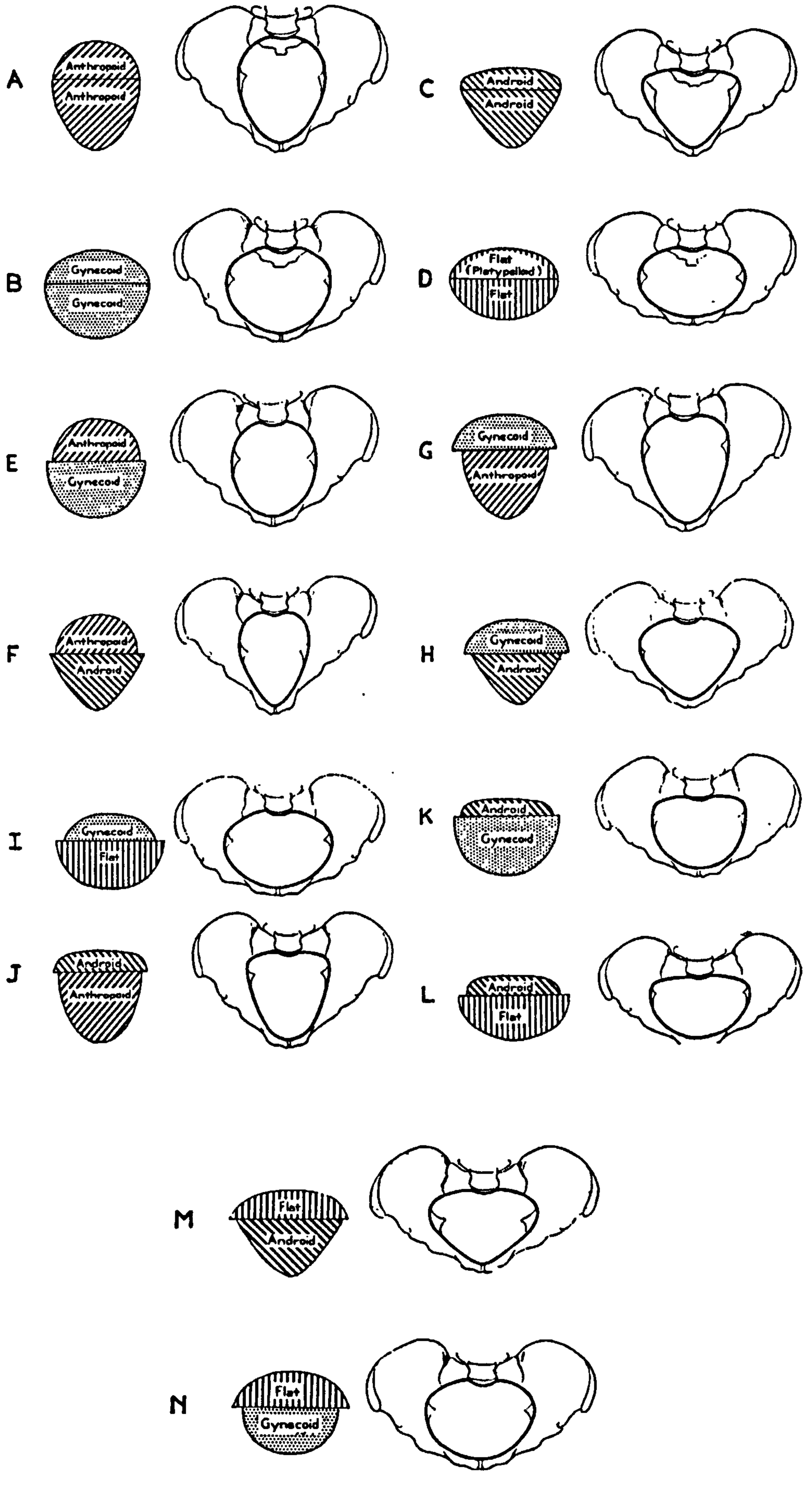



**Figure 2.9 Classification of pure and mixed pelvic types by combined pelvic segments. The pure forms are denoted by the letters A-D and mixed types are designated by letters E-N**
**(From Steer, 1975: 24-25. Original Figure No. 13)**

It is interesting to note that when the earlier classifications are compared to those of Caldwell and Moloy (1933) similarities can be observed. For instance, Weber (1830. Cited in Caldwell and Moloy, 1933 and Turner, 1886) and Steins' (1844. Cited in Caldwell and Moloy, 1933, Steer, 1975 and Turner, 1886) mesatipellic configurations, and Hart's (1916) ischiopubic variant are identifiable with Caldwell and Moloy's (1933) gynecoid shape. Likewise Weber's (1830) wedge-shaped pelvis, Stein's (1844) truncated-cordate (blunt heart-shaped) form and Hart's (1916) iliosacral variant each appear similar to the android pelvis described by Caldwell and Moloy (1933). Furthermore, Weber's (1830) four-sided, Stein's (1844) elliptical in the conjugate diameter and Turner's (1886) dolichopellic pelves all appear to conform to the morphology of Caldwell and Moloy's (1933) anthropoid classification. And finally, the oval and elliptical in the transverse diameter pelves of Weber (1830) and Stein (1844) respectively compare favourably with Turner's (1886) and Caldwell and Moloy's (1933) platypelloid form.

In 1938 Greulich and Thoms reported on the dimensions of the pelvic inlet obtained by the application of Thoms' method of radiographic pelvimetry on 789 white females. The authors employed the classificatory system devised by Thomas (1937) and Thoms and Wilson (1938), which had been based on the relative size of the anteroposterior and the transverse diameters of the inlet, and comprised the following definitions:

| | |
|---|---|
| 1) Dolichopellic | Antero-posterior (A-P) diameter exceeds the maximum transverse diameter. |
| 2) Mesatipellic | Maximum transverse diameter either equals A-P diameter or exceeds it by no more than 1 cm. |
| 3) Brachypellic | Transverse diameter exceeds the A-P diameter by 1.1 to 2.9 cm. |
| 4) Platypellic | Maximum transverse diameter exceeds A-P diameter by 3 cm or more. |

Textbooks of the day described the normal female pelvis as one where the maximum transverse diameter exceeded the antero-posterior one by 2 cm or more (i.e. brachypellic or platypellic).

Greulich and Thoms' (1938) work found that it was actually the dolichopellic and mesatipellic types that exhibited the greatest incidence. The authors also investigated what they termed the functional adequacy of the various type of pelves by calculating the percentage of each pelvic type that required some form of operative intervention (Caesarean section, version-extraction, mid forceps and outlet forceps) during delivery. Their results showed that the lowest incidence of such procedures was in the dolichopellic group, followed by, in ascending order, mesatipellic, brachypellic and platypellic. This led

them to conclude that the type of pelvis which had been considered normal for nearly two hundred years was not the most frequently occurring type, nor was it the most obstetrically adequate as gauged by the increase in relative frequency of operative intervention required during labour. In addition, adequate nutrition in early life coupled with other factors prevent diseases such as rickets developing. This condition may result in the anteroposterior flattening of the adult pelvis and led the authors to concur that the degree of anteroposterior flattening that was considered to be characteristically feminine, could rather be explained by inadequate nutrition and other factors.

In the same year, in attempting to develop a more scientific approach to pelvimetry, Hanson and Calif (1938) published a paper that presented the most practical methods then available for metrical analysis of the classically defined pelvic diameters, utilizing internal instrumental pelvimetry and radiography in living subjects.

They reappraised three parameters; subpubic angle, narrow pelvic plane and pelvic inlet. The first of these, the subpubic angle, was recognized as an indicator of a contracted pelvic outlet, and so accurate measurement of this component was a necessity. Hanson and Calif (1938) were the first researchers to raise the issue of error sources within earlier calculations of the pelvic outlet and suggested that they could be minimized by selecting a point nearer to the pubic arch and employing this to define the base from which the subpubic angle is subtended. A point, 3 cm below the pubic arch was designated, and the transverse dimension created defined as the interpubic diameter. The authors reported that in the last 100 consecutive cases that they had dealt with at the San Joaquin General Hospital (at French Camp, California), this angle had demonstrated a range of 95-132° (an average of 107° was stated). They concluded that angles measuring 100° or less should be regarded as android in nature.

The second parameter that they investigated was the narrow pelvic plane, which was defined as the pelvic level bounded by the sacral apex posteriorly, the ischial spines laterally, and the lower border of the symphysis pubis anteriorly. Hanson and Calif (1938) suggested that as these points did not lie in the same plane, it would be beneficial to transfer the posterior point to the level of the junction between the fourth and fifth sacral vertebrae, in order to produce a more representative view. They concurred with Caldwell and Moloy (1933) in recognising this plane as an important marker of android configuration. Hanson and Calif's paper (1938) arose from previous work that they mentioned, notably Hanson's method for measuring the bispinous diameter in living individuals using a pelvimeter. They noted how six years later, he had submitted a method for elucidating the interischial diameter, which he reiterated in this 1938 paper with Calif.

They described how these measurements were obtained and stated that the lower limits of normal for each of these respectively, was 9.5 cm and 10.0 cm.

Caldwell and Moloy's (1933) study stimulated Hanson and Calif (1938) to devise a simple and more accurate method for measuring the anterior and posterior sagittal diameters, the spinopubic diameter and sacropubic diameter. Methods for practically assessing these with a pelvimeter were described. In the aforementioned 100 consecutive cases, the following results were recorded: anterior sagittal diameter range 4.7-7.4 cm (6.48 cm average); posterior sagittal diameter range 3.5-8.0 cm (5.59 cm average) and spinopubic diameter range 7.3-9.4 cm (8.30 cm average). In 19 of the cases (19%), the posterior sagittal diameter exceeded the anterior and in eight patients (8%), the posterior sagittal diameter measured 4.5 cm or less. Hanson and Calif (1938) proffered that the latter characteristic should be regarded as a strongly android characteristic.

The third parameter that they assessed was the pelvic inlet. They modified the radiographic approach to the determination of pelvic inlet dimensions by replacing the plumb-bob with an ordinary level, so that the estimate of the distance between the X-ray table and the upper border of the pubis could be determined without interference by abdominal protrusion. Those characteristics identified as the most important android features of the pelvic inlet (long straight anterior puboiliac section, short posterior sagittal diameter and narrow retropubic angle [Caldwell and Moloy, 1933]) were easily determined by the modified radiographic approach suggested by Hanson and Calif (1938). They recommended that measurements of 3.5 cm or less attained for the posterior sagittal diameter should be defined as positively android.

In the last section of their paper, Hanson and Calif (1938) proposed an alternative classification for the pelvis, based on the work of Caldwell and Moloy (1933) and Thoms (who had revised Turner's 1886 classification and added a fourth type - brachypellic to the list [1937]). This is presented in Table 2.6.

**Table 2.6 Hanson and Calif's (1938) classification of the pelvis (adapted from an un-numbered figure on page 235)**

| Pelvic classification | Characteristics | Measurements |
|---|---|---|
| 1. Gynecic | a) Mesatipellic | |
| | b) Dolichopellic | Anterior-posterior diameter > Transverse diameter |
| | c) Brachypellic | Anterior-posterior diameter < Transverse diameter |
| | d) Platypellic | Anterior-posterior diameter << Transverse diameter |
| | e) Asymmetric | |
| 2. Android | | |

Only the final paragraph of their work refers to the importance that this research may have in the field of obstetrics.

However, despite this, there have been discrepancies with the specific terminology applied to the classificatory systems and this is most notable with respect to the term 'gynaecoid'. Hanson and Calif (1938), who proffered an alternative system, which has been presented above in Table 2.6, suggested that the word 'gynecic' should be used in preference to gynaecoid because the former literally means pertaining to women, whereas the latter strictly refers to a male pelvis possessing female characteristics.

### 2.3.2 Frequency of pelvic types

Caldwell *et al.*, (1939) examined the Hamann-Todd collection to assess the frequency of each of the four pure types of pelvic configuration assigned by Caldwell and Moloy (1933). According to Rothschild and Rothschild (1995), this collection, which was assembled between 1913 and 1933, consists of defleshed cadavers of known ancestry, sex, age and cause of death. They discovered that almost 50% of females were represented by the gynecoid type. Thirty-three percent of white females and 16% of black females exhibited an android configuration, while about 24% of white females and 41% of black females were classified as anthropoid. The platypelloid form was found to be present in less than five percent of all females.

In his 1975 publication, Steer presents details of the pelvic types of the majority of patients presenting at the Sloane Hospital for Women in New York, over a 24 year period from 1951-1975. A total of 9946 individuals were clinically evaluated, and of these, 7788 (78.3%) exhibited the gynecoid form of pelvis (Steer, 1975). The remaining 2158 (21.7%) were spread between the pure android, anthropoid and platypelloid forms, in addition to the ten mixed configurations (*ibid.*). One thousand and fifty two patients were examined radiographically and of these, 268 (25.5%) were gynecoid, 150 (14.3%) anthropoid and the remaining 634 (60.2%) comprised android, platypelloid, mixed types (ten) and rachitic pelves (*ibid.*). When all cases (clinical and radiographic) were combined, 8056 (73.6%) individuals exhibited a gynaecoid configuration. The remaining 2942 (26.4%) was split between pure forms of android, anthropoid and platypelloid, ten mixed types and rachitic varieties, but none of these individual groups amassed more than 6.5% of the total on their own (*ibid.*).

Steer (1975) also documented the outcome of labours for a total of 1052 patients that had been typed radiographically (*ibid.*). The probability of serious arrest requiring mid-forceps

delivery or Caesarean section was calculated for each of the pelvic types (four pure, ten mixed and rachitic). The lowest score (5.6%) was realized by the women possessing gynaecoid configurations (*ibid.*). All of the other groups (with the exception of anthropoid-gynaecoid [9.3%] ) expressed percentages in excess of 10% (range 12%-56%). The greatest probability of serious arrest in this survey was exhibited by individuals with flat-android pelvic forms (*ibid.*).

### 2.3.3 Comparing skeletal and radiographic methods

Schroeder *et al.* (1997) undertook a study to compare skeletal and radiographic approaches to pelvimetry using 50 pelves from the University of Texas Donor Programme. These specimens consisted of 30 white male and 20 white female, aged 30-93 years and of known ancestry, age at death, stature and weight. The authors ensured that the mean age was the same between the two sexes to avoid any sex biased increases in dimensions that transpire with advancing age (Hulth *et al.*, 1995). Seven measurements were taken: pelvic height, pelvic breadth, anterior upper spinal breadth, breadth at symphysis, transverse diameter of pelvic brim, height of ilium and sacro-iliac breadth. For four of these (pelvic height, anterior upper spinal breadth, breadth at symphysis and sacro-iliac breadth), the two methods produced significantly different data, with the skeletal measurements producing larger values. Of these four parameters, the pelvic height could in part be explained by the distortional effects generated due to the fact that the measurement is not orientated in a plane parallel to the radiograph (Work by Bohrer and Daniels in 1969 documented how rotational errors could be introduced thus leading to dimensional underestimates). However, a high correlation coefficient (0.8669) indicates that a correction factor could be applied to rectify this and scale between the two methods. In the case of the sacro-iliac breadth, however, the correlation coefficient was extremely low (0.3028) and indicates that the two methods are not interchangeable. For the other three measurements (pelvic breadth, transverse diameter of pelvic brim and height of ilium), the two methods did not produce significantly different results.

### 2.3.4 Effects of sex and age on pelvimetry

The transverse diameter measurement has been found to be larger in females than in males and this has been reported from both direct skeletal measurement of the pelvis (Schroeder

*et al.*, 1997; Tague, 1989) and radiographic studies (Caldwell *et al.*, 1939; LaVelle, 1995; Reynolds and Hooton, 1936; Schroeder *et al.*, 1997; Thoms and Greulich, 1940; Young and Ince, 1940).

Most recently, females have formed the subject for a twin study of the effect of genetic and environmental factors on pelvic morphology (Sharma, 2002). Sixty pairs of female twins (30 monozygotic and 30 dizygotic) with a mean age of 17.53 years (SD = 2.77) were selected for examination from the twin registry of the Department of Anthropology at Panjab University in Chandigarh, India. A number of these twins had constituted a longitudinal growth study. All individuals were described as post-menarchal, and the author employed this status as an indicator of growth and pelvic remodelling cessation. Six pelvic measurements were then taken, with bilateral landmarks only utilising the right aspect of the body. Statistical analyses undertaken on the results suggested that there were greater environmental influences on pelvic morphology between twin types (monozygotic twins exhibited a smaller total among-pair and within-pair mean square than dizygotic counterparts where inequalities in variance were noted). Although environmental influences were reported as exerting a greater influence overall, these varied in level of effect between the various measurements.

Age formed the basis for a study conducted by Hulth *et al.* in 1995. They undertook radiographic examination of 216 Swedish adults (100 male and 116 female), and divided them into three age groups: 18-39 years, 40-59 years and 60+ years. Results indicated that the transverse diameter of the pelvic brim was significantly larger in the 40-69 year and 60+ year groups compared to the 18-39 year olds. There was no significant difference noted between the 40-59 year and 60+ year groups.

In her work conducted on the Christ Church, Spitalfields collection, Cox (1989) also found that older females possessed larger capacity pelves than their younger counterparts. However, rather than this representing an age related phenomenon, it was proposed that natural selection was responsible and that females with larger pelves were simply living longer (*ibid.*).

## 2.4 MODELLING OF THE PELVIS

In the nineteenth century artistic and "sculptured" representations of the human skeleton, the pelvis and vertebral column were often depicted as those of an erect quadruped

(Davies, 1956). Earliest radiographic investigations seemed to purport that the human pelvis was directed horizontally, but examination of pathological specimens, such as those presented by Davies (*ibid.*), appeared to be in disagreement.

The body of the pubic bone actually lies horizontally, not vertically. This area is the site of attachment for the adductor muscles, which are contained in the medial compartment of the thigh (Stone and Stone, 1997; Gosling *et al.,* 1996) and therefore must be situated between the thighs, rather than anterior to them. In addition to this, the anterior superior and inferior iliac spines form origins for some of the anterior compartment muscles of the thigh (*sartorius* and *rectus femoris* respectively [Gosling *et al.*, 1996; Snell, 1986; Stone and Stone, 1997]) and as such, is positioned in the anterior aspect of this area.

If the musculature in the posterior part of the thigh is also considered, then it can be clearly appreciated that the hamstring muscles (consisting of *biceps femoris*, *semimembranosus* and *semitendinosus*) which take their origin from the ischial tuberosity (Gosling *et al.,* 1996; Snell, 1986; Stone and Stone, 1997) enable walking to take place by drawing the knee posteriorly. This transpires because the area is situated posterior to the femur. If the pelvis was orientated in the horizontal plane, then the ischial tuberosity would lie anteromedial to the femur and it would be impossible to walk backwards (Davies, 1956). The plane of the pelvic inlet can therefore be perceived as lying at an acute incline to the coronal plane, rather than sitting at right angles to it. This strongly suggests that the adoption of a bipedal posture was achieved not from rotating the pelvis about the femora, but from adaptive angulation of the vertebral column (particularly at the lumbosacral articulation) and concurrent flexion of the musculature inherent within the back (Davies, 1956). This is further discussed in chapter 3, section 3.4.

The distribution of stresses within the pelvis, and indeed within the human skeleton as a whole, has long fascinated clinicians and engineers alike. Understanding of the mechanical behaviour of biological systems is a critical ingredient in the evaluation of normal function as well as a vital prerequisite for the prevention, diagnosis and treatment of pathological conditions.

Within the pelvis, these biomechanical studies have tended to focus on either the hip or sacro-iliac joint. In the case of the former, a number of publications have documented mathematical, physiological and radiographical approaches to the subject. In 1968 Williams and Svensson determined the forces acting in the muscles bridging the hip joint in a man standing on one leg and two years later McLeish and Charnley (1970) specifically investigated the abduction forces extant in maintaining this position. A mathematical

model was developed in 1977 by Goel and Svensson, in an attempt to further evaluate the forces acting in both muscles and ligaments of the pelvis in an individual standing on one leg.

Other studies, such as that proffered by Brinckmann *et al.* (1981b) have attempted to calculate the compressive stresses acting across the hip joints in both healthy and pathological hips. They examined the radiographs of 343 healthy adults (165 male, 178 female) and 289 patients with idiopathic osteoarthrosis (142 male, 147 female). Their results indicated that compressive forces operating across the hip joint were of minor importance with respect to the aetiology of the pathology.

Correct pelvic tilting is known to effect the curvature of the lumbar spine and thus to reduce the compressive and shear forces acting along it (Gracovetsky *et al.*, 1989; Kiefer *et al.*, 1997). Stabilization of the lumbar region of the vertebral column is fundamentally controlled by the amount of pelvic tilt, and this in turn is regulated by the position and effective co-ordination of spinal stabilizing muscles. In 1999, Brumagne and colleagues examined a small sample of 11 subjects (eight female and three male), aged 20-26 years with a piezoresistive electrogoniometer and three-dimensional video analysis to ascertain the repositioning accuracy of pelvic tilting on standing. They found that, in healthy subjects, precise repositioning of the back and pelvis was easily achieved.

Recent work, conducted in 1997 by Zheng and colleagues, presented a quasi-static biomechanical model of the sacro-iliac joint. However, this work was only based on the examination of one female cadaver. The authors, nevertheless, proceeded with this single specimen and found that when a load of 1000 N was applied to the sacrum, it resulted in a translation of the joint in the direction of the force of about 1.5 mm, 1.8 mm and 0.5 mm in the supero-inferior, antero-posterior and lateral directions respectively. Furthermore, application of a load of 50 N to the sacrum culminated in rotational movement in the direction of the load of 1.6° axially, 1.0° in flexion or extension, and 1.1° in lateral bending. The authors concluded that the limited movement observed could be explained mechanically by considering the pelvis as a stable complex three link structure which prohibited excess motion at the sacro-iliac joint. However, it must be borne in mind that these results herald only from one female cadaver, and further experimentation on a larger sample when various factors can be controlled for, needs to be undertaken in order to fully understand the precise biomechanical modelling in operation.

# CHAPTER 3 THE HUMAN VERTEBRAL COLUMN

The vertebral column is a segmented, flexible structure which extends from the cranium to the pelvis in humans and fulfils a number of roles:

1) To transmit the weight of the upper body to the lower limbs (Aiello and Dean, 1990).

2) To protect the spinal cord (Aiello and Dean, 1990; Palastenga *et al.*, 1994; Snell, 1986; Schwartz, 1995; Steele and Bramblett, 1988; White and Folkens, 1991).

3) To provide an articulation for the ribs (Aiello and Dean, 1990).

4) To support the thoracic cage (Palastenga *et al.*, 1994; Snell, 1986; Schwartz, 1995; Steele and Bramblett, 1988; White and Folkens, 1991).

5) To afford sites of attachment for muscles (Aiello and Dean, 1990; Palastenga *et al.*, 1994; Steele and Bramblett, 1988; White and Folkens, 1991).

6) To act as a shock absorber (Palastenga *et al.*, 1994; Snell, 1986).

7) To act as a haemopoetic tissue (Creager, 1992; Gosling *et al.*, 1996; Kumar and Clark, 1987).

The vertebrae, excluding the sacrum and coccyx, constitute approximately 75% of the total length of the presacral spine. The remaining 25% is comprised of intervertebral discs (Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991). The anatomy of this structure will now be considered in more detail.

## 3.1 ANATOMY OF THE VERTEBRAL COLUMN

Generally speaking, there are 33 vertebrae which form the human vertebral column (Figure 3.1). These comprise seven cervical, twelve thoracic, five lumbar, five sacral and four coccygeal (Gosling *et al.*, 1996; Gunn, 1996; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991). Variations may occur in the relative numbers

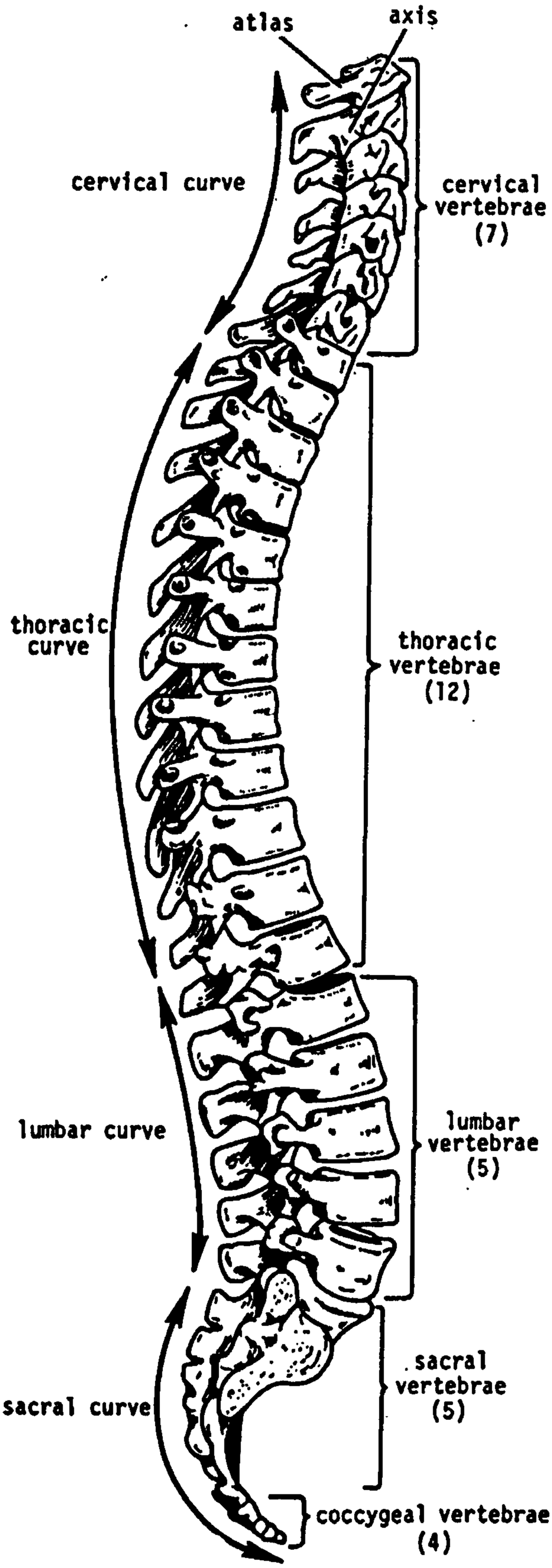



**Figure 3.1 Right lateral view of the vertebral column (From Snell, 1986: 923. Original Figure No. 12-3A)**

of vertebrae present, sometimes in as much as 10% of individuals (White and Folkens, 1991).

Despite the fact that regional differences are apparent in the spine, vertebrae do tend to exhibit a common anatomical morphology (Schwartz, 1995; Snell, 1986). Typically they consist of an anteriorly positioned body and a posteriorly placed vertebral arch (Gunn, 1996; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991). These two structures enclose the vertebral foramen in which lies the spinal cord and meninges (except the endosteal layer of the dura mater) (Gosling *et al.*, 1996; Gunn, 1996; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991). Each vertebral arch is constructed from two pedicles, which form the sides of the arch, and a pair of flattened laminae, which complete it posteriorly (Gunn, 1996; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991). The vertebral arch gives rise to seven processes: four articular (Gunn, 1996; Schwartz, 1995; Snell, 1986; White and Folkens, 1991), two transverse (Gosling *et al.*, 1996; Snell, 1986) and one spinous (Gosling *et al.*, 1996; Schwartz, 1995; Snell, 1986).

The articular facets consist of two superior and two inferior elements which arise from the junction of the pedicles and laminae (Gunn, 1996; Snell, 1986; White and Folkens, 1991). The transverse process is directed laterally from this aforementioned junction and the spinous process points posteriorly from the laminae. The transverse and spinous processes provide an attachment site for both muscles and ligaments (Snell, 1986).
The pedicles are notched on their superior and inferior borders to produce superior and inferior vertebral notches (Gunn, 1996; Snell, 1986). The superior vertebral notch of one vertebra and the inferior one of the adjacent vertebra form the intervertebral foramen, which transmits spinal nerves and blood vessels (Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991). Anatomical features peculiar to each of the different types of vertebrae will now be discussed, except those of the sacrum and coccyx, which have been reviewed previously in sections 2.1.2 and 2.1.3 respectively. Table 3.1 summarizes these characteristics.

### 3.1.1 Cervical vertebrae

The cervical region of the vertebral column consists of seven vertebrae. The third through to sixth share similar characteristics and are referred to as typical vertebrae (Figure 3.2), whereas the first (atlas), second (axis) and seventh elements each possess distinguishing

**Table 3.1 General features exhibited by the different types of vertebrae**

| | Vertebra type | | | | |
|---|---|---|---|---|---|
| | **Cervical** | **Thoracic** | **Lumbar** | **Sacral** | **Coccygeal** |
| **Number** | 7 | 12 | 5 | 5 (fused in adult) | 4 (usually fused) |
| **Shape of body** | Rectangular | T1-T3 Rectangular<br>T4-T9 Heart-shaped<br>T10-T12 Kidney-shaped | Kidney-shaped | Wedged shaped bone<br>Concave anteriorly | Triangular<br>(fused structure) |
| **Pedicle** | Short and round<br>Projects posterolaterally | Short<br>Projects posteriorly | Short and thick<br>Projects posteriorly | Short<br>Project posteriorly and laterally | Absent |
| **Lamina** | Long and thin | Short, deep and imbricated | Short and thick<br>Inclined inferiorly | Inclined inferiorly, medially and laterally | Rudimentary in first<br>Absent in 2-4 |
| **Superior articular facet orientation** | Postero-superior | Posterior<br>(except T1 – postero-superior) | Concave facet faces:<br>Medial (upper)<br>Posterior (lower) | S1 – Postero-inferior<br>Rest fused to intermediate sacral crest | - |
| **Inferior articular facet orientation** | Antero-inferior | Anterior<br>(except T12 - lateral) | Convex facet faces:<br>Lateral (upper)<br>Anterior (lower) | Fused to intermediate sacral crest | - |
| **Spinous process** | Short, posteriorly inclined<br>Bifid at tips | Long, inferiorly inclined in mid-section | Short, flat and quadrangular (superior-inferiorly deep) | Fused to form medial crest | - |
| **Transverse process** | Pierced by foramen transversarium | Thick<br>Articulates with rib tubercle | Sharp ended<br>Directed laterally and posteriorly | Fused with costal element to form lateral crest | - |
| **Specific characteristic features** | Developed uncinate process<br>Transverse foramen | Costal facets<br>(on vertebral body)<br>(on transverse process) | - | - | Rudimentary structure |

**ATLAS**

**AXIS**

**TYPICAL**

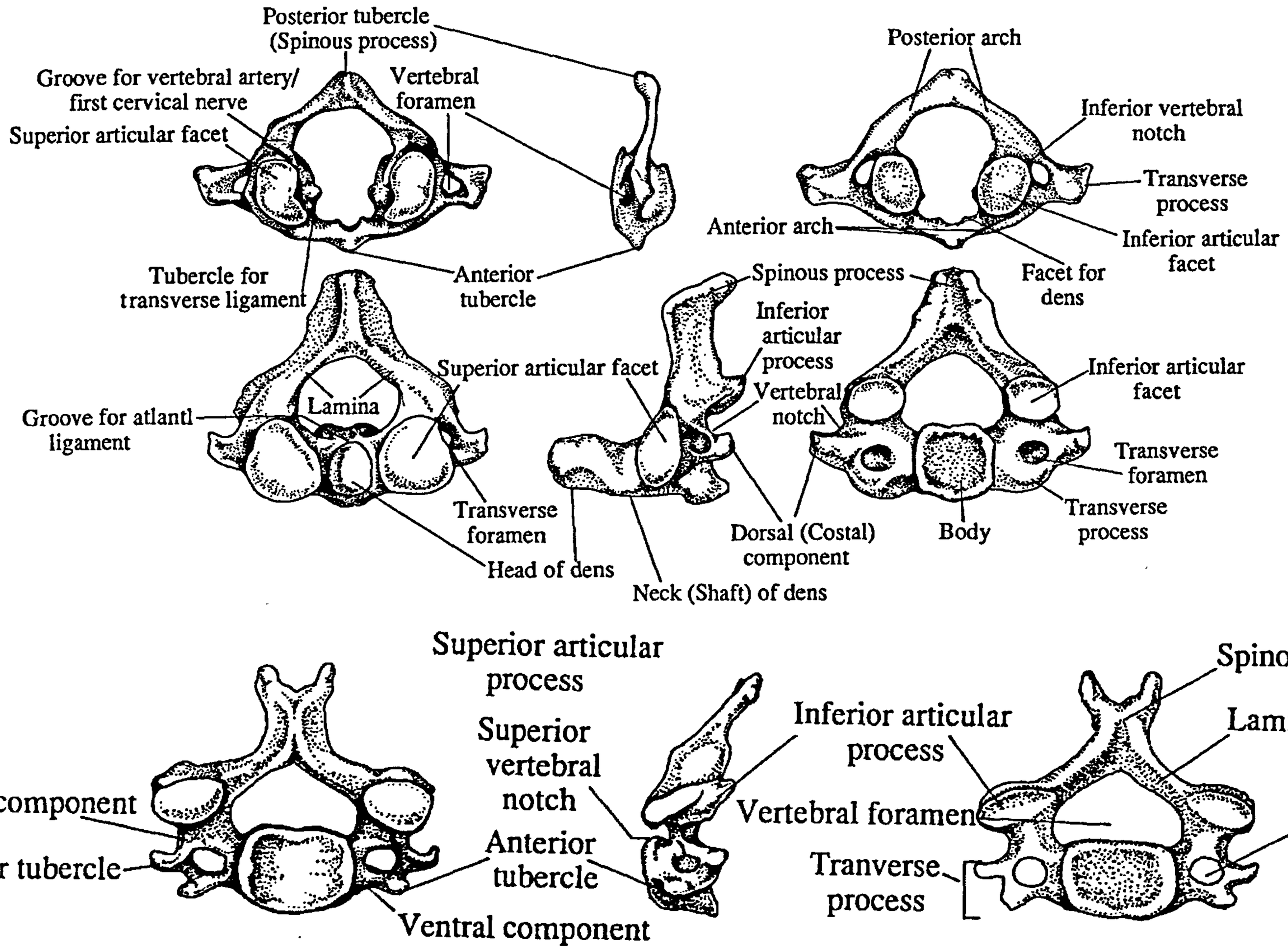



**Figure 3.2 Cervical vertebrae**

**Atlas (*top row*), axis (*middle row*) and typical cervical vertebra (*bottom row*) in superior (*left*), left lateral (*middle*) and inferior (*right*) view**
**(Top and middle row images from Schwartz, 1995: 87. Original Figure No. 3-7. Bottom row image from Schwartz, 1995: 83. Original Figure No. 3-3)**

features and are known as atypical vertebrae (Figure 3.2) (Aiello and Dean, 1992; Gosling *et al.*, 1996; Snell, 1986).

The cervical bodies are roughly rectangular in shape, with a wider medio-lateral than anteroposterior aspect (Snell, 1986). Small uncinate processes form synovial joints at the periphery. The pedicles are short, round and project posterolaterally and the laminae are long and thin (Gunn, 1996; Steele and Bramblett, 1988). The vertebral foramen is large and triangular (Gunn, 1996; McMinn and Hutchings, 1985; Snell, 1986; Steele and Bramblett, 1988). Superior articular facets are small, flat and face posteriorly, whereas the inferior counterparts are directed anteriorly (Gunn, 1996; Schwartz, 1995; Snell, 1986; White and Folkens, 1991). The transverse process possesses anterior and posterior tubercles and is pierced by the *foramen transversarium* to allow passage of the vertebral vessels (Gosling *et al.*, 1996; Gunn, 1996; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991), although the vertebral artery only passes through the first six cervical vertebrae (Gunn, 1996; Snell, 1986). The spinous processes are small and bifid (Gosling *et al.*, 1996; Gunn, 1996; McMinn and Hutchings, 1985; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991).

The atlas differs from the general cervical structure in that it does not have a body (Gosling *et al.*, 1996; Gunn, 1996; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991) and spinous process (Snell, 1986; White and Folkens, 1991). It basically consists of anterior and posterior arches and intervening lateral masses (Gosling *et al.*, 1996; Gunn, 1996; Schwartz, 1995; Snell, 1986), which exhibit articular surfaces on the upper and lower aspects. These facets form the articulation for the atlanto-occipital joint and atlanto-axial joint respectively (Gunn, 1996; Snell, 1986).

The axis demonstrates a peg-like odontoid process (or dens) on its superior aspect, which represents the body of the atlas (Gosling *et al.*, 1996; Gunn, 1996; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988). This process is secured within the articular fovea of the atlas by the apical, alar and transverse ligaments (Gosling *et al.*, 1996; Snell, 1986).

The seventh cervical vertebra is known as the *vertebra prominens* and has the longest, non-bifid spinous process (Gosling *et al.*, 1996; Gunn, 1996; Schwartz, 1995; Snell, 1986), which is the first to be felt in the neck (Snell, 1986). It demonstrates a small vertebral foramen and a large transverse process (Gunn, 1996; Snell, 1986).

### 3.1.2 Thoracic vertebrae

The twelve vertebrae that constitute the thoracic region of the spine gradually increase in size as they progress inferiorly (Gosling *et al.*, 1996; Snell, 1986). They possess heart shaped bodies (Gunn, 1996; Snell, 1986; Steele and Bramblett, 1988), very short and posteriorly directed pedicles and short, deep, imbricated laminae (Gunn, 1996). The vertebral foramen is relatively small and circular in appearance (Gunn, 1996; McMinn and Hutchings, 1985; Snell, 1986; White and Folkens, 1991). Superior articular facets tend to point posterior and the inferior ones, anteriorly (Schwartz, 1995; Snell, 1986). The only real exception to this is seen in the twelfth thoracic vertebra, where the inferior articulations face laterally (McMinn and Hutchings, 1985; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988). The transverse process is a thick, strong structure and possesses facets for articulation with the rib tubercles (Gosling *et al.*, 1996; Gunn, 1996; Schwartz, 1995) - except usually for the eleventh and twelfth vertebrae (Gunn, 1996; McMinn and Hutchings, 1985; Steele and Bramblett, 1988; White and Folkens, 1991). The spinous process is long and inclined inferiorly in the mid-region (Gosling *et al.*, 1996; Gunn, 1996; McMinn and Hutchings, 1985; Schwartz, 1995; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991).

Costal facets are present on the vertebral bodies for articulation with the rib heads (Gosling *et al.*, 1996; Gunn, 1996; McMinn and Hutchings, 1985; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991) and take the form of demifacets - the superior component situated at the root of the pedicle (Gunn, 1996) and the inferior element at the lower border of the body (*ibid.*). Some of the thoracic elements deviate from this pattern. The first thoracic vertebra bears a complete costal facet just below the border of the superior surface and, inferiorly, a demifacet that is confluent with the perimeter of the inferior surface (Schwartz, 1995; Scheuer and Black, 2000; Steele and Bramblett, 1988). In addition, it also possesses so called 'butting facets', a superiorly facing articular shelf located on the laminae and associated with the superior articular facet. These entities serve to limit the downward displacement of the inferior articular surface of the seventh cervical vertebra (Scheuer and Black, 2000).

Generally speaking, the tenth through to twelfth (and sometimes the ninth) vertebrae do not display inferior costal facets, but demonstrate a singular complete articular facet on either side of the body (Gunn, 1996; McMinn and Hutchings, 1985; Scheuer and Black, 2000; Steele and Bramblett, 1988; White and Folkens, 1991). Figure 3.3 demonstrates these characteristics.

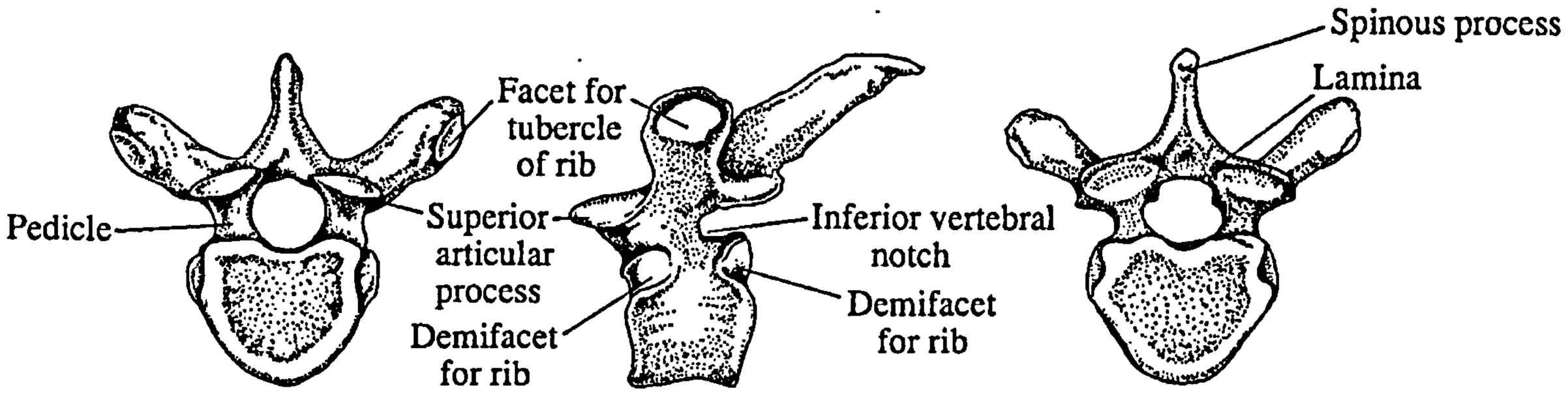



**Figure 3.3**
**Typical thoracic vertebra in superior (*left*), left lateral (*middle*) and inferior (*right*) view**
**(From Schwartz, 1995: 83. Original Figure No. 3-3)**

### 3.1.3 Lumbar vertebrae

A typical lumbar vertebra (Figure 3.4) exhibits a kidney-shaped body (Gunn, 1996; Snell, 1986; Steele and Bramblett, 1988); short, thick, posteriorly directed pedicles; and a short, thick, inferiorly inclined lamina (Gunn, 1996; Steele and Bramblett, 1988). The vertebral foramen is small and triangular (Gosling *et al.*, 1996; Gunn, 1996; McMinn and Hutchings, 1985; Snell, 1986). Superior articular facets face medially and posteriorly and exhibit elevations along the posterior border, known as mamillary processes (Gunn, 1996; McMinn and Hutchings, 1985). The inferior articular facets are directed laterally and anteriorly (Gunn, 1996; Snell, 1986; White and Folkens, 1991). When viewed from the posterior aspect, the four articular processes of the first two lumbar vertebrae form a vertical rectangle; those of the third and fourth, a square; and those of the fifth vertebra, a horizontal rectangle (McMinn and Hutchings, 1985; White and Folkens, 1991). Transverse processes are directed laterally and posteriorly and comprise sharp-ended long elements (Gunn, 1996; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991). Spinous processes, on the other hand, are short, flat and quadrangular in shape and project posteriorly (Gosling *et al.*, 1996; McMinn and Hutchings, 1985; Schwartz, 1995; Snell, 1986; White and Folkens, 1991).

The fifth lumbar vertebra articulates with the sacrum at the lumbosacral joint.

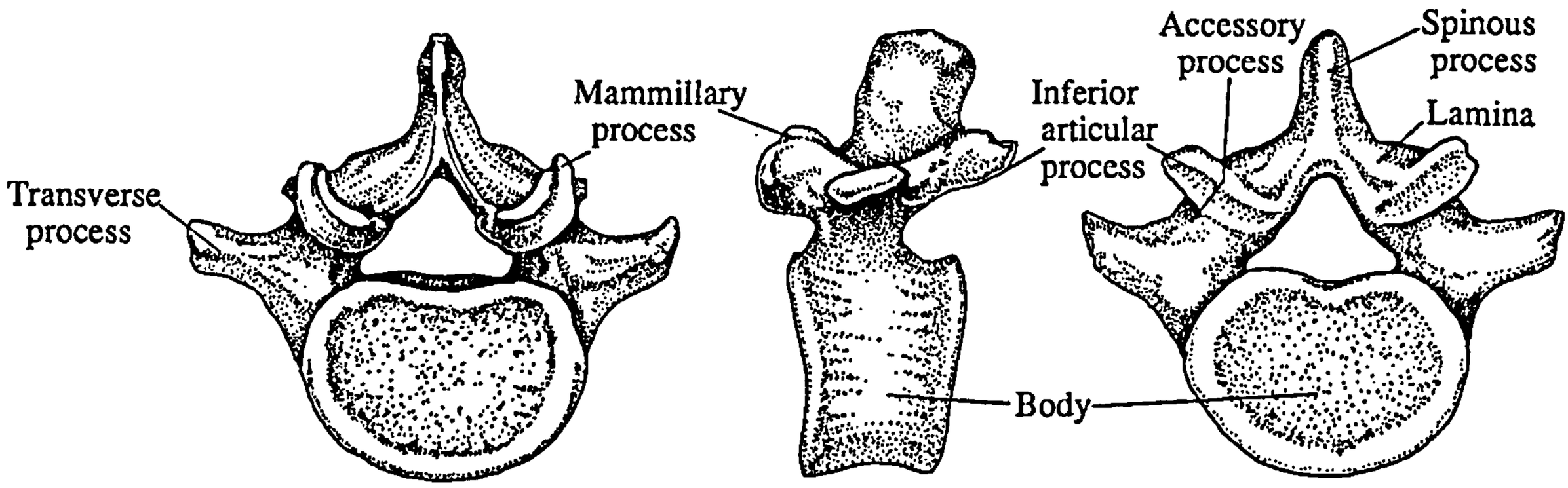



**Figure 3.4**
**Typical lumbar vertebra in superior (*left*), left lateral (*middle*) and inferior (*right*) view**
**(From Schwartz, 1995: 83. Original Figure No. 3-3)**

Intervertebral joints consist of two types: those that manifest between the vertebral bodies and those acting between the vertebral arches. The former are secondary cartilaginous joints formed between an intervertebral disc and the hyaline covered vertebral body. In the inferior part of the cervical region, small synovial joints are also observed at the lateral aspects of the intervertebral discs, between the upper and lower surfaces of the vertebrae (Gunn, 1996; Snell, 1986). Articulations between the vertebral arches are synovial in nature and take place at the apophyseal joints, formed from superior and inferior articular facet interaction (Gosling *et al.*, 1996; Gunn, 1996; Snell, 1986).

A number of ligaments, both internal (posterior longitudinal ligament, ligamentum flavum) and external (anterior longitudinal ligament, supraspinous ligaments, interspinous ligaments, ligamentum nuchae) to the vertebral canal serve to connect the vertebrae and restrict movement within the structure as a whole (Snell, 1986). This anatomical arrangement reduces the need for excessive (and wasteful) muscular activity in maintaining an upright posture, as well as eliciting various movements (Aiello and Dean, 1992).

## 3.2 THE INTERVERTEBRAL DISCS

These semi-elastic and fibrocartilaginous structures, which act as shock absorbers when the load on the vertebral column suddenly increases, consist of two parts: a peripheral annulus fibrosus and a central nucleus pulposus (Collins, 1949; Gosling *et al.*, 1996; Gunn, 1996; Mankin and Radin, 1997; Resnick and Niwayama, 1978; Snell, 1986; White and Folkens, 1991) (Figure 3.5).

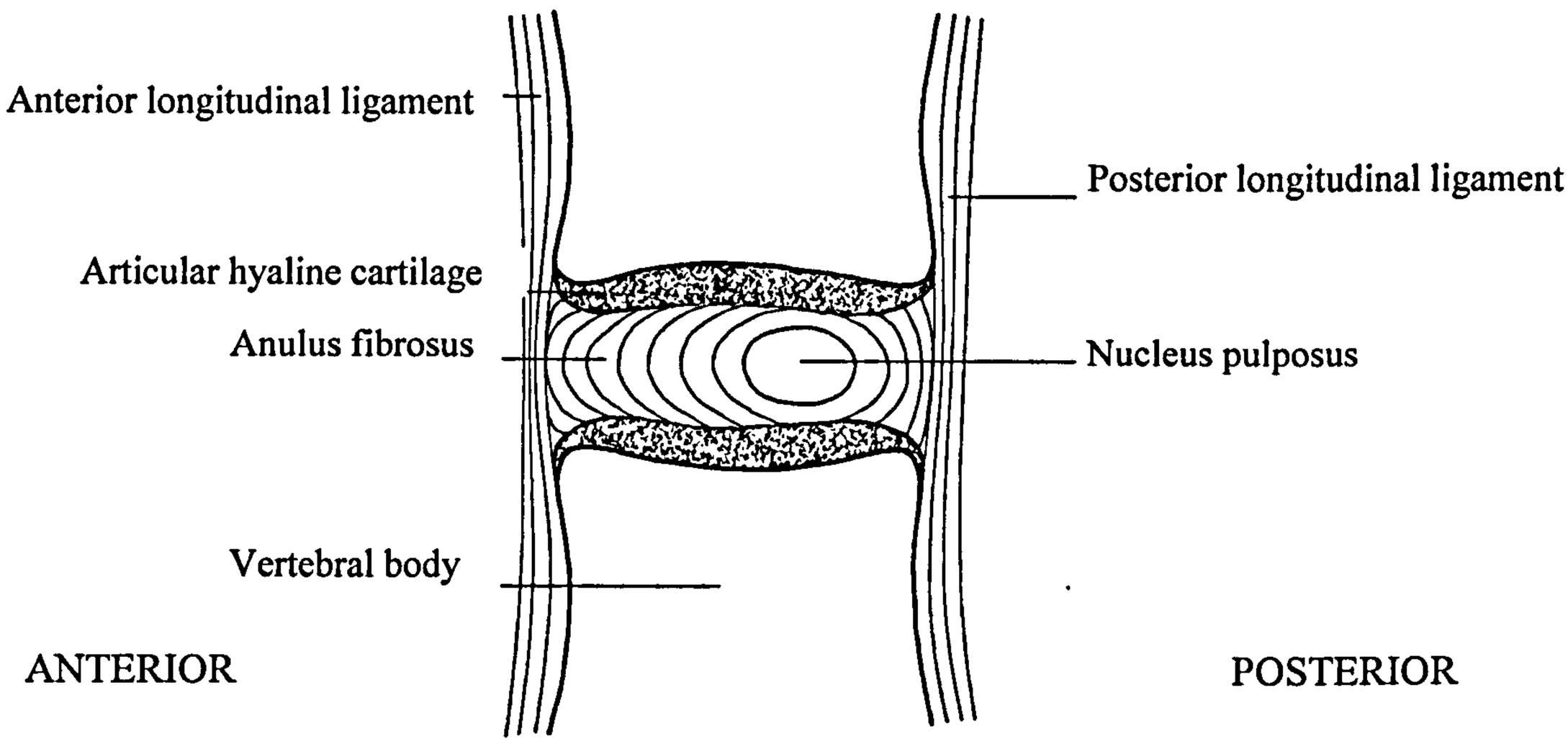



**Figure 3.5 Stylized sagittal section through an intervertebral disc (Adapted from Gunn, 1996: 117. Original Figure No. 9.14)**

The annulus fibrosus is comprised of concentrically arranged, predominately type I collagen fibres in a fibrocartilage medium (Collins, 1949; Jayson, 1998; Jurmain, 1999; Kang *et al.*, 1997; Mankin *et al.*, 1986; Resnick and Niwayama, 1978). These fibres are situated in the outer periphery, but progressively transform to type II at the internal border with the nucleus pulposus (Eyre and Muir, 1976). This arrangement reflects the functional adaptation of the intervertebral disc to its role in weight bearing; type I fibres, mainly responsible for resisting tensile loads, are located externally and type II, characteristically involved in withstanding compressive loads, are arranged on the inner aspect. The collagen fibres which, according to various authors, account for between 50-55% (Mankin and Radin, 1997) and 60-70% (Pedrini-Mille *et al.*, 1983) of the dry weight, are organized into lamellae which vary in size throughout the intervertebral disc, although most are

approximately 20 μm thick (Mankin and Radin, 1997). Those positioned in the anterior third are the most substantial and distinct, while those located in the posterior two-thirds are thinner and more densely packed (Parke and Schiff, 1971). Individual collagen fibres are positioned obliquely between adjacent vertebral bodies (at angles of between 40-70° [Pedrini-Mille *et al.*, 1983]) and reverse their orientation in alternate lamellae (Jayson, 1998; Naylor, 1971; Naylor *et al.,* 1975; Snell, 1986). The most peripheral fibres are attached to the anterior and posterior longitudinal ligaments (Dickson and Wright, 1984; Snell, 1986).

The remainder of the annulus fibrosus consists of between 65-70% water (Naylor, 1971; Urban and McMullin, 1985), proteoglycans and principal glycosaminoglycans (including chondroitin sulphate and keratan sulphate) (Gower and Pedrini, 1969; Oegema *et al.,* 1983) and some glycoprotein (Pearson *et al.,* 1969). The random assembly of the fibres (0.1-0.2 μm diameter) within the substance of the collagenous plates, in combination with the high proportion of interstitial fluid and proteoglycans (Inoue and Tetsuaki, 1975; Skaggs *et al.,* 1944; Urban and McMullin, 1985), confers flexibility to the intervertebral disc.

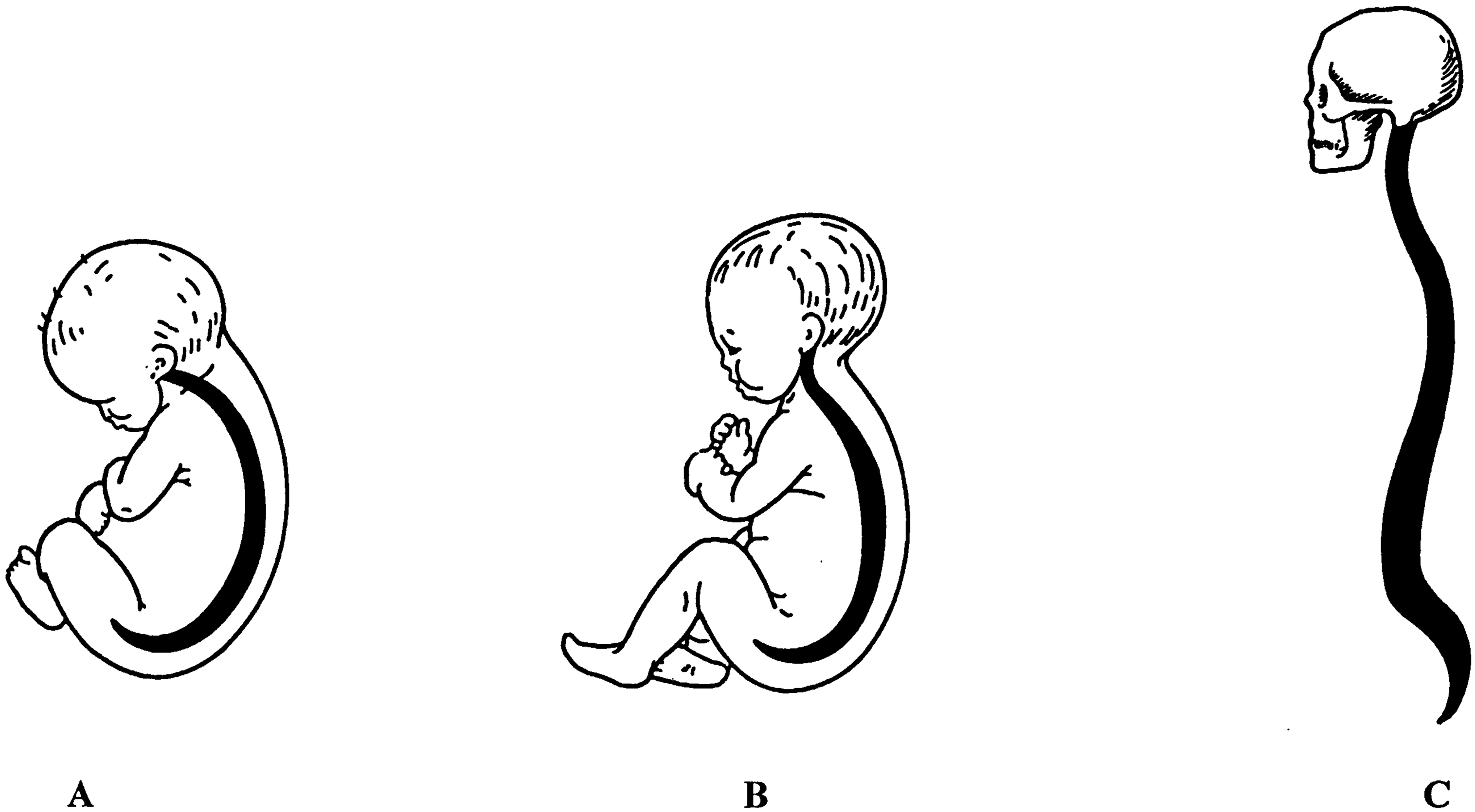
The nucleus pulposus contains a largely water based (between 65-88%, [Mankin and Radin, 1997]) gelatinous material which is proteoglycan rich (Skaggs *et al.,* 1944) and interspersed with cartilage cells and collagen fibres (Collins, 1949; Fithian *et al.,* 1990; Iatridis *et al.*, 1996; Jayson, 1998; Kang *et al.*, 1997; Snell, 1986). It is mainly types II, VI, IX and XI which represent the collagen composition (Iatridis *et al.*, 1996) and account for between 20-30% of the dry weight (Gower and Pedrini, 1969; Naylor, 1971). These fibres are randomly dispersed in the central region, but assume a more oblique orientation as they draw closer to the superior and inferior vertebral cartilaginous plates. They eventually become embedded in this cartilage at the peripheral attachment of the nucleus pulposus (Parke and Schiff, 1971). The nucleus pulposus also contains glycosaminoglycans, the amounts of which are variable and depend upon the age of the individual and the presence of degenerative change, but usually constitute around 50% keratan sulphate, 40% chondroitin 6-sulphate, 5% chondroitin 4-sulphate and <2% hyaluronic acid (Mankin and Radin, 1997). Other glycoproteins (Pearson *et al.,* 1969) and lysosomal enzymes (Naylor *et al.,* 1975) are also evident. The nucleus pulposus tends to be situated towards the posterior aspect of the disc (Gosling *et al.*, 1996; Parke and Schiff, 1971; Snell, 1986), and it is the semifluid nature of this entity which permits it to change shape and allow one vertebra to rock forwards or backwards upon its neighbour (Snell, 1986).

The discs, which represent around 25% of the presacral length of the spine (Collins, 1949; Snell, 1986; Steele and Bramblett, 1988; White and Folkens, 1991), are absent from the atlanto-axial, intersacral and intercoccygeal articulations (Schwartz, 1995; Snell, 1986; White and Folkens, 1991). They vary in size and morphology throughout the vertebral column (Mankin and Radin, 1997), but are basically identical in their organization. The discs are the thickest in the cervical and lumbar regions (Collins, 1949; Resnick and Niwayama, 1978; Snell, 1986; White and Folkens, 1991) where the greatest movement occurs. Unfortunately, their resilience is lost with increasing age (Snell, 1986) as the water content of the nucleus pulposus diminishes (Iatridis *et al.*, 1997; Jayson, 1998) and the proteoglycan content decreases (Adams and Muir, 1976; Coventry *et al.*, 1945; Gower and Pedrini, 1969; Iatridis *et al.*, 1997; Kang *et al.*, 1997; Lipson and Muir, 1981) from around 65% dry weight, to about 30% (Iatridis *et al.*, 1996). Indeed water content is around 90% at birth, and then decreases to about 80% at 20 years and 70% after sixty (Buckwalter, 1995; Iatridis *et al.*, 1996). Collagen loss also occurs, but it is far less marked (Iatridis *et al.*, 1997). In senescence they become very thin and less elastic and it becomes impossible to distinguish between the two structural components (Coventry, 1969).

The intervertebral disc is essentially, as noted earlier in this section, a shock absorber which resists compressive axial biomechanical loading. This is realized through two processes. In the first instance, the annulus fibrosus withstands this pressure by modifying its shape – that is to say it loses height but gains width (Broberg, 1983; Jayson, 1998). Secondly, the hyperhydrated nucleus pulposus can also alter its morphology in response to this stress. With the onset of ageing and degenerative changes, the intervertebral disc becomes incapable of redistributing forces in an isotropic fashion and so pressure loading becomes confined to specific areas and may result in focal damage (Jayson, 1998).

## 3.3 CURVATURE OF THE VERTEBRAL COLUMN

When viewed laterally, the adult human vertebral column is observed to consist of four curves (Figure 3.6C). Those in the cervical and lumbar regions are convex anteriorly, or lordotic (Aiello and Dean, 1990; Clemente, 1997; Gosling *et al.*, 1996; Gunn, 1996; Jones *et al.*, 1992; Palastanga *et al.*, 1994; Snell, 1986; Steele and Bramblett, 1988) and those in the thoracic and sacral segments are concave anteriorly, or kyphotic (Aiello and Dean, 1990; Gosling *et al.*, 1996; Gunn, 1996; Jones *et al.*, 1992; Palastanga *et al.*, 1994; Snell, 1986; Steele and Bramblett, 1988). The thoracic and sacral kyphosis represents the



A B C

**Figure 3.6 Lateral view of curves in the human vertebral column. A) In the newborn B) At three to four months C) In the adult (Adapted from Snell, 1986: 932. Original Figure No. 12-8)**

primary curvatures that develop *in utero* and present at birth (Gunn, 1996; Schwartz, 1995) (Figure 3.6A).

The secondary curvatures develop postnatally and animal studies have demonstrated how hind leg bipedalism intensifies lordotic curvature in both the cervical (Riesenfeld, 1966) and lumbar (Preuschoft *et al.*, 1988; Riesenfeld, 1966) spine. This led to the general conclusion that if locomotor behaviour is modified towards bipedality, a lordosis gradually develops (Preuschoft *et al.*, 1988). Abitol (1987a) had documented similar findings a year earlier on his studies of human children between one and five years of age. Essentially a lordosis develops within the cervical region when an infant begins to hold the head upright around three to four months of age (Aiello and Dean, 1990; Gunn, 1996; Palastanga *et al.*, 1994; Rose and Gamble, 1994; Snell, 1986) (Figure 3.6B) and in the sacral area between 12-18 months of age, once the child gains experience in the support of the erect body against gravity, balance, equilibrium and reciprocating motion (Rose and Gamble, 1994), and thus achieves independent ambulation (Aiello and Dean, 1990; Gunn, 1996; Snell, 1986). This curvature is not fully acquired until after two years when bipedal locomotion and posture are fully developed (Palastanga *et al.*, 1994). It is the development of these secondary curvatures that makes the vertebral column a flexible support, conferring a resilience to axial compression, and thus enabling humans to efficiently balance their weight over the feet.

The lordotic nature of the human spine is accentuated more in females than in males as a result of reproductive requirements (i.e. an increased birth canal in the pelvis) and the more acute angle of the female sacrum (Aiello and Dean, 1990; Palastanga *et al.*, 1994). Indeed, during the latter part of pregnancy, lordosis increases in order to preserve the centre of gravity over the area of contact with the ground (Palastanga *et al.*, 1994; Snell, 1986). Pathological conditions can also increase the lumbar lordosis and these include flexure contraction of the hip (Whittle, 1996).

The curvature also changes with age, with the elderly exhibiting the C-shaped curve reminiscent of the fetal curve. This alteration is largely due to the degenerative changes affecting the intervertebral discs (Palastanga *et al.*, 1994; Snell, 1986).

These extreme curvatures that have just been described are not observed in large apes (Aiello and Dean, 1990), although they, along with humans, do exhibit a lumbosacral angle, or promontorium. Research has discovered that the size of this angle is directly proportional to increasing upright posture (Abitol, 1987b) and that in some species, where

the fetal head is unusually large, an expansion in the size of the birth canal has necessitated sacral repositioning with a consequent increase in this angle (Schultz, 1961).

Thoracic spinal curvature has largely been shown to be a function of vertebral body morphology (Edmondston *et al.*, 1994; Manns *et al.*, 1996; Punjabi *et al.*, 1991), which due to the configuration of the vertebral bodies, accounts for the anterior concavity of the thoracic curve (Punjabi *et al.*, 1991). Goh and associates (1999) investigated the contribution of the intervertebral discs to this thoracic kyphosis. They examined 93 (35 female and 58 male) lateral spine radiographs and 12 midsagittal CT films of *ex vivo* spines and determined the kyphosis from the Cobb angle (McAlister and Shackelford, 1975). Their results showed that the thoracic curvature was dependant on the vertebral body morphology and the intervertebral discs, although a poorer association was noted with the latter. This relationship was also found to be stronger in females. The general trend was for a more pronounced anterior wedging in the midthoraic vertebral bodies and intervertebral discs. Focussed biomechanical loads act at the apex of this thoracic kyphosis (Korovessis *et al.*, 1998; Singer *et al.*, 1994) and the significant association found between the antero-posterior height ratio and the angle of kyphosis further attests to the nature of this loading pattern and the resulting influence on the midthoraic vertebral shape (Goh *et al.*, 1999; Manns *et al.*, 1996; Puche *et al.*, 1995).

## 3.4 BIOMECHANICS OF THE VERTEBRAL COLUMN

### 3.4.1 Movement

The vertebral column consists of a very complex set of active and passive components. The vertebrae themselves are stacked on top of one another and are separated by intervertebral discs. Ligaments form strong attachments between individual elements and serve to restrict movement between adjacent vertebrae. Despite this, the summation of all of the movements elicited at each point confers an impressive degree of mobility to the spine as a whole.

Movements such as flexion, extension and rotation all occur within the vertebral column, but are usually accompanied by hip involvement to some extent (Aiello and Dean, 1990). Furthermore, this movement is dependent upon the thickness of the intervertebral disc and the orientation of the articular facets. The cervical vertebrae are the most mobile. They

permit flexion, extension, rotation, lateral flexion and circumduction of the head (Snell, 1986). In apes, the longer jaws and spinous processes tend to restrict the movements of flexion and extension respectively. Furthermore, lateral flexion is also limited by the relatively higher placed shoulders in these species.

The lumbar vertebrae constitute the next most flexible part of the vertebral column and allow flexion, extension and lateral flexion and rotation (Snell, 1986). In apes this movement is limited due to the close proximity of the ribs to the ilia. This arises not only because of the reduced number of individual vertebrae in this section of the spine, but also as a direct result of the relatively longer iliac blades. The articular facets in this part of the vertebral column consist of concave superior articular facets (facing medially) and convex inferior articular facets (directed laterally). This neatly interlocking configuration prevents rotational movement from occurring and prohibits anterior and lateral slip of a vertebra upon the adjacent, inferiorly positioned neighbour (Aiello and Dean, 1990).

At the articulation of L5 and S1, the anteriorly orientated inferior articular facets of the former serve a very important role in preventing the whole vertebral column from sliding anteriorly off of the highly angled sacrum (Aiello and Dean, 1990; Gosling *et al.*, 1996). In apes, where the sacrum is less acutely angled, there is no change in orientation of the lower lumbar articular facets (Aiello and Dean, 1990).

In the thoracic region, the major movement is rotation (Gosling *et al.*, 1996), but the general structure of the thorax (which acts like a parabolic girder in supporting the trunk) stiffens this area and renders it less mobile than the two aforementioned (Gosling *et al.*, 1996; Snell, 1986).

### 3.4.2 Modelling strategies

The study of posture dynamics is important to the understanding of disorders of impaired equilibrium and protective reactions to unexpected displacements of the human body, as well as helping with design of prostheses and functional neuromuscular stimulation as aids to patients with impaired postural stability and locomotion. Several interacting systems are involved in the dynamics of human posture and locomotion: skeletal, neuromuscular and sensory. Human posture control is maintained by somatosensory, vestibular and visual feedback, integrated within the locomotor and central nervous systems. Muscular and

skeletal organization necessarily entails certain constraints to motion. Certain muscles within the body will therefore be perceived as "prime postural muscles" and are often among the most powerful muscles.

The ligamentous spine supporting the weight of the trunk is inherently unstable. A shift in the centre of gravity of the trunk requires counterbalancing with an active contralateral muscle force. The spine with its ligaments intact, but devoid of muscles, is an extremely unstable structure (White and Panjabi, 1976). The ligaments, muscles and complex neuromuscular controls are required to provide stability of the trunk in a given posture and to produce movements in a given posture subject to physiologic criteria. This posture stability refers to stability of equilibrium and stability of motion in the neuro-musculo-skeletal system. However, it is also appropriate to focus on skeletal properties with emphasis on the static stability provided by among other structures, ligaments and muscles. One definition is that of clinical stability, which is described as the vertebral column's ability to prevent damage and/or irritation to important neural structures when placed under loading, by restricting the amount of displacement taking place (White and Panjabi, 1976). Any disruption of the components holding the spine together, such as ligaments, discs or facets, will decrease the clinical stability of the spine and Webb *et al.*(1976) formulated a tetrad of such clinical stability problems. These include loss of normal cervical lordosis, compression or fracture of subadjacent vertebra, widening of the interspinous space and subluxation of the facet joint.

Bergmark (1989) discussed how models of the human spine are divided into two schools of thought - the simplest force couple model, and the more sophisticated complex models. The former can account for compressive forces between joints, but cannot express tensile forces occurring in ligaments and muscles. The latter, on the other hand, can evaluate loading forces contributed by independent groups of different aligned muscles (*ibid.*). Both models can be employed to determine any force acting on the vertebral column in the transverse plane.

Forces extant in the head, neck and trunk are transmitted from the chest to the pelvis via active components such as muscles and abdominal pressure, and via the vertebral column by active and passive components including bones and ligaments. The articular facets in the vertebral column have a dual role to play in this, in that they transfer forces and confer kinematic constraints to the movement of motion segments (*ibid.*). The articular facets of adjacent vertebra, at different levels in the spine, possess varied geometrical orientation and these influence the kinematic behaviour of the spine (White and Panjabi, 1978). They also serve to transfer shear forces acting on the upper vertebrae in an anterior direction

between two adjacent elements (Bergmark, 1989). The posterior force is counteracted, in the first instance, by the passive stretching of the interspinous ligament (Berksson *et al.*, 1979).

White and Panjabi (1978) noted that a geometric coupling exists between rotation and lateral bending in the spine and that these are different depending on the level of the vertebral column examined. In the thoracic region, lateral bending is combined with rotation of the spinous process towards the convex aspect and the circumferential orientation of the associated articular facets do not restrict rotational motion of adjacent vertebra (Bergmark, 1989). The facet moves to a more radial orientation in the lower thoracic and upper lumbar (T12-L1) levels and this prevents axial rotation occurring and confers the highest rotation stiffness of any of the spinal segments (Bergmark, 1989; Markolf, 1972). In the lower lumbar region, the articular facets become inclined towards the sagittal plane (Bergmark, 1989; Taylor and Twomey, 1986) and this allows an increase in rotational activity to take place, with the spinous process being directed towards the concave side (White and Panjabi, 1978). The role of the anterior, middle and posterior layers of the thoracolumbar fascia must not be underestimated in all of this. These layers are all involved in force transfer in one of three ways: a) from the muscle to the skeleton, b) directly between skeletal elements, and c) between the vertebral column and the *erector spinae* muscle (Bergmark, 1989). The last of these is particularly important as a stabilising factor in the lumbar spine.

Evaluation of the biomechanical behaviour of the vertebral column can only be realized if the relationship between mechanical characteristics, such as load, force, moment and associated deformation of the motion segment is known. In extension, compressive forces are transmitted through the mechanical contact between the tips of the articular facets and the arc of the vertebra positioned inferiorly (Bergmark, 1989). In flexion, tensile forces are transmitted through the capsular ligaments (Adams *et al.*, 1980). In the neutral position, minimal, if any part of the compressive force, is transferred by the articular facets (Adams and Hutton, 1980).

The flexion-extension, axial rotation and lateral bending characteristics are all very important when considering mechanical stability in the sagittal and frontal planes of the vertebral column (Berksson *et al.*, 1979; Markolf, 1972; Nachemson *et al.*, 1979; Panjabi *et al.*, 1976a, b; Schultz *et al.*, 1979). Stiffness characteristics, however, are not linear (Bergmark, 1989) and depend upon aspects of loading elsewhere (Panjabi *et al.*, 1977).

Markolf (1972) showed that the thoracic motion segment of the thoracic region was of greater stiffness in flexion-extension and lateral bending then the lumbar counterparts. One aspect, however, that tended to be overlooked by some investigators (Nachemson *et al.*, 1979; Panjabi *et al.*, 1976a, b; Schultz *et al.*, 1979), was that of axial preload and its influence on bending characteristics.

According to Bergmark (1989), the lumbar spine is modelled as five jointed, rigid vertebrae, with a rigid pelvic base. Each vertebra is allowed to rotate about all three axes (coronal, sagittal and transverse), and because of conferment of these three degrees of freedom, any instability mode may transpire. However, as the intervertebral discs are rendered relatively stiff in respect of axial and shear deformation, it is also assumed that perturbations of this nature can be disregarded.

Muscles that are included within the model include *erector spinae* (which is considered as the most important stabilising and equilibrating component [Bergmark, 1989]), *transversospinalis*, *interspinalis*, *intertransversarii* and *quadratus lumborum*.

In the normal standing position, the motion segments of the vertebral column are considered in the neutral position and the passively carried local moments are regulated by the *interspinales*, *multifidis* and *spinalis* muscles, due to their longest leverage in the sagittal plane (*ibid.*).

Lateral support is conferred generally by the local *erector spinae* muscle fibres, *quadratus lumborum*, *intertransversarii* and the transverse abdominal muscles, with minimal assistance from *internal oblique* (*ibid.*), and is responsible for dealing with the distribution of outer forces on the body. The main local lateral support, on the other hand, is accorded by the former three of the aforementioned group and elicits actions depending on local factors (i.e. the posture of the lumbar spine). Bearing this in mind, if an increase in load is not accompanied by improved muscular tone (for instance in obese individuals or during pregnancy), then back pathology could be exacerbated or initiated.

Broberg and Von Essen (1980) and Broberg (1983) both presented theoretical studies on the mechanical behaviour of intervertebral discs, particularly with respect to stiffness characteristics. The earlier paper, however, neglected one point. In all models of deformation of the disc, the volume inside each fibre layer must remain constant, since the fluid component can be regarded as incompressible when compared with other sources of volume change i.e. geometric changes, fibre elongation and end plate bulging. This latter source was ignored in the earlier paper but included in the later research on the basis of experimental results. The more realistically shaped disc was then subjected to various

deformations and loads, such as compression, flexion-extension, lateral bending, axial rotation, anterior-posterior shear and lateral shear.

Results revealed that an increase in intervertebral disc stiffness was generated with higher compressive preloads in flexion-extension, axial rotation and lateral bending. A major part of the fibre strain seemed to originate from the axial load, at least at higher load levels. Naturally, bending, shear or axial rotation on top of a high axial load is aggravating, but the increase of fibre strain is very moderate.

In conclusion, the authors found that an interesting observation arising from the comparisons conducted was that within normal physiological limits, bending, shear or axial rotation does not seem to constitute a risk of fibre ruptures, except in combination with very high axial loads. At pure compression, the likelihood of fibre rupture is not very great because end plate failure occurs earlier (Perry, 1957). A high axial load combined, for instance, with a large amount of shear could perhaps lead to fibre rupture before end plate failure, since such a combination gives higher fibre forces at the same nucleus pressure than the purely axial load.

Lumbar discs can withstand this loading as a result of the structure of the thoracic and abdominal cavities. They have been converted into almost rigid walled cylinders containing air and liquid/semisolid matter respectively by the action of the trunk musculature. Morris *et al.* (1961) investigated this by examining the action and effect of thoracic and abdominal muscles under various loading conditions in ten healthy male subjects. Loading was basically divided into two categories: static, where the subjects pulled on a strain ring; and dynamic, where weights were lifted. Intrathoracic and intra-abdominal pressures were recorded along with the electrical activity of the muscles of the trunk. Their results, for this extremely small sample, certainly seemed to support the hypothesis that both thoracic and abdominal chambers were capable of transmitting some of the forces generated in loading the trunk, and thus relieving the spine of this load.

It has already been noted that the vertebral column is vertical in the coronal plane and curved in the sagittal plane, thus producing the characteristic four curves. In this way, the spine resembles a vertical column which has buckled under application of an axial load (Meakin *et al.*, 1997; Miller and Dickson, 1996). This notion, has subsequently led to a number of publications concerning the mathematical applications of buckling theory. Crisco and colleagues (1992) published results of experimental buckling of human cadaveric spines and subsequently produced a model for interpreting the results (Crisco and Panjabi, 1992).

Meakin and associates (1996) were the first researchers to apply buckling theory as a model for flexion and curvature within the human lumbar spine. Other studies prior to this had utilized these principles, but only to investigate the mechanism of scoliosis - either as a direct result of buckling (Belytschko *et al.*, 1973; Lindbeck, 1985; Patwardhan *et al.*, 1986), or as a condition influencing the normal vertebral column (Miller and Dickson, 1996; Pelker and Gage, 1982).

Meakin *et al.* (1996) developed two simple models to examine static and dynamic parameters. To achieve this, they considered the spine as an Euler[1] column, which could buckle under an axial load, and as an Euler pendulum which, when displaced by a lateral force, can express periodic motion.

Their results indicated that the vertebral column acts like an Euler column buckled in the second (n=2) mode. This structure is beneficial in that it can support increased loads without generating postural change (i.e. stooping). If the spine is flexed, then it acts like an Euler pendulum, by changing its shape from a second (n=2) to an unbuckled mode. The pendular activity is terminated in the required position in an n=1 buckled mode by the intermediacy of spinal muscular contraction.

From the anatomical point of view, spine stiffness can be seen to present in two forms: intrinsic and active. Intrinsic stiffness arises from the structural properties of the intervertebral discs and ligaments. Active stiffness originates in the contractility of the surrounding musculature (Meakin *et al.*, 1996; Morris *et al.*, 1961). Ebara and associates (1992) documented how the intrinsic stiffness within the vertebral column can be reduced to 65% of its normal value by intervertebral disc degeneration or damage. Clinical instability (where a patient uses their arms to rise from a sitting or stooping position) may be related to a decrease in the intrinsic stiffness. Pope and Panjabi (1985) considered instability as a loss of stiffness in their static modelling of spinal instability. Together with this, muscular weakness will also render an individual less able to sustain a static carriage. If dynamic behaviour is considered, then it is ineffective adaptive control (comprising active and passive elements) that becomes responsible for spinal instability.

[1] Leonhard Euler (1707-1783) was an important Swiss mathematician who was largely responsible for composing most of the language and notation that is employed in modern mathematics (Boyer, 1991).

# CHAPTER 4 BIPEDAL POSTURE AND LOCOMOTION

There is a tendency in all primates to assume erect posture and some bipedalism, but it is only in the hominids that efficient bipedalism, as the primary form of locomotion, is exacted (Jurmain and Nelson, 1994; Lewin, 1998). The structural changes required for this form of locomotion are all observed in the earliest hominids from East and South Africa (Jurmain and Nelson, 1994), and basically consist of evolutionary adaptations which have allowed the species to assume an upright posture with the centre of gravity positioned directly over the relatively small rectangle formed by the lateral margins of the feet, and with hips and knees extended.

Only humans display an alternating bipedal gait (Campbell, 1998). This permanent balancing act has led to important changes in the structure and function of the human skeleton, so that the weight of the whole body may be transported with maximum stability and minimum effort (Campbell, 1998). In order to appreciate the ramifications of this, it is important to understand the role of the centre of gravity in this scenario, because the energy that is available for locomotory purposes is directly related to the position of this entity. The centre of gravity describes the centre of mass operating in one axis only - that defined by the direction of gravity (Winter, 1990). It can also be considered as the point at which all of the weight of the body may be concentrated, and about which the object can, in theory, be balanced (Bell, 1998).

Larger bodies possess the energetically advantageous anterior centre of gravity, whereas smaller organisms (and most primates are considered as such), demonstrate a posterior one (Kimura *et al.*, 1979). These facts explain why the hindlimb evolved as the dominant appendage - a posterior centre of gravity allows for practicable sitting and the forelimbs are free for manipulation (Jurmain and Nelson, 1994; Lewin, 1998; Palastenga *et al.*, 1994; Tattersall, 1998). The low centre of gravity developed due to the expansion and advancement of the hindlimb, the reduced musculature in the forelimb, and changes in the morphology of the trunk (Campbell, 1998; Palastenga *et al.*, 1994). In adult humans the body is not fixed and rigid, so no unique centre of gravity exists for it (Duval-Beaupère *et al.*, 1992). However, if motion is minimized and an individual assumes the standard anatomical position[1], the centre of gravity can be determined to lie in the midline, just anterior to the second sacral vertebra (Aiello and Dean, 1990; Bell, 1998; Palastenga *et al.*,

[1] The standard anatomical position is described when an individual stands upright with the upper limbs by the side of the body and the face and palmar aspect of the hands all facing forward (Snell, 1986; Steele and Bramblett, 1988)

1994; Whittle, 1996). Other authorities have described its position as lying between and a little above the hip joints (Jones *et al.*, 1992)

Other research has examined the relationship between the vertebrae, the sacrum or the coxofemoral rotation axis and the centre of weight that they support. Results from these investigations have shown that the centre of weight supported by the coxofemoral joint generally lies in front of T9 (range T8 to T10) (Duval-Beaupère *et al.*, 1992).

It is outside the remit of this thesis to investigate the complex aspects of bipedal locomotion (or gait analysis) in humans and the complex issues surrounding the ecological factors responsible for the development of bipedalism, but rather to examine the evolutionary changes that have affected the pelvis and vertebral column in the acquisition of an upright posture. It is hoped that when the results of this research is reviewed in light of this information, a fuller understanding of the implications of these evolutionary adaptations in health and disease may be realized.

## 4.1 EVOLUTION OF THE HUMAN PELVIS

Berge's (1998) ontogenetic study of the hominoid pelvis, confirmed views that pelvic growth patterns differ greatly between humans and the African apes. She further concluded that at the time of birth, distinct features develop in the human pelvis. These include the acetabulo-cristal buttress, which is situated on the anterior aspect of the ilium and extends to an area of the iliac crest close to a second feature, known as the cristal tubercle. This entity is anteriorly positioned very close to the anterior superior iliac spine (Berge, 1998). The appearance of these traits allows for the development of a more sagittally orientated ilia, and a proportionally narrower pelvis. (*ibid.*). Pelvic proportions and orientation progressively alter during the early years of childhood as bipedal practices are explored. This is succeeded in adolescence by additional changes in the proportions of the pelvis (*ibid.*). These changes will be considered in greater detail in sections 4.1.1 and 4.1.2 below.

### 4.1.1 The Ilium

A number of adaptations have occurred in the innominate bone. The blade of the ilium has become more laterally oriented (Robinson, 1972) as it has shortened and widened (Aiello and Dean, 1990; Campbell, 1998; Jones *et al.*, 1992; Jurmain and Nelson, 1994; Lewin,

1998; Lee, 1999; Lewin, 1999) and this resulted in the development of an S-shaped crest, a convex gluteal surface and a concave iliac fossa (Aiello and Dean, 1990; Jones *et al.*, 1992; Lee, 1999; Robinson, 1972). This structural change is important as certain muscles (*iliacus* and gluteal) effecting movement originate from this area and as the hindlimb power developed, there was a concomitant increase in the muscle bulk, necessitating a greater surface area for attachment. The iliac crest itself forms the attachment site for the lateral abdominal muscles and therefore acts in the capacity as a stress member for the parabolic girder balancing the trunk above the pelvis (Aiello and Dean, 1990; Campbell, 1998).

This specific shape further allowed more stable weight support in the erect position by lowering the centre of gravity (Jurmain and Nelson, 1994). This, together with the lumbar curvature and longer hindlimbs, brought the knees closer to the centre of the body to form the valgus angle of the femur. It also steered the great toe in line with the other toes (Lewin, 1998; 1999).

As the ilial length reduced, the size of the pelvic inlet was maintained by other means. The posterior expansion of the ilium and well developed sciatic notch bears testimony to this permutation (Robinson, 1972).

In the ischium, the main anatomical changes reflected an alteration in the function of the hamstring muscles. Although these muscles are still involved in femoral extension, constant activity is not a requirement of bipedal posture and so the ischial body and tuberosity have concomitantly reduced in length and width (Lee, 1999; Robinson, 1972). In addition to the abridgement of the ischial tuberosities, they have also migrated further apart. The lateral and superior displacement of these entities has led, not only to the acquirement of a more stable sitting position, but also to conferment of enhanced leverage to *biceps femoris* (Aiello and Dean, 1990; Campbell, 1998), one of the main components of the hamstring muscles.

The relative transmutation of musculature within the thigh and gluteal regions has, for the greater part, allowed the more efficient adoption of bipedal posture and locomotion. If the flexor and extensors of the hip are examined, it can be appreciated that their development in humans is relatively greater than in other primates. This reflects that humans depend entirely upon these structures for locomotory purposes involving movement of a proportionately heavier lower limb (Campbell, 1998). The rotation of the innominate bone has therefore led to the lateral aspect now facing anteriorly (Lee, 1999). Indeed, the anterior location of the iliac fossa and posterior orientation of the gluteal region further

enhance the trunk balancing abilities of the *iliacus* and gluteal muscles respectively (Aiello and Dean, 1990; Lee, 1999). In apes, the *gluteus medius* and *minimus* are femoral extensors, but in humans they abduct this element (Lee, 1999).

The most important extensors of the hip joint are the "hamstrings", which lie in the posterior compartment of the thigh. These consist of three muscles; *biceps femoris, semitendinosus* and *semimembranosus*. *Biceps femoris* possesses two heads - the long one takes its origin from the ischial tuberosity and sacrotuberous ligament (Gosling *et al.*, 1996; Snell, 1986; Stone and Stone, 1997) and the short one, from the linea aspera, lateral supracondylar ridge and lateral intermuscular septum (Clemente, 1997; Gosling *et al.*, 1996; Palastanga *et al.*, 1994; Snell, 1986; Stone and Stone, 1997). *Biceps femoris* inserts into both the lateral condyle of the tibia and the lateral aspect of the head of the fibula (Gosling *et al.*, 1996; Palastanga *et al.*, 1994; Snell, 1986; Stone and Stone, 1997). *Semitendinosus* and *semimembranosus* each take their origins from the ischial tuberosity (*ibid.*) and insert into the medial shaft of the tibia and posterior part of the medial condyle of the tibia respectively (*ibid.*). It is quite interesting to note that the actual origin of *semimembranosus* lies on the superior aspect of the ischial tuberosity and in close proximity to the acetabular rim (Stern and Susman, 1983). This arrangement has led to a decrease in the width of the tuberoacetabular sulcus (*ibid.*) and could have arisen as a direct result of load bearing stresses acting on the sacrum. The weight of the trunk depresses the anterior aspect of the sacrum and induces the posterior part to rise. The sacrotuberous ligament, which is attached to the sacrum and the ischial tuberosity, prevents this latter action from occurring. Resultant tension in this ligament could explain why the ischial tuberosity appears to be located in a more superior position (Aiello and Dean, 1990).

The extensor action of these muscles is very important in locomotion and has been reinforced by the action of *gluteus maximus* (Jurmain and Nelson, 1994). In other primates this muscle acts as an abductor (Campbell, 1998; Jones *et al.*, 1992), but in humans, although the upper part serves to undertake this movement, the lower aspect, which lies posterior to the acetabulum due to the change in curvature of the blade of the ilium, elicits extension of the hip (as well as lateral rotation of the thigh and extension of the trunk [Gosling *et al.*, 1996; Palastanga *et al.*, 1994; Snell, 1986; Stone and Stone, 1997]). *Gluteus maximus* is not a postural muscle as such (Stone and Stone, 1997), but mainly functions in forceful extension encountered in running (Campbell, 1998; Clemente, 1997; Gosling *et al.*, 1996; Palastanga *et al.*, 1994; Stone and Stone, 1997), climbing (Campbell, 1998; Gosling *et al.*, 1996; Palastanga *et al.*, 1994; Stone and Stone, 1997), walking

upstairs (Campbell, 1998) and rising from a sitting or squatting position (Campbell, 1998; Clemente, 1997; Palastanga *et al.*, 1994; Snell, 1986; Stone and Stone, 1997).

During bipedal locomotion, weight transference occurs through each of the lower limbs in turn. During each swing phase of the gait cycle, the unsupported side of the pelvis is subject to downward displacement, but contraction of the opposing gluteal muscles (notably *gluteus medius* and *minimus*) guards against this tilting by abducting the hip on that side (Gosling *et al.*, 1996; Jurmain and Nelson, 1994; Lee, 1999; Lewin, 1998; McMinn and Hutchings, 1985; Rose and Gamble, 1994; Palastanga *et al.*, 1994; Snell, 1986; Stone and Stone, 1997; Whittle, 1996), and ensuring that the body's centre of gravity remains over the three loading centres in the foot (heel, hallux and fifth toe), otherwise known as the pedal triangle (Campbell, 1998). Simultaneous contraction of the associated adductors of the thigh help to maintain the balance (Gosling *et al.*, 1996; Palastanga *et al.*, 1994). This arrangement is unique to humans, with respect to their attachment sites. *Gluteus medius* has its origin on the outer surface of the ilium, between the posterior and mid gluteal lines, and inferior to the iliac crest (Gosling *et al.*, 1996; Snell, 1986; Stone and Stone, 1997) and inserts onto the lateral surface of the greater trochanter (Gosling *et al.*, 1996; Snell, 1986; Stone and Stone, 1997). The origin of *gluteus minimus* lies on the outer surface of the ilium between the mid (anterior) and inferior gluteal lines (Gosling *et al.*, 1996; Snell, 1986; Stone and Stone, 1997) and inserts into the anterior surface of the greater trochanter (Gosling *et al.*, 1996; Snell, 1986; Stone and Stone, 1997). In other primates, the *gluteus medius* and *gluteus minimus* are positioned posteriorly to the hip joint and thus act mainly as extensors, while *gluteus maximus* behaves as an abductor (as already noted) (Aiello and Dean, 1990; Tuttle *et al.*, 1979).

Two osteological structures on the ilium, the iliac tubercle and iliac pillar, are unique to humans (Mednick, 1955) in this respect and serve to focus contractional forces elicited by the *gluteus medius* when it abducts the hip (Aiello and Dean, 1990). The leverage of these muscles has necessarily increased by the accompanying lateral extension of the ilium and lengthening of the femoral neck (Campbell, 1998).

The anterior inferior iliac spine is particularly pronounced (unlike in other apes [Aiello and Dean, 1990; Robinson, 1972]) and this represents the area where the anterior head of the *rectus femoris* (one of the most important flexor muscles) takes its origin (Gosling *et al.*, 1996; Snell, 1986; Stone and Stone, 1997). The posterior head takes its origin on the ilium above the acetabulum (Gosling *et al.*, 1996; Snell, 1986; Palastanga *et al.*, 1994; Stone and Stone, 1997). The iliofemoral ligament also attaches to the anterior inferior iliac spine and

extends anterior to the hip joint to the intertrochanteric line of the femur (Gosling *et al.*, 1996; McMinn and Hutchings, 1985; Palastanga *et al.*, 1994; Snell, 1986). This structure further serves to maintain balance by tightening during full extension of the hip and thus preventing hyperextension from taking place (Aiello and Dean, 1990). *Sartorius* and *tensor fasciae latae* have their origins on, and in the vicinity of, respectively, the anterior superior iliac spine (Gosling *et al.*, 1996; Snell, 1986; Stone and Stone, 1997) and the latter certainly is provided with more efficient direction for operation (particularly in relation to the operation of *gluteus maximus*) in this regard.

### 4.1.2 The Sacrum

The human sacrum is wider than those of other primates (Aiello and Dean, 1990; Campbell, 1998; Palastanga *et al.*, 1994; Robinson, 1972) in relation to body weight, trunk length and the articular area for the fifth lumbar vertebra (Abitbol, 1987a; Leutenegger, 1977). In addition, it has a greater longitudinal curvature and larger articular surface (Aiello and Dean, 1990). These characteristics strongly support the theory that this skeletal element supports the entire weight of the upper body in bipedal posture.

The increased sacral width essentially pushed the ilia apart, and led to an increase in the separation of the sacro-iliac joints, so that they became positioned more vertically over the hip bones. This adaptation effectively diminished the rotational movement of the innominate bones at the sacro-iliac joint and thus reduced the stress placed on the symphysis pubis (Leutenegger, 1977). A further result of this sacral expansion is that the basin of the false pelvis now began to serve an important role in helping to support the abdominal viscera. The anterior superior iliac spine assists with this function by "bending" itself further around and producing a change in the position of the inguinal ligament which attaches there (Gosling *et al.*, 1996; McMinn and Hutchings, 1985; Snell, 1986) and also onto the pubic tubercle (*ibid.*). This structure forms an important conformational feature in the otherwise cavernous anteroinferior pelvis (Robinson, 1972).

The large, posteriorly facing aspect of the sacrum (together with the large iliac tuberosities) also fulfils a major role in bipedal stance, by providing an adequate attachment site and increased leverage for the *erector spinae* muscle (Campbell, 1998), which serves to balance the vertebral column on the pelvis (Aiello and Dean, 1990).

Some investigators such as Lovejoy and colleagues (1973) have postulated that the adoption of a horizontal position by the sacrum has arisen as a result of reproductive

requirements. In this scenario, the enlarged fetal head is free to pass through an adequately sized anteroposterior diameter, due to the posterior placement of the sacrum. If this arrangement had not been realized, then these authors concur that the relatively short human ilium would render the anteroposterior diameter too small to accommodate parturition. Other authorities (Abitbol, 1987b; Stern and Susman, 1983) have been quick to point out that this orientation may be attributed to the demands of bipedalism anyway. Indeed, Stern and Susman (1983) stressed that a sacrum positioned posterior to the hip joint would essentially bring the gravitational line of the vertical upper body closer to the acetabulum, instead of anterior to it, thus enhancing locomotor ability.

## 4.2 RECIPROCITY BETWEEN BIPEDALISM AND REPRODUCTION

Modification in the female pelvis has occurred all the way around the pelvic inlet for two basic reasons. In the first instance, it was vital to maintain a large enough true pelvis in a structure where the innominates were reducing in length, and secondly, there had to be allowance for an increase in the absolute size of the true pelvis in the latter aspects of hominid evolution, so that the increasing fetal head size (due to encephalization) at birth could be accommodated (Robinson, 1972). In order to achieve this, the ilium expanded backwards (which assisted in moving the centre of gravity backwards too - a favourable outcome with the trunk in an erect position) and the sacrum expanded in breadth. However, this arrangement led to a decrease in the axis between the sacrum and the acetabulum which impacted upon the dimensions of the birth canal. As a direct result, the angulation with the ischium began to increase to compensate and this culminated in the formation of a relatively deep sciatic notch and an accentuated ischial spine.
It is the latter which forms the insertion site for the sacrospinous ligament (Gosling *et al.*, 1996; Palastanga *et al.*, 1994; Snell, 1986) and the important *levator ani* (comprising *levator prostatae* or *sphincter vaginae* anteriorly, *puborectalis* and *pubococcygeus* intermediately, and *iliococcygeus* posteriorly) and *coccygeus* muscles which form the inferior pelvic wall, or pelvic floor (Clemente, 1997; Gosling *et al.*, 1996; Palastanga *et al.*, 1994; Snell, 1986). Abitbol (1988) opined that it was this musculature (supporting the contents of the abdominopelvic cavity) that stressed the ischial spines and led to their prominent appearance.

From the point of view of sexual dimorphic characteristics, the sciatic notch is normally more acute in the male, a configuration resulting from an accentuated angulation of the

ilium (Campbell, 1998). This means that although the female birth canal (and therefore the morphology of the pelvis) is functionally governed by reproductive requirements and related to the size of the fetal head which needs to pass through it at birth, a male pelvis is controlled solely by locomotor factors (*ibid.*). Moscucci (1990) noted how such authors as Garson (1881-2) and Vrolik (1826) had published on this aspect of adaptation during the nineteenth century, and noted how bipedalism had severely restricted the capaciousness of the pelvis and the birth canal itself (Aiello and Dean, 1990). Reproductive demands have certainly led to less efficient bipedalism in females, a point all too clearly evidenced by the differences observed between male and female Olympic running and jumping records (Jones *et al.*, 1992).

In humans the size of the newborn body and head is large compared to the size of the birth canal. This fact means that for the first time, among the primates, the sagittal diameter of this canal became critical as a direct consequence of the altered relationship between the sacrum and the diminished pubic symphysis (Lee, 1999; Robinson, 1972) - which was now lying in closer approximation due to the ilial shortening.

Contemplation of the skeletal adaptations to bipedalism has, so far, concentrated on the pelvis. There are, however, other osseous manifestations. Those concerned with vertebral structure and femoral realignment shall be discussed next.

## 4.3 BIOMECHANICAL ASPECTS OF THE ATLANTO-OCCIPITAL ARTICULATION

As a consequence of the upright posture in humans, the head, although it is heavy, is balanced on top of the vertebral column. This led, in the past, to the suggestion that a clear relationship must exist between the position of the occipital condyles and foramen magnum and posture (Aiello and Dean, 1990; Jones *et al.*, 1992). Early researchers documented their beliefs that a more anteriorly positioned occipital condyle was indicative of erect posture and bipedal locomotion (Broom, 1938; Dart, 1925) and this is now accepted as fact (Lewin, 1998; 1999).

During the evolutionary process, the face/muzzle began to reduce in size and the brain started to enlarge. This development meant that the centre of gravity of the head moved almost over the pivot point upon the vertebral column (Campbell, 1998) and this alteration in position clearly effected the forces required to balance and move the head on the

cervical spine. This is mirrored in the anatomy and power of the neck musculature (Palastanga *et al.*, 1994) and the development of the spinous processes in the cervical region. It would not have been desirable for the centre of gravity to be perfectly balanced over the occipital condyles, because there are no powerful prevertebral muscles to support the head from the front. As a consequence, the centre of gravity lies just anterior to the occipital condyles and is balanced by the postvertebral musculature.

In all primates, the weight of the head and face anterior to the occipital condyles is heavier than that posterior to them. This means that more force is required to raise the face and the nuchal attachment area is extremely pronounced as a result. In contrast, the nuchal area is comparatively small in humans (Campbell, 1998; Jones *et al.*, 1992; Palastanga *et al.*, 1994).

The spinous processes also differ between human and great apes. Where the latter all express a long, pronounced morphology, the former exhibits relatively short structures along the length of the vertebral column (Aiello and Dean, 1990; Campbell, 1998; Palastanga *et al.*, 1994), reflecting a somewhat diminished responsibility in maintenance of balance of the head at the top of this vertical structure.

## 4.4 LUMBAR CURVATURE AND THE ROLE OF THE SACRO-ILIAC JOINT

A rotation of the sacrum in relation to the ilium would have assisted in maintaining the trunk vertically, but that arrangement would have led to obstruction of the birth canal by the coccyx. Likewise, a complete rotation of the whole pelvis could have straightened the spine, but that would have produced an inferiorly directed pair of ischia and thus resulted in an inability to extend the femur past this point. A compromise was met by leaving the pelvis in an almost original attitude and then rotating the sacrum in the opposite direction to that required to make the vertebral column vertical. The strong lumbar curvature then ensued, in order to effect erection of the spine.

The ilial angulation also influences the sacral position in the pelvis so that the symphysis pubis and the sacrum have acquired the position almost, of the floor and roof of the pelvic cavity respectively, (rather than the anterior and posterior walls) and the vertebral column has come to lie at about right angles to the axis of the pelvic canal (Campbell, 1998; Robinson, 1972). As a consequence of this adaptation, the area of articulation between the sacrum and innominate has also enlarged due to the increased weight transmission levelled

upon it (Lee, 1999; Robinson, 1972). This element itself has also become more incongruous, thus facilitating intrapelvic stability (Lee, 1999). This phenomenon also explains the relative enlargement in the structure of the acetabulum and femoral head during evolutionary processes. The sacro-iliac joint is also situated closer to the hip joint (Aiello and Dean, 1990; Jones *et al.*, 1992), thus decreasing the forces that are transmitted through the ilium to the acetabulum in the upright posture (Aiello and Dean, 1990) as well as enhancing transmission of the weight of the trunk more efficiently and conferring greater stability (Campbell, 1998).

Indeed, it is noted that if the centres of the sacro-iliac joint and the acetabulum form a vertical line when the sagittal plane of the pelvis is viewed laterally, then erect posture becomes effortless (Lee, 1999). In this case, the bodyweight is more efficiently balanced and tends to extend the pelvic girdle on the femora, but slight mobilization of *psoas major* can be called into play to maintain the optimal bipedal stance (*ibid.*).

Enlargement of the anterior and posterior aspects of the innominate bones have allowed greater areas of origin of muscles to develop and hence even greater leverage across the hip joint (Campbell, 1998), thus aiding locomotion. This is also noted with respect to the attachment of a complex of three sets of muscles (*iliocostalis* - laterally, *longissimus* - intermediate and *spinalis* - medially) which comprise the *erector spinae* (Aiello and Dean, 1990; Clemente, 1997; Gosling *et al.*, 1996; McMinn and Hutchings, 1985; Snell, 1986; Stone and Stone, 1997), and which interconnect the sacrum, iliac crest, base of the skull and intervening vertebrae and ribs (Clemente, 1997; Gosling *et al.*, 1996; Stone and Stone, 1997). This muscle is of particular importance in movements of the vertebral column, but especially with respect to extension, and therefore maintenance, of bipedal posture.

Specific, as well as general, changes are also evident in the vertebral column and these are demonstrated by consideration of the individual vertebral elements. Although the vertebrae are wider than they are tall in both humans and apes (Rose, 1975), other proportional relationships of individual vertebrae and major segments within the vertebral column do exist between these species. Humans possess a comparatively larger lumbar region in relation to total presacral length (Aiello and Dean, 1990) and the size of individual elements progressively increases down the spine (Aiello and Dean, 1990; Campbell, 1998; Palastanga *et al.*, 1994). The lumbar vertebrae themselves are also remarkably wide for the given length of the trunk (Schultz, 1961) and display greater robusticity when compared to the large apes (*ibid.*). This adaptive increase in size can be

explained by increases in lengths and breadths of the lumbar vertebrae which have developed in response to increased transmitted loads generated by a bipedal posture (Campbell, 1998; Rose, 1975; Schultz, 1953, 1961). One other specific attribute of the lumbar region is the wedging that occurs due to inferiorly progressing decreasing posterior vertebral body height. The lumbosacral index numerically represents the ratio of posterior to anterior height and in comparison with large apes, this value is particularly low for the fifth human lumbar vertebra, in which there is marked posterior wedging of the element.

Facet orientation, as already seen, also plays a major role in the type of movement permitted. In the cervical region, the superior articular facets of the atlas are more concave in apes than in humans (Aiello and Dean, 1990). The odontoid peg is also more vertical in humans, when viewed from the lateral aspect (*ibid.*). The angulation of the superior articular facets of the cervical vertebrae in general to the transverse plane is also smaller in humans (*ibid.*).

## 4.5 FEMORAL-PELVIC RESPONSES TO BIPEDALISM

Ruff (1995) examined the functional relationship between pelvic and femoral structure in humans by using theoretical biomechanical models and empirical tests in modern samples of individuals with differing body structure.

He noted that a long femoral neck increases the mediolateral bending of the femoral shaft and thus decreases the reaction forces in the gluteal abductors and hip joint. If the increased femoral length is combined with an increased biacetabular breadth, then further increases in the mediolateral bending of the femoral diaphysis may take place and abductor and joint reaction forces will be maintained at "normal" levels.

When *Homo erectus* and "*erectus*-like" specimens were examined, it was observed that these each possessed long femoral necks and a greatly increased mediolateral (relative to anteroposterior) bending strength of the femoral shaft. There was, however, no decrease in hip size and therefore most likely an increase in abductor force (relative to body size). Ruff (1995) suggested that this pointed to a long femoral neck and biacetabular breadth in early *Homo*.

The *Homo* specimens also exhibited a very wide transverse structure and a much shorter anteroposterior element, characteristics that had been noted in *Australopithecus*, and this was strongly suggestive of a non-rotational birth process. During, or after, transition to rotational birth in the late Pleistocene, the biacetabular breath decreased, thus reducing the

weight of the body moment about the hip joint and allowing the femoral neck (abductor moment arm of model) to also decrease. Both of these changes led to a reduced mediolateral bending of the proximal femoral shaft.

The acetabulum also plays a role in the orientation of the femur. In the human pelvis it has become much deeper and faces anterolaterally and inferiorly (Lee, 1999). This serves to project the femoral neck anteriorly and along with that ensures that the leg adducts at heel strike during the gait cycle to place the foot beneath the acetabulum (*ibid.*). This arrangement renders the superior border of the articular surface susceptible to the greatest pressure during bipedal motion.

# CHAPTER 5 JOINT DISEASE IN THE VERTEBRAL COLUMN

It is a fundamental fact of life that "ageing is a form of inescapable deterioration which afflicts complex organisms" (Kirkwood and Holliday, 1986:1). The gradual deterioration of tissues within the body, which occurs with advancing age, leads to a whole host of degenerative processes. Skeletal material, and joints in particular, are no exception and express such changes through both proliferative and destructive mechanisms. However, age is not the only predisposing factor to the development of joint disease. Ethnic group, sex, genetic predisposition, pre-existing or intercurrent disease, occupational practices and diet are other factors, among the many, that contribute to its occurrence.

Essentially there are two areas in the spine that may develop degenerative change. These are a) the diarthrodial, apophyseal, zygapophyseal or facet joints, and include the Luschka joints in the cervical spine and b) the amphiarthroses, or intervertebral discs. The diarthrodial (hereafter referred to as apophyseal) joints allow movement, but provide minimal support. The amphiarthroses (hereafter referred to as intervertebral discs), on the other hand, afford support but with nominal movement. This functional difference is reflected in the inverse pattern of degenerative joint disease occurring between the two joints (Knüsel *et al.*, 1997). Degenerative joint disease in the apophyseal joints reflects stresses in the vertebral column by movement reducing or accentuating curvature. The intervertebral joints reflect curvature and distance away from the line of gravity and the greatest changes are found at points furthest away. The apophyseal joints are synovial in nature and develop osteoarthritic change. The intervertebral discs are fibrocartilaginous and degenerative change may produce vertebral spondylosis (osteophytosis) or herniation. These three manifestations present the most frequently encountered types of vertebral pathology, both in clinical contexts and in palaeopathology. As such, they have been selected for further examination in this thesis and are discussed in turn in the subsequent sections.

## 5.1 OSTEOARTHRITIS

Osteoarthritis is a condition that has been present throughout human history, with skeletal material from the Neolithic period demonstrating evidence of the disease (Dieppe, 1994). As a consequence, it is often referred to as the commonest occurring joint condition

(Aufderheide and Rodríguez-Martin, 1998; Centeno, 1999; Cooper, 1994; Dieppe, 1994; Doherty *et al.,* 1998; Hope *et al.*, 1989; Kumar and Clark, 1987; McKeag, 1992; Roberts and Manchester, 1995; Rogers, 2000; Rogers and Waldron, 1995; White and Folkens, 1991), but the exact definition of what constitutes this condition is still controversial. The suffix "itis" tends to imply an inflammatory component in the aetiopathogenesis, but a number of authorities state that there is no such thing (Collier *et al.*, 1991; Ortner and Putschar, 1985; Schwartz, 1995). Other researchers argue that although not an attribute of the condition in itself, inflammatory changes may complicate the disease process, while others, such as Jasin (1989) recognize a significant inflammatory component, particularly with respect to synovial inflammatory responses. The latter discusses immunological mechanisms which contribute to both the maintenance and the severity of synovitis in osteoarthritis. Mankin *et al.* (1986), however, point out that the role of inflammation in the initiation and progression of cartilage damage, is far from clear. The term degenerative joint disease has also been suggested (Aufderheide and Rodríguez-Martin, 1998; Collier *et al.*, 1991; Dieppe, 1994; Jurmain, 1999; Mankin *et al.*, 1986; McKeag, 1992; Ortner and Putschar, 1985; White and Folkens, 1991), but has also received negative reviews as this label implies a condition that is primarily associated with increasing age (Dieppe, 1987). An alternative term, osteoarthrosis, has also been introduced (Collier *et al.*, 1991; Gardner, 1983; Mankin *et al.*, 1986; McKeag, 1992; Schwartz, 1995) in an attempt to reduce emphasize the inflammatory aspect. However, in the United Kingdom and the United States, at present, the term osteoarthritis appears to be the preferred notation and so will be used in the context of this thesis.

Perhaps the absolute terminology is not of primary importance here. Dieppe (1994) notes that other means of defining this condition exist, such as those recorded by Mankin *et al.* (1986), which include clinical, pathological, biochemical, biomechanical, histological, not to mention therapeutic, parameters. Delegates attending the Workshop of the (a)etiopathogenesis of osteoarthritis in July 1985 at Airlic, Virginia, actually felt that "no one cared very much for it (this definition)" (Mankin *et al.*, 1986:1132). This clearly shows that further clarification of the nature of this condition is required. Suffice it to say, that at this time, it is universally felt that there is no satisfactory name and no satisfactory definition (Cooper, 1994; Dieppe, 1994; Doherty *et al.,* 1998).

A complete understanding of this condition is warranted, both from the clinical and osteological perspective, not only to advise about those individuals most predisposed to

developing the disease, but also to potentially inform about morphological factors influencing the development of osteoarthritis in the past.

### 5.1.1 Osteoarthritis - The clinical condition

The aetiology and pathogenesis are unknown, but are thought to involve complex interactions of intrinsic abnormalities in connective tissue integrity and extrinsic physical insults to joints. As Dieppe (1994) points out, "osteoarthritis" is currently considered as a heterogeneous process, rather than a disease entity.

#### *a) Aetiology*

Osteoarthritis is a condition that affects the synovial joints and has a multifactorial aetiology (Figure 5.1) whereby age, systemic factors (chemical, dietary, hormonal and immunological) and genetic predisposition all play an important role (Jurmain, 1999; Rogers and Waldron, 1995). Local biomechanical factors (Figure 5.2) will also affect the site and severity of the osteoarthritis (Dieppe, 1990; Jurmain, 1999; Rogers, 2000; Rogers and Waldron, 1995).

Although degenerative joint change is almost an inevitable consequence of ageing and would be expected to occur in most individuals with the passage of time, some authorities have proposed that the patterning of involvement could possibly mirror specific types of occupational activity undertaken by the individuals concerned. However, both clinical and anthropological literature demonstrates that no unequivocal relationship exists between particular types of specific activity and the development of this condition (Knüsel, 2000). This mainly arises due to the fact that a diverse number of aetiopathogenic factors conceal or disguise such an association and the effects of this are reflected by the noticeable variation in the distribution and severity of joint degeneration between different groups of individuals and where different roles were evident. In consequence, care must be exercised with respect to such assumptions, because parameters such as age, health status and cultural practices can also have a bearing on some distributions.

From the evolutionary perspective, it has been postulated that joints undergoing the most rapid evolutionary change are the most susceptible to developing osteoarthritis (Lim *et al.*, 1995). This is due to an increased loading as a result of a mismatch between the design

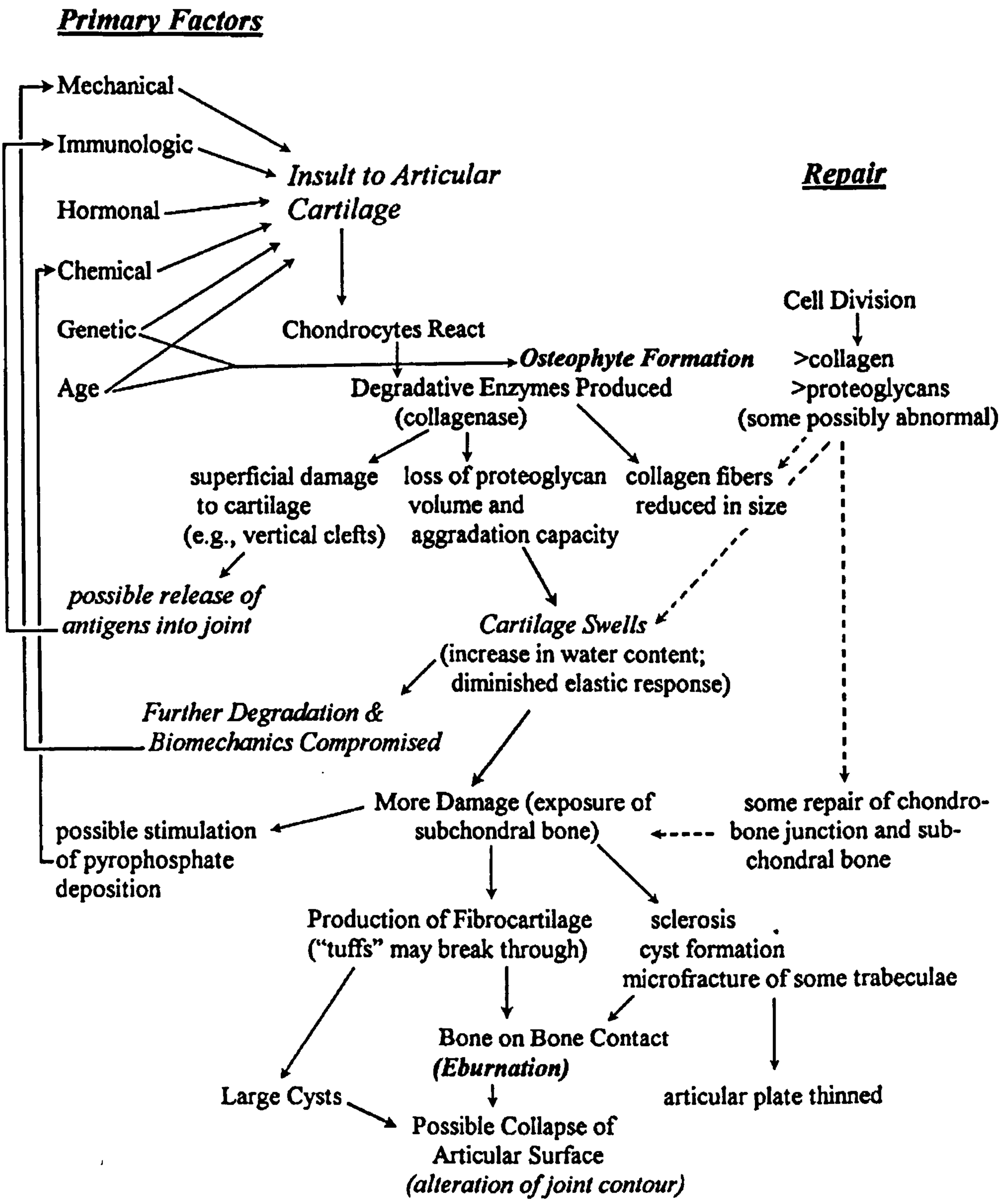



**Figure 5.1 A model of the aetiopathogenesis of osteoarthritis (From Jurmain, 1999: 66. Original Figure No. 2-7)**

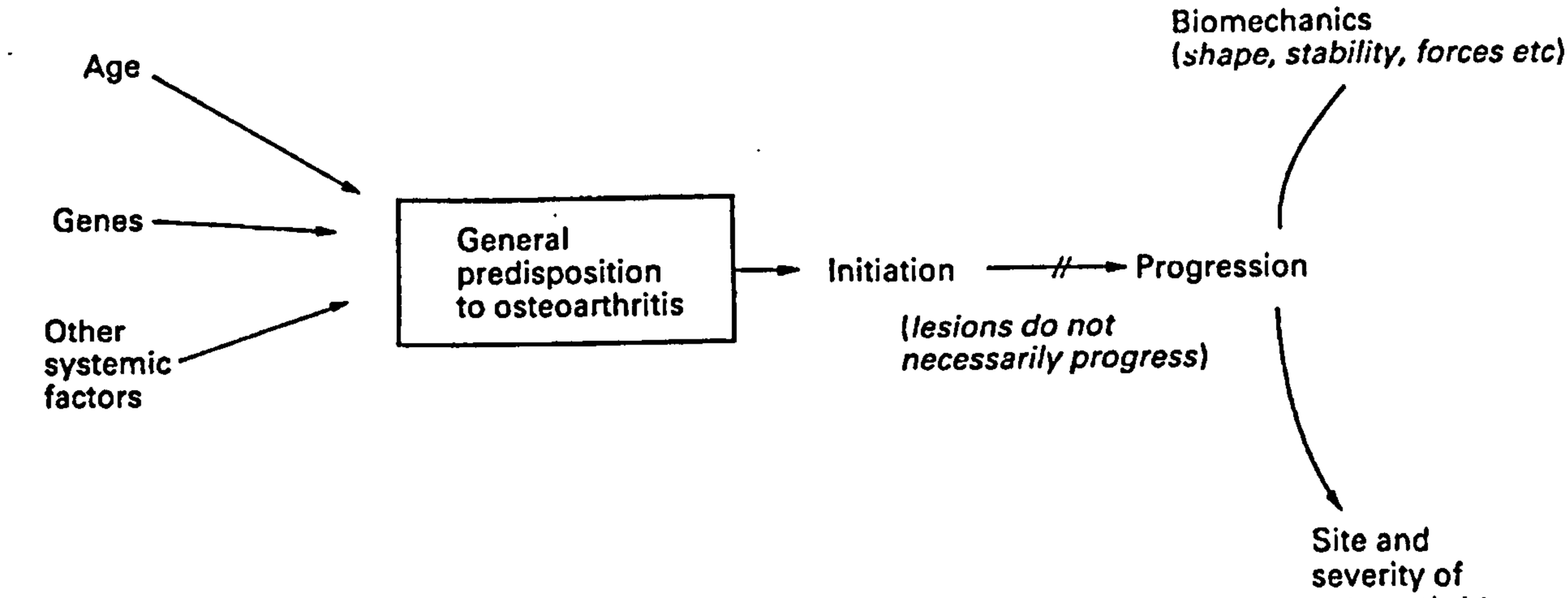



**Figure 5.2 The role of biomechanics in the aetiopathogenesis of osteoarthritis (From Dieppe, 1990: 263. Original Figure No. 1)**

and functionality. Lim and colleagues (1995) examined hand skeletons of 32 elderly human and 32 elderly rhesus macaques, each group consisting of 25 females and seven males. The human archaeological specimens, derived from Barton upon Humber, were anthropologically aged and all assessed to be greater than 45 years. The age range of the rhesus macaques was 15-28 years (average lifespan in captivity 25-35 years), with a mean age of 18 years. As such, the authors felt that use of these two species samples were comparable. The prevalence of osteoarthritis was noted in the distal interphalangeal joints and the thumb base. In the former, 26.7% of the human and 50% of the macaque bones displayed osteoarthritic lesions. In the thumb base, the prevalence rates for humans and macaques were recorded as 37.5% and 3.3% respectively. This led the authors to conclude that the decreased prevalence of thumb base osteoarthritis in macaques could be due to the rudimentary design of this structure.

In many ways, osteoarthritis can be considered basically as a form of joint failure that develops when the biomechanical stresses across a joint become too great for the joint to accommodate (Dickson and Wright, 1984; Rogers, 2000). Dieppe (1990) has described it as an abnormal state of a synovial joint, rather than a disease process itself. Causes are

divided into two categories (Altman, 1997; Gardner, 1983): a) Primary or idiopathic, where there is no observable cause; and b) Secondary, where the condition is related to a predisposing factor. The former usually accounts for around 80% of cases (Aufderheide and Rodríguez-Martin, 1998) and in some cases can involve multiple (usually three plus) joints. This condition is referred to as primary generalized osteoarthritis (PGOA) (Dickson and Wright, 1984) or generalized osteoarthritis (GOA) (Cooper, 1994; Jurmain, 1999; Kellgren and Moore, 1952; Mankin *et al.*, 1986). Individual factors responsible for both primary and secondary forms of osteoarthritis are presented in Tables 5.1a and 5.1b respectively.

***b) Epidemiology***

The site of osteoarthritic manifestations varies between individuals of different ethnicities. Even after adjustments for age and weight, African American females demonstrate a higher prevalence of osteoarthritis of the knee, than white American counterparts (Anderson and Felson, 1988). In addition, South African blacks (Solomon *et al.*, 1975), East Indians (Mukhopadhaya and Barooah, 1967) and South Chinese (Hoaglund *et al.*, 1973) all exhibit lower incidences of osteoarthritis of the hip than European or American whites. Other authors have also found greater prevalence rates for osteoarthritis of the hip in European samples, when compared to Oriental and Negroid populations (Doherty *et al.*, 1998). The latter included study of African groups from South Africa (Solomon *et al.*, 1976), Nigeria (Ebong, 1985; Ali-Gombe *et al.*, 1996) and Liberia (Valkenburg, 1983). Despite these findings, some publications also report an increased prevalence of knee osteoarthritis in African Jamaicans than in European counterparts (Bremner *et al.*, 1968). Rates for arthroplasty for primary osteoarthritis of the hip were examined in a population based study conducted in San Francisco by Hoaglund *et al.* in 1995, and showed that this surgical procedure was more commonly undertaken in white Americans rather than Asians, Hispanics and black Americans. Although the authors do not mention it, socio-ecomomic factors could be influencing this outcome.

The prevalence of osteoarthritis is also variable between the sexes and depends upon, among other features, the joint considered and age. Generally speaking, most authors tend to generally report a greater predilection for females (Centeno, 1999; Dieppe, 1994; Kelsey and Hochberg, 1988; Kumar and Clark, 1987; Nevitt and Felson, 1996; Rogers, 2000;

**Table 5.1a (contd) Classification of primary osteoarthritis**

| Cause | References |
|---|---|
| Immunological responses | Charrière *et al.*, 1988; Doherty *et al.*, 1990; Guerassimov *et al.*, 1999; Hopkinson *et al.*, 1992; Karapoulos *et al.*, 1996; Mollenhauer *et al.*, 1988; Revell *et al.*, 1988; Sakata *et al.*, 2001; Shiokawa *et al.*, 2001 |
| Increased bone mass | Cooper *et al.*, 1994; Hannan *et al.*, 1993; Hart *et al.*, 1994, 2002; Nevitt *et al.*, 1995 |
| Obesity (diet and body conformation influences) | Alla-Kokko *et al.*, 1990; Altman *et al.*, 1987; Anderson and Felson, 1988; Aufderheide and Rodríguez-Martin, 1998; Cooper, 1994; Davis *et al.*, 1988, 1990; Dieppe, 1990; Felson, 1988, 1990; Felson *et al.*, 1988, 1992; Hart and Spector, 1993; Hubert *et al.*, 1993; Mankin *et al.*, 1986; McAlindon *et al.*, 1996a, b; Schouten *et al.*, 1992; Schwartz *et al.*, 1981; Silberg and Silberg, 1960; Sokoloff, 1989; Solomon *et al.*, 1982; Sowers *et al.*, 1991 |

**Table 5.1a Classification of primary osteoarthritis**

| Cause | References |
|---|---|
| Sex | Dieppe, 1990; Mankin *et al.* 1986; Peyron, 1986; White and Folkens, 1991 |
| Age (increasing) | Acheson and Collart, 1975; Dieppe, 1990; Felson and Zhang, 1998; Felson *et al.*, 1987; Kumar and Clark, 1987; Lawrence *et al.*, 1966; Mankin *et al.* 1986; Moscowitz, 1993; Ortner and Putschar, 1985; Peyron, 1986; Rogers, 2000; White and Folkens, 1991 |
| Genetic – includes:<br>• familial tendency (family and twin studies)<br>• mutation of the type II precollagen gene<br>• polymorphism of vitamin D receptor gene<br>• plasticity of chondrocyte phenotype | Cooper *et al.*, 1994; Kellgren *et al.* 1963; Mankin *et al.* 1986; Spector *et al.*, 1996a; Stecher, 1953<br>Aigner *et al.*, 2001; Alla-Kokko *et al.*, 1990; Eyre *et al.*, 1991; Keen *et al.*, 1997; Knowlton *et al.*, 1990; Kumar and Clark, 1987; Palotie *et al.*, 1989; Pattrick *et al.*, 1989; Pun *et al.*, 1994; Reginato *et al.*, 1994; Rogers, 2000; Stokes *et al.*, 2002; Uitterlinden *et al.*, 1997; Vikkula *et al.*, 1993; White and Folkens, 1991 |
| Mechanical factors (altered joint biomechanics) | Bird *et al.*, 1978; Bovenzi *et al.*, 1980; Kumar and Clark, 1987; Klunder *et al.*, 1980; Mankin *et al.* 1986; Ortner and Putschar, 1985; Rogers, 2000; Swann and Seedhom, 1993; White and Folkens, 1991 |
| Biochemical abnormalities – includes:<br>• alteration in proteoglycans<br>• damage to collagen structure<br>• hyperhydration of cartilage<br>• increased synthesis of degradative substances such as collagenases (including proteases, metallo-proteases, serine proteases, and thiol proteases)<br>• decreased production of protease inhibitors<br>• effects of interleukins and growth hormone<br>• elevated serum nitrate and nitrite levels | Alaaeddine *et al.*, 2001; Ali and Rees, 1992; Arner and Pratta, 1989; Baici *et al.*, 1995a, b; Berardi *et al.*, 2001; Brinkerhoff, 1991; Buttle *et al.*, 1993; Campbell *et al.*, 1988; Dean *et al.*, 1989; Del Carlo and Loeser, 2002; DiGiovine *et al.*, 1987; Ersoy *et al.*, 2002; Farrell *et al.*, 1992; Jasin, 1988; Goldberg *et al.*, 1991; Goldring *et al.*, 1988; Hamerman, 1989; Hamerman and Klagsburn, 1985; Howell and Pelletier, 1993; Kanabe *et al.*, 2001; Le and Vilcek, 1987; Little *et al.*, 2002; Lohmander *et al.*, 1993a, b; Mankin *et al.*, 1986; Martel-Pelletier *et al.*, 1990, 1991a, b, 1994; McGuire-Goldring *et al.*, 1984; Melchiorri *et al.*, 1998; Mohtai *et al.*, 1993; Murphy *et al.*, 1991; Pelletier *et al.*, 1987; Pitsillides *et al.*, 1994; Reboul *et al.*, 1996; Sandy *et al.*, 1992; Stamen Kovic *et al.*, 1988; Stefanovic-Racic *et al.*, 1993; Testa *et al.*, 1994; Walkovits *et al.*, 1992; White and Folkens, 1991; Woessner and Selzer, 1984; Yasuda and Poole, 2002 |

**Table 5.1a (contd) Classification of primary osteoarthritis**

| Cause | References |
|---|---|
| Immunological responses | Charrière *et al.*, 1988; Doherty *et al.*, 1990; Guerassimov *et al.*, 1999; Hopkinson *et al.*, 1992; Karapoulos *et al.*, 1996; Mollenhauer *et al.*, 1988; Revell *et al.*, 1988; Sakata *et al.*, 2001; Shiokawa *et al.*, 2001 |
| Increased bone mass | Cooper *et al.*, 1994; Hannan *et al.*, 1993; Hart *et al.*, 1994, 2002; Nevitt *et al.*, 1995 |
| Obesity (diet and body conformation influences) | Alla-Kokko *et al.*, 1990; Altman *et al.*, 1987; Anderson and Felson, 1988; Aufderheide and Rodríguez-Martin, 1998; Cooper, 1994; Davis *et al.*, 1988, 1990; Dieppe, 1990; Felson, 1988, 1990; Felson *et al.*, 1988, 1992; Hart and Spector, 1993; Hubert *et al.*, 1993; Mankin *et al.*, 1986; McAlindon *et al.*, 1996a, b; Schouten *et al.*, 1992; Schwartz *et al.*, 1981; Silberg and Silberg, 1960; Sokoloff, 1989; Solomon *et al.*, 1982; Sowers *et al.*, 1991 |

**Table 5.1b Classification of secondary osteoarthritis**

| Cause | References |
|---|---|
| Abnormalities of joints<br>(including congenital, mal-alignment and decreased size of joint contact) | Aufderheide and Rodríguez-Martin, 1998; Collier *et al.*, 1991; Dickson and Wright, 1984; Dieppe, 1990, 1994; Jurmain, 1999; Kumar and Clark, 1987; Mankin *et al.*, 1986; Ortner and Putschar, 1985; Rogers, 2000 |
| Structural disorders in children<br>(including Perthes disease and slipped femoral epiphysis) | Dieppe, 1994; Kumar and Clark, 1987; Mankin *et al.*, 1986; |
| Trauma<br>(including fractures, dislocations, meniscectomy and occupational hazards) | Alla-Kokko *et al.*, 1990; Aufderheide and Rodríguez-Martin, 1998; Collier *et al.*, 1991; Cooper *et al.*, 1994; Dickson and Wright, 1984; Dieppe, 1990, 1994; Doherty *et al.*, 1983; Felson *et al.*, 1987; Jacobsen, 1977; Jurmain, 1999; Kannus and Järvinen, 1989; Kellgren and Lawrence, 1958; Kumar and Clark, 1987; Lane, 1995; Mankin *et al.*, 1986; Ortner and Putschar, 1985; Rogers, 2000; White and Folkens, 1991 |
| Infection | Aufderheide and Rodríguez-Martin, 1998; Dieppe, 1994; Jurmain, 1999 |
| Exercise/activity | *Predisposing*: Cheng *et al.*, 2000; Kujala *et al.*, 1994; Lane, 1995; McAlindon *et al.*, 1999; Spector *et al.*, 1996b; West, 1985<br>*Opposing*: Hannan *et al.*, 1993; Sutton *et al.*, 2001; White *et al.*, 1993 |
| Metabolic abnormalities<br>(including defects in cartilage structure, chondrocyte function and synovial fluid composition) | Aufderheide and Rodríguez-Martin, 1998; Collier *et al.*, 1991; Dieppe, 1994; Jurmain, 1999; Kumar and Clark, 1987; Mankin *et al.*, 1986; Ortner and Putschar, 1985 |
| Crystal deposition diseases<br>(as *posthoc* and *propter hoc* phenomenon) | Dieppe, 1994; Dieppe and Watt, 1985; Felson *et al.*, 1989; Hochberg, 1984; Jurmain, 1999; Kumar and Clark, 1987; Mankin *et al.*, 1986; Rogers and Waldron, 1995 |
| Other joint diseases<br>(including inflammatory arthritis, DISH and endemic arthropathies) | Aufderheide and Rodríguez-Martin, 1998; Collier *et al.*, 1991; Dickson and Wright, 1984; Dieppe, 1994; Jurmain, 1999; Mankin *et al.*, 1986; Sokoloff, 1985; White and Folkens, 1991 |

**Table 5.1b (contd) Classification of secondary osteoarthritis**

| Cause | References |
|---|---|
| Vascular abnormalities (including avascular necrosis) | Aufderheide and Rodríguez-Martin, 1998; Kumar and Clark, 1987; Mankin *et al.*, 1986 |
| Neuropathy (including diabetes mellitus and peripheral nerve lesions) | Aufderheide and Rodríguez-Martin, 1998; Collier *et al.*, 1991; Jurmain, 1999; Kumar and Clark, 1987; Mankin *et al.*, 1986 |
| Endocrine | Mankin *et al.*, 1986 |
| Other e.g. frostbite, Caisson's disease | Mankin *et al.*, 1986 |

Silman and Newman, 1996), by a ratio of between 2:1 (Kumar and Clark, 1987) and 3:1 (Hope *et al.*, 1989). Cooper (1994) reports that female: male ratios in the hand and knee vary between 4:1 and 1.5:1 in various studies. This sexual variation has led, over the past century, to the suggestion that the development of osteoarthritis is hormonally mediated (Cecil and Archer, 1926; Kellgren and Moore, 1952; Rosner *et al.,* 1986; Spector and Campion, 1989). The manifestation of joint symptoms around the time of the menopause has been documented by many authors (Cecil and Archer, 1926; Kellgren and Moore, 1952; Stecher *et al.,* 1949) and has led to the suggestion that hormonal deficiency in the postmenopausal period (particularly of oestrogen) may increase the risk or severity of osteoarthritis in females (Nevitt and Felson, 1996). A number of animal models has revealed that cartilage metabolism is affected by sex hormones (Da Silva *et al.,* 1994; Rosner *et al.,* 1979, 1982, 1986; Tsai and Liu, 1993) and these studies have all proposed that human female propensity to osteoarthritis is ultimately influenced by a variation in oestrogen synthesis or control. Despite this theory, however, research conducted within the last decade or so, examining menstrual (Anderson and Felson, 1988; Hannan *et al.,* 1990; Hochberg *et al.,* 1995a; Samanta *et al.,* 1993; Spector *et al.,* 1990; Tepper and Hochberg, 1993) and obstetric (Samanta *et al.,* 1993; Spector *et al.,* 1990; Tepper and Hochberg, 1993) histories of women, has not revealed any positive correlation between these parameters and predilection to osteoarthritis. Other authorities maintain that oestrogen could potentially affect the development of the disease through alteration of cartilage metabolism by cytokines (such as interleukin 1 [IL-1], interleukin 6 [IL-6] and tumour necrosis factor α [TNF-α]) (Guerne *et al.,* 1990; Pelletier *et al.,* 1993) or growth factors (such as insulin-like growth factor 1 [IG-1] and transforming growth factor β [TGF-β]) (Lieberman *et al.,* 1994; Romagnoli *et al.,* 1994). Oestrogen also has an effect on bone metabolism and when present in greater concentrations potentially leads to a higher bone mass. This, in turn, could place increased biomechanical loads on cartilage during joint loading and thus precipitate osteoarthritic development (Radin, 1976). Additional mechanisms by which oestrogen may influence the risk of osteoarthritis include protection against vascular defects in subchondral bone, enhanced neuromuscular protection during excessive joint loading and antioxidant capacity (Nevitt and Felson, 1996).

Osteoarthritis is an age progressive condition (Aufderheide and Rodríguez-Martin, 1998; Centeno, 1999; Rogers, 2000), with a mean age of onset around 50 years (Hope *et al.*, 1989; ; Kumar and Clark, 1987) and occurs in about 10% of the population as a whole (Kumar and Clark, 1987). Dickson and Wright (1984) purport that 60% of individuals

greater than 35 years demonstrate osteoarthritic change in at least one joint. By the age of 40 years, around 90% of individuals exhibit evidence of some form of degenerative change in weight bearing joints, despite the evident absence of clinical symptoms (Moskowitz, 1997). Estimates for prevalence in individuals over 60 years of age vary between authors, with some reporting values as low as 10% (Hamerman, 1989). Most authorities, however, purport higher rates. Kumar and Clark (1987) state that 50% of those over 60 years will demonstrate evidence of the condition, while White and Folkens (1991) assert that all individuals over 60 years of age possess features of osteoarthritis, especially in the lower thoracic and lumbar regions of the vertebral column. Cooper (1994) noted how, in 1926, Heine had reported on an almost universal evidence of cartilage damage in individuals over 65 years, while Lawrence *et al.* (1966) reported that 85% of 55-64 year olds exhibited some radiographic evidence of osteoarthritis in one or more joints. Doherty *et al.* (1998) further note that at 65 years, at least one joint is involved in 50% of the population. During the eighth decade of life, prevalence is recorded as increasing once again, with around 80% of individuals exhibiting radiographic manifestations (Cooper, 1994). The continuing prevalence in those over 65 years of age is less distinctive and it has been purported that a plateauing of prevalence in the very old may be occurring (Bagge *et al.*, 1992).

The Framingham Osteoarthritis Study (Felson *et al.*, 1987) was a longitudinal study taken from the Framingham Heart Study cohort. This latter group was a population based in Massachusetts which was first studied in 1948 and then every two years subsequent to that. Between September 1983 to September 1985, the prevalence of osteoarthritis was assessed radiographically in 1424 subjects aged 63-94 years (mean 73 years). The grading scale adopted was that devised by Kellgren and Lawrence (1957 – further detailed in section 5.1.1e) and results revealed that 27% of individuals less than 70 years, 34% of those aged 70-79 years, and 44% of those individuals older than 80 years demonstrated evidence of the disease. It was also noted that a significantly higher proportion of females than males demonstrated symptomatic disease (11% of all women as opposed to 7% of all men [p=0.003]).

In the thirty years prior to publication, Peyron (1986) had been reviewing the available epidemiological evidence for osteoarthritis. He reported that 2% of females and 3% of males less than 45 years of age were afflicted. These values increased to 24% for females and 30% for males in the age group of 45–64 years, and finally to 58% and 68% for females and males respectively in those individuals greater than 65 years of age.

Recent work (Verzijl *et al.*, 2002) suggests a potential underlying cause of this age related phenomenon. It has long been noted that the stiffness of the articular collagen network

increases with age (Basser *et al.,* 1998; Grushko *et al.,* 1989), and that this change inevitably leads to modification in the tensile properties of the tissue (Kempson 1982, 1991). Verzijl and colleagues have identified the source of this so called "stiffening"; an accumulation of advanced glycation end product crosslinks. These effectively stiffen the cartilage and render it unable to resist damage (Freeman, 1975; Weightman, 1976), thus predisposing the joint to the development of osteoarthritis.

Climate has also been forwarded as another important epidemiological factor. Some studies report that osteoarthritis occurs less frequently as Northern latitude increases (Blumberg *et al.*, 1961; Bremner *et al.,* 1968). Conversely, comparisons of populations in Jamaica and Great Britain (Bremner *et al.,* 1968) have also revealed no significant difference in the prevalence of the disease between the two groups. This strongly supports the theory that ancestry, culture and environment are all important parameters affecting the overall expression of osteoarthritis.

### *c) Pathogenesis*

Despite the continuing debate over nomenclature for this condition, all researchers are agreed on one aspect - and that is that the hallmark of this condition is cartilage degeneration (Aufderheide and Rodríguez-Martin, 1998; Centeno, 1999; Cooper, 1994; Dieppe, 1990, 1994; Jasin, 1989; Jurmain, 1999; Kumar and Clark, 1987; McKeag, 1992; Rogers, 2000; White and Folkens, 1991). Osteoarthritis is usually applied to synovial, or diarthrodial joints (Jurmain, 1999) and this includes the apophyseal (also known as zygoapophyseal or interfacetal) joints of the vertebral column. It does not refer to the arthropathy associated with the articulations of the vertebral body (also referred to as syndesmoses or amphiarthroses). This arises subsequent to intervertebral disc degeneration and is detailed later, in section 5.2.

In order to appreciate the pathogenesis of this condition, it is necessary to understand the anatomical and biological aspects of a synovial joint. Two articular bony surfaces are covered by hyaline cartilage (Dickson and Wright, 1984; Jurmain, 1999) and enclosed within a capsule, which is lined by a synovial membrane that secretes a viscous, synovial fluid (*ibid.*). Two forms of lubrication exist. Hydrostatic influences operate under high loads with a fluid film being generated between, and separating, the surfaces (Jurmain, 1999; McKeag, 1992). With low loads, surface to surface contact is prohibited by the development of a glycoprotein lubricating boundary (Jurmain, 1999; McKeag, 1992). Each

of these processes confers low frictional properties to the joint (Dickson and Wright, 1984). The joint is surrounded and stabilized by muscles, tendons and ligaments and integrity is further assured by fibrocartilaginous partitions in the joint itself and close-fitting joint congruity (Jurmain, 1999).

Cartilage is essentially composed of three elements; water, chondrocytes and a matrix (the latter comprising proteoglycans, collagen and non-collagenous proteins) (Hamerman, 1989). The hyaline cartilage is composed of a meshwork of collagen fibres (Figure 5.3). Between 5-20% of these are type IX (Vasios *et al.*, 1988), although the majority consist of high tensile strength type II collagen fibres (Gardner, 1983; Hamerman, 1989; Mankin *et al.*, 1986), which comprise around 70% of the collagen (Mankin *et al.*, 1986) and 15% of the tissue (Jurmain, 1999). Close to the articular surface they lie approximately parallel to the surface, but at deeper levels they are oriented at right angles and are attached to the subchondral bone (Dickson and Wright, 1984) (Figure 5.3). This meshwork contains the cartilage matrix, composed of relatively sparse chondrocytes, accounting for < 5% of the cartilage composition (McKeag, 1992); and proteoglycans aggregates, consisting of approximately 20% of the matrix (Mankin *et al.*, 1986) and 20% of the tissue (Jurmain, 1999). The latter entities incorporate long filamentous cores of hyaluronic acid, stabilized by small binding sites, and along which are attached numerous side chains of proteoglycans (Dickson and Wright, 1984; Hamerman, 1989; Mankin *et al.*, 1986; McKeag, 1992) (Figure 5.4). These individual proteoglycan molecules contain a central protein core with glycosaminoglycan side chains of keratan sulphate and chondroitin sulphate (Dickson and Wright, 1984; Hamerman, 1989; Jurmain, 1999; Mankin *et al.*, 1986) (Figure 5.4). The proteoglycan aggregates are interspersed in the collagen network and attract fluid by osmosis (Gardner, 1983), thus tumefying and stretching the collagen meshwork. This confers turgidity to the cartilage and is largely responsible for creating the load bearing properties of the articular cartilage (Jurmain, 1999; Mankin *et al.*, 1986). Indeed, many authors report on the hydrolytic degradation of proteoglycan aggregates being a major feature of osteoarthritis development. The overall water content of the articular cartilage is variably reported, with values of 65-75%, 67-8%, >70% and 75-80% reported by Gardner, (1983), Mankin *et al.* (1986), Hamerman (1989) and McKeag (1992) respectively.

In the development of osteoarthritis, load bearing areas of joints exhibit the principal damage (Dickson and Wright, 1984). In the initial stages, three processes occur simultaneously: first there is a loss of proteoglycans (Doherty *et al.*, 1998;

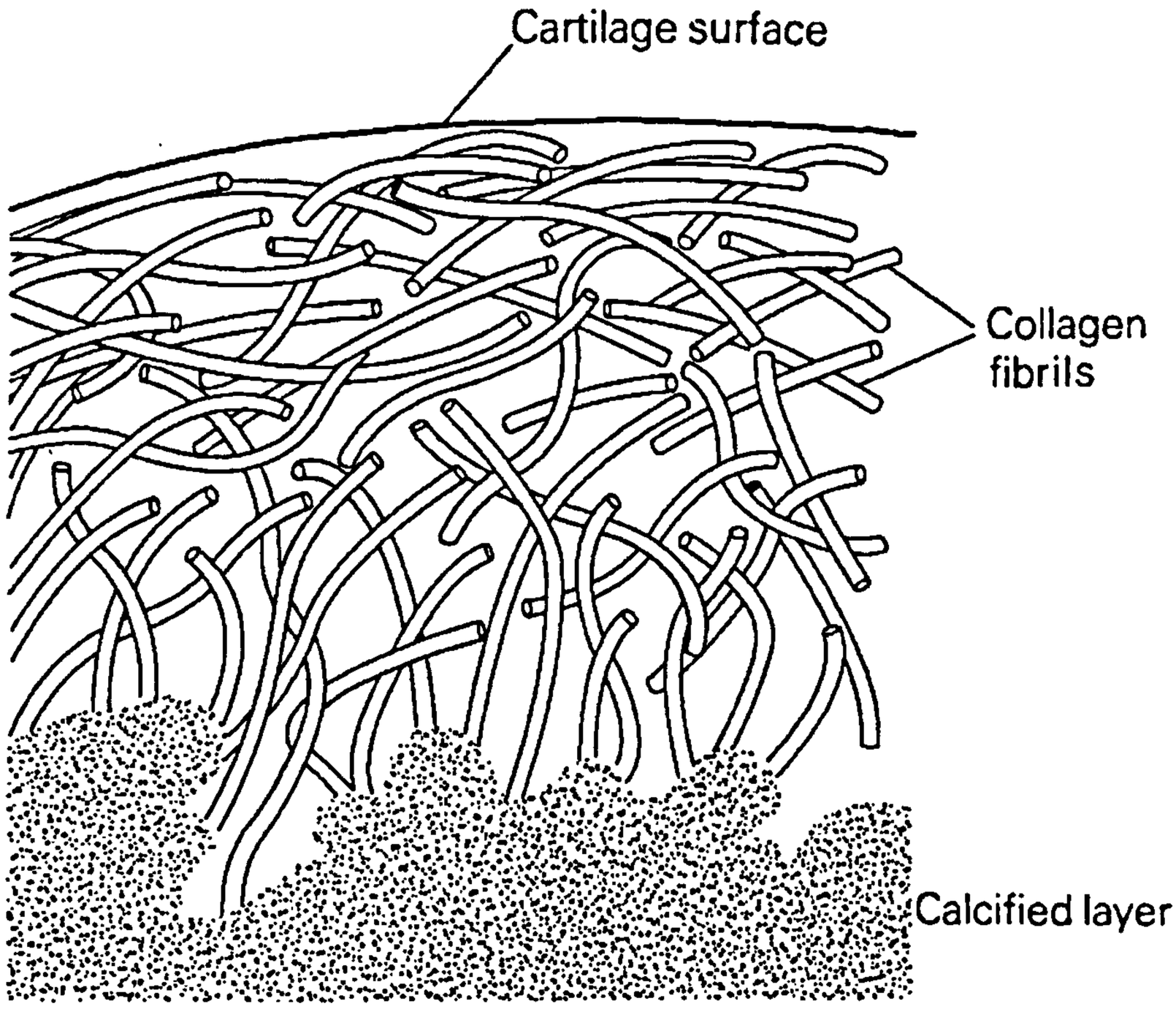
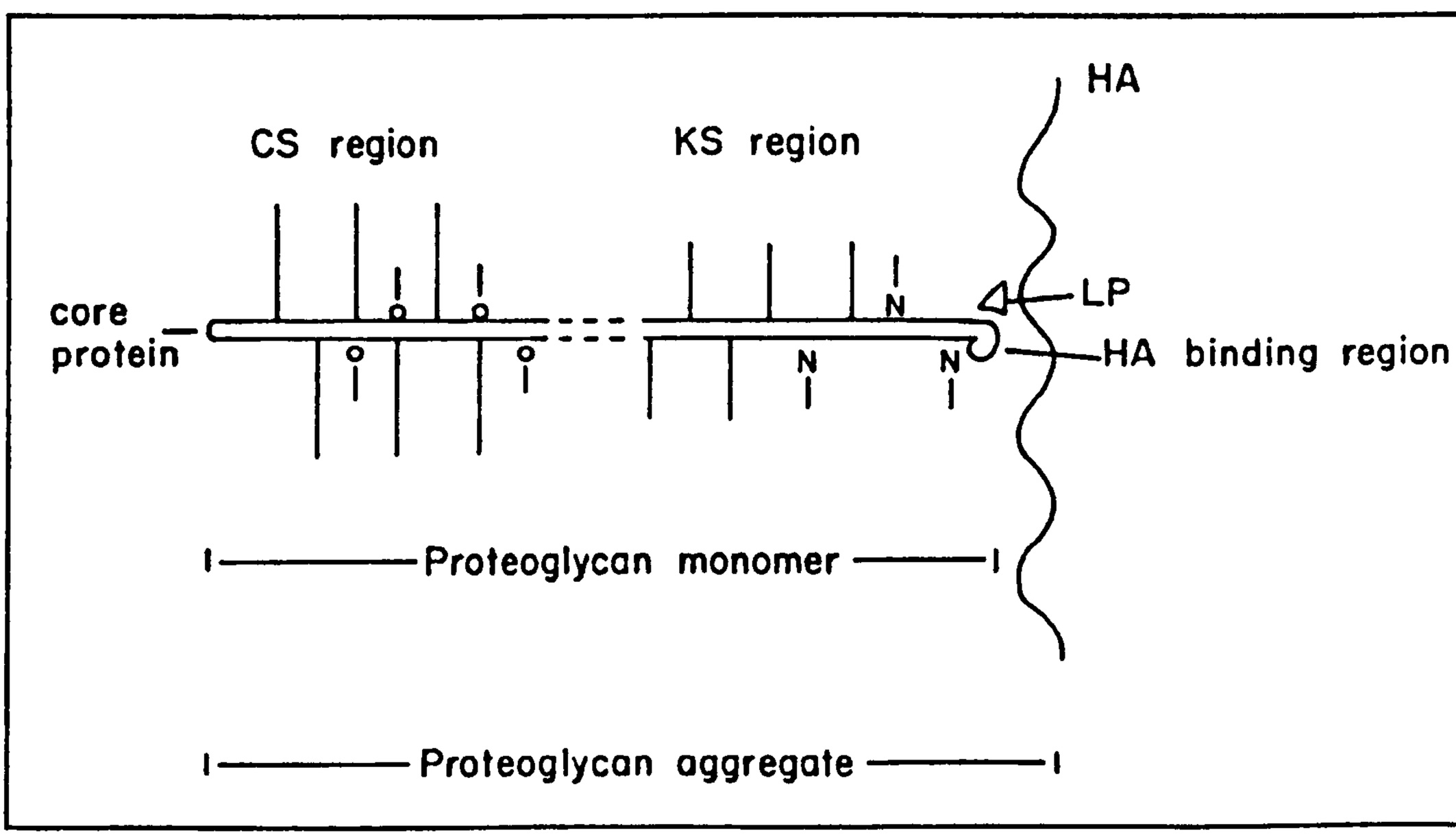



**Figure 5.3 The structure of collagen in cartilage**
**(From Dickson and Wright, 1984: 179. Original Figure No. 13.1)**




Key:

CS Chondroitin sulphate KS Keratan sulphate HA Hyaluronic acid

**Figure 5.4 The structure of the proteoglycan aggregate in articular cartilage**
**(From Hamerman, 1989: 1325. Original Figure No. 5)**

Hamerman, 1989; Kumar and Clark, 1987; Mankin *et al.*, 1986) then an increase in hydration due to the alteration of proteoglycans (Hamerman, 1989; Heingard *et al.*, 1987; Mankin and Thrasher, 1975; Mankin *et al.*, 1986), and finally cellular proliferation. On a biochemical level, these changes are all different from those associated with ageing cartilage (Brandt, 1988; Hamerman, 1989; Mankin *et al.*, 1986) (Table 5.2). Molecular disorganization has also been implicated by the presence of amyloid, an amorphous homogeneous hyaline-like substance commonly found in the cartilage of older individuals (Goffin *et al.*, 1981), and also recognisable in osteoarthritis (Egan *et al.*, 1982).

**Table 5.2 Changes in cartilage associated with ageing and osteoarthritis (Adapted from Hamerman, 1989: 1326. Original Table No. 2)**

| Criterion | Osteoarthritic change | Age related change |
|---|---|---|
| Water | Increased content | Decreased content |
| | | |
| *Proteoglycans* | | |
| Monomer size | Decreased | Decreased |
| Link protein | Normal | Fragmented |
| Aggregation | Diminished | Normal |
| | | |
| *Glycosaminoglycans* | | |
| Hyaluronate | Decreased | Increased |
| Keratan sulphate | Decreased | Increased |
| Chondroitin sulphate | Decreased | Normal/Slightly less |
| Chondroitin sulphate 4/6 ratio (The ratio of chondroitin sulphate on the fourth to sixth carbon atom) | Increased | Decreased |
| | | |
| Proteases | Increased | Normal |

Osteoarthritis consequently leads to a splitting, or fibrillation, of the cartilage itself (Altman, 1997; Collier *et al.*, 1991; Dieppe, 1994; Doherty *et al.*, 1998; Gardner, 1983; Hamerman, 1989; Hough, 1997; McKeag, 1992; Meachim, 1972). The disruption confined to the surface tangential layer is termed flaking, whereas involvement of the deeper radial layer is referred to as fibrillation (Doherty *et al.*, 1998; Hough, 1997). Collagen fibres, which are normally orientated parallel to the joint surface, become disorganized (Hough, 1997; Kumar and Clark, 1987) and some even break away, exposing the underlying bone (Aufderheide and Rodríguez-Martin, 1998; Collier *et al.*, 1991; Doherty *et al.*, 1998; Kumar and Clark, 1987; Rogers, 2000). This exposed bone subsequently thickens and

becomes hardened (sclerosed) and radiographically white (eburnation) (Altman, 1997; Aufderheide and Rodríguez-Martin, 1998; Collier *et al.*, 1991; Cooper, 1994; Dieppe, 1994; Doherty *et al.,* 1998; Gardner, 1983; Hamerman, 1989; Hough, 1997; Mankin *et al.*, 1986; Ortner and Putschar, 1985; Rogers *et al.,* 1987; Schwartz, 1995; White and Folkens, 1991).

Grooving may also develop within the joint in addition to this (Ortner and Putschar, 1985; Schwartz, 1995). Nodular new bone formations, known as osteophytes, form at the joint surfaces (Altman, 1997; Aufderheide and Rodríguez-Martin, 1998; Collier *et al.*, 1991; Cooper, 1994; Dieppe, 1994; Doherty *et al.,* 1998; Gardner, 1983; Hamerman, 1989; Hough, 1997; Kumar and Clark, 1987; Mankin *et al.*, 1986; Ortner and Putschar, 1985; Rogers, 2000; Schwartz, 1995; White and Folkens, 1991) and enlarge these areas, thus diminishing the stresses acting on an individual area.

Regions of porosis also develop, and infiltration of synovial fluid into these entities produces subchondral cysts (Altman, 1997; Aufderheide and Rodríguez-Martin, 1998; Cooper, 1994; Dieppe, 1994; Doherty *et al.,* 1998; Gardner, 1983; Mankin *et al.*, 1986; Schwartz, 1995). The synovial tissues themselves simultaneously begin to thicken (Doherty *et al.,* 1998; Kumar and Clark, 1987; Rogers, 2000), and this process includes the capsule of the joint (Aufderheide and Rodríguez-Martin, 1998; Dieppe, 1994; Doherty *et al.,* 1998).

### *d) Clinical features*

The clinical features of osteoarthritis are varied and differ between individuals. Generally speaking, the symptoms that are most often reported include pain, stiffness and instability. Pain may be experienced both at rest (Dieppe, 1990, 1994; Doherty *et al.,* 1998; Hope *et al.*, 1989; Kumar and Clark, 1987) and on movement (Dickson and Wright, 1984; Dieppe, 1990, 1994; Doherty *et al.,* 1998; Hope *et al.*, 1989; Mankin *et al.*, 1986; Moskowitz, 1997; Rogers, 2000; Rubenstein and Wayne, 1991). It is also worse at the end of the day (Doherty *et al.,* 1998; Hope *et al.*, 1989; Kumar and Clark, 1987; Rubenstein and Wayne, 1991).

Stiffness in the joint is particularly noticeable in the morning (Dieppe, 1990, 1994; Doherty *et al.,* 1998; Hope *et al.*, 1989; Kumar and Clark, 1987; Moskowitz, 1997; Rubenstein and Wayne, 1991), and joint instability is also frequently reported (Dickson and Wright, 1984; Dieppe, 1994; Hope *et al.*, 1989).

Clinical signs that occur on examination include a swollen joint (Dickson and Wright, 1984; Dieppe, 1990; Kumar and Clark, 1987; Moskowitz, 1997; Rogers, 2000) which is warm, red and tender (Doherty *et al.,* 1998; Moskowitz, 1997; Rubenstein and Wayne, 1991). A joint effusion may be present (Doherty *et al.,* 1998; Mankin *et al.*, 1986; Rubenstein and Wayne, 1991) and associated musculature may appear wasted (Doherty *et al.,* 1998; Kumar and Clark, 1987). Movement at the joint is limited (Dieppe, 1990, 1994; Doherty *et al.,* 1998; Mankin *et al.*, 1986) and may produce an audible crepitus (Collier *et al.*, 1991; Dieppe, 1990, 1994; Doherty *et al.,* 1998; Kumar and Clark, 1987; Mankin *et al.*, 1986; Moskowitz, 1997). In many cases there will be a fixed deformity (Collier *et al.*, 1991; Doherty *et al.,* 1998; Kumar and Clark, 1987) and obvious immobility (Rubenstein and Wayne, 1991).

Although the distal and proximal interphalangeal joints, first metacarpal phalangeal joint, first metatarsal phalangeal joint, and knee and hip joints rank among those that are most commonly affected by osteoarthritis (Dickson and Wright, 1984; Cooper, 1994; Dieppe, 1990, 1994; Hope *et al.*, 1989; Ortner and Putschar, 1981; Rogers, 2000 166), the cervical and lumbar spine follow close behind (Cooper, 1994; Dickson and Wright, 1984; Dieppe, 1990, 1994; Hope *et al.*, 1989; Rogers, 2000). More specifically, the areas that display such a predilection include the lower cervical and upper thoracic (C6-T1), upper and mid thoracic (T2-T5), and mid lumbar (L2-L4) regions (Aufderheide and Rodríguez-Martin, 1998). Rubenstein and Wayne (1991) report that of all the sites affected in the human skeleton, 40% include the cervical and lumbar regions of the vertebral column.

Little correlation, however, seems to exist between symptoms reported and the degree of pathological or radiological change (Gore *et al.,* 1987; Hadler, 1985; Moskovitz, 1997). McKeag (1992) estimated that 40.5 million adults are thought to have osteoarthritis and that 27 million of these will have symptoms related to the disease. Indeed Hochberg and colleagues (1989) reported on a multistage, stratified probability sample of a civilian, non-institutionalized population of 6913 individuals aged 25-74 years. Three hundred and nineteen (4.6%) of these people exhibited radiographic changes indicative of osteoarthritis. Of these, 141 (44%) in total reported associated knee pain. Grade 2 and Grade 3/4 radiographic changes were demonstrated by 66.7% (29.5% of the total) and 33.3% (14.7% of the total) of these respectively.

### *e) Radiographic features and other imaging mediums*

It has been documented that by 60 years of age, between 60-80% of individuals will exhibit evidence of osteoarthritic changes on radiographic examination (Jones *et al.*, 1995). Other authors have previously attributed higher percentages at a younger age. Collier *et al.* (1991) and Rubenstein and Wayne (1991) noted that 80% of individuals aged over 55 years displayed such characteristics. These features include a loss of joint space, marginal osteophytes, subchondral sclerosis and cysts (Aufderheide and Rodríguez-Martin, 1998; Collier *et al.*, 1991; Cooper, 1994; Dieppe, 1990, 1994; Doherty *et al.*, 1998; Hope *et al.*, 1989; Kellgren and Lawrence, 1957; Kumar and Clark, 1987; McAlindon and Dieppe, 1989; Preidler and Resnick, 1996; Rogers, 2000; Rubenstein and Wayne, 1991) as well as evidence of calcification - either linear in nature (characterized by pyrophosphate deposition) or diffuse (representing precipitation of hydroxyapatite) (Kumar and Clark, 1987).

Kellgren and Lawrence (1957) developed a five point scoring system for radiographs. This classification was summarized by Cooper (1994) and is reproduced in Table 5.3. Of the various radiographic criteria available, this is the most widely implemented (Doherty *et al.*, 1998).

However, as noted in the previous section, only a minority of radiographically positive joints will result in problems (Cobb *et al.*, 1957; Dieppe, 1990; Lawrence *et al.*, 1966). Dieppe (1994) puts this around 50%.

**Table 5.3 Classification of radiographic manifestations of osteoarthritis (From Cooper, 1994: 7.3.1. Original Figure No. 3.1)**

| Grade | Classification | Description |
|---|---|---|
| 0 | Normal | No features of osteoarthritis |
| 1 | Doubtful | Minute osteophytes, doubtful significance |
| 2 | Minimal | Definite osteophytes, unimpaired joint space |
| 3 | Moderate | Moderate diminution of joint space |
| 4 | Severe | Joint space greatly impaired with sclerosis of subchondral bone |

Imaging techniques for osteoarthritis now encompass additional approaches. Radio isotopes employed for bone scanning often accumulate on osteoarthritic joints and gamma cameras used in scintigraphy can demonstrate the pattern of uptake. The use of

### *f) Investigations*

There are no specific diagnostic markers of osteoarthritis (Doherty *et al.,* 1998; Moskowitz, 1997). The erythrocyte sedimentation rate (ESR) is normal and rheumatoid factor is absent (Collier *et al.*, 1991; Dickson and Wright, 1984; Dieppe, 1990; Kumar and Clark, 1987; Moskowitz, 1997). Similarly, blood counts and plasma viscosity are normal (Dickson and Wright, 1984; Moskowitz, 1997) and tests for antinuclear antibodies are negative (Dickson and Wright, 1984; Dieppe, 1990; Kumar and Clark, 1987). Synovial aspirates usually demonstrate <100 white blood cells (WBC) per $mm^3$ and mainly consist of monocytes (Dieppe, 1990; Rubenstein and Wayne, 1991). They may also reveal breakdown products of cartilage (keratan sulphate, collagen X-linking compounds, collagen propeptides), bone (osteocalcin, collagen X-linking compounds) and synovial products (hyaluronan, collagen type III propeptide). These substances can also be demonstrated in serum and urine (Dieppe, 1990), particularly keratan sulphate (Campion *et al.*, 1991; Carroll *et al.*, 1992; Mehraban *et al.*, 1991; Moskowitz, 1997; Thonar and Glant, 1992; Thonar *et al.*, 1993) and hyaluronate (Goldberg *et al.*, 1991). Electron microscopy may reveal the presence of hydroxyapatite crystals (Dickson and Wright, 1984; Kumar and Clark, 1987), but this examination is not routinely performed. Further to this, concentrations of catabolic enzymes, such as collagenases, stromelysin and tissue inhibitors of metalloproteinases may be elevated in joint aspirates of individuals demonstrating primary or traumatic osteoarthritis (Lohmander *et al.*, 1993a, b; Walkovits *et al.*, 1992).

Osteoarthritis is very variable in its presentation and results not only in substantial morbidity, but also raises important challenges in health care and resource implications (Badley *et al.,* 1994; Steven, 1992; Yellin, 1992), not to mention significant costs to society (Dell'Accio *et al.,* 2001; Gardner, 1983; Lozada and Altman, 1997). The latter cost includes a patient's loss of ability for self-care, reduced recreational and vocational pursuits, in addition to the more obvious depletion of health resources. Recent developments in the understanding of the aetiopathogenesis of the disease have ultimately led to enhanced approaches to management, which for the most part aim to implement more preventative measures and incorporate more comprehensive approaches to treatment overall. Current management strategies are presented in Appendix 1, Volume 2.

technetium-99M scintigraphy has been suggested as a potential diagnostic tool (Hutton *et al.*, 1986; Preidler and Resnick, 1996; Resnick and Niwayama, 1995), but poor specificity of changes implies that this approach can only technically be employed as a screening method (Dieppe *et al.*, 1993).

Ultrasonography has been employed in diagnosis (Aisen *et al.*, 1984; Grassi and Cervini, 1998; Karim *et al.*, 2001; Martel *et al.*, 1991), but only small areas of cartilage can be viewed at any one time due to the restricted accessibility of this method.
Pathological changes that transpire in both soft and hard tissues, such as the alteration in water and fat content, are readily revealed by magnetic resonance imaging (MRI) and provide a much higher contrast resolution that that of computed tomography (CT) scanning, together with optimal image modality (Lang *et al.*, 1992). For this reason, a number of authors have utilized this approach in assessing cartilage volume, both generally (Kneeland, 2000; Loeuille *et al.*, 1998; Peterfy *et al.*, 1994; Raynauld *et al.*, 2000) and with specific reference to that in the knee joint (Cicuttini *et al.*, 1999; Eckstein *et al.*, 1998; Olivier *et al.*, 2001; Peterfy *et al.*, 1994). Unfortunately, no mention is made in the literature of the application of this technique to joints in the vertebral column. Most recently, Beuf and colleagues (2002) have employed this approach to discern variation in the trabecular bone structure of normal and osteoarthritic knees in 28 subjects. One disadvantage, however, is that resolution between cartilage and synovial fluid can be complicated due to the high water content of the two tissues (Doherty *et al.*, 1998). Furthermore, there are also the magnetic effects of bone (when juxtaposed to cartilage) that also need to be considered (*ibid.*). As a final point, there are also the varying levels of manual manipulation that are required for this process, necessitating a substantial amount of time (Cicuttini *et al.*, 1999; Eckstein *et al.*, 1998; Peterfy *et al.*, 1994). Despite these limitations, however, this approach may have potential if cartilage can be utilized as a marker for osteoarthritis.

Computed tomography scanning, in turn, despite its lack of effect for the primary diagnosis of osteoarthritis, provides an excellent contrast resolution which is able to detect small intra-articular bodies in advanced cases of the disease (Preidler and Resnick, 1996)
Finally, magnetic resonance (MR) spectroscopy can also be used to exhibit lesions associated with the condition (Dieppe, 1990).

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### 5.1.2 Diagnosis of osteoarthritis in dry bone

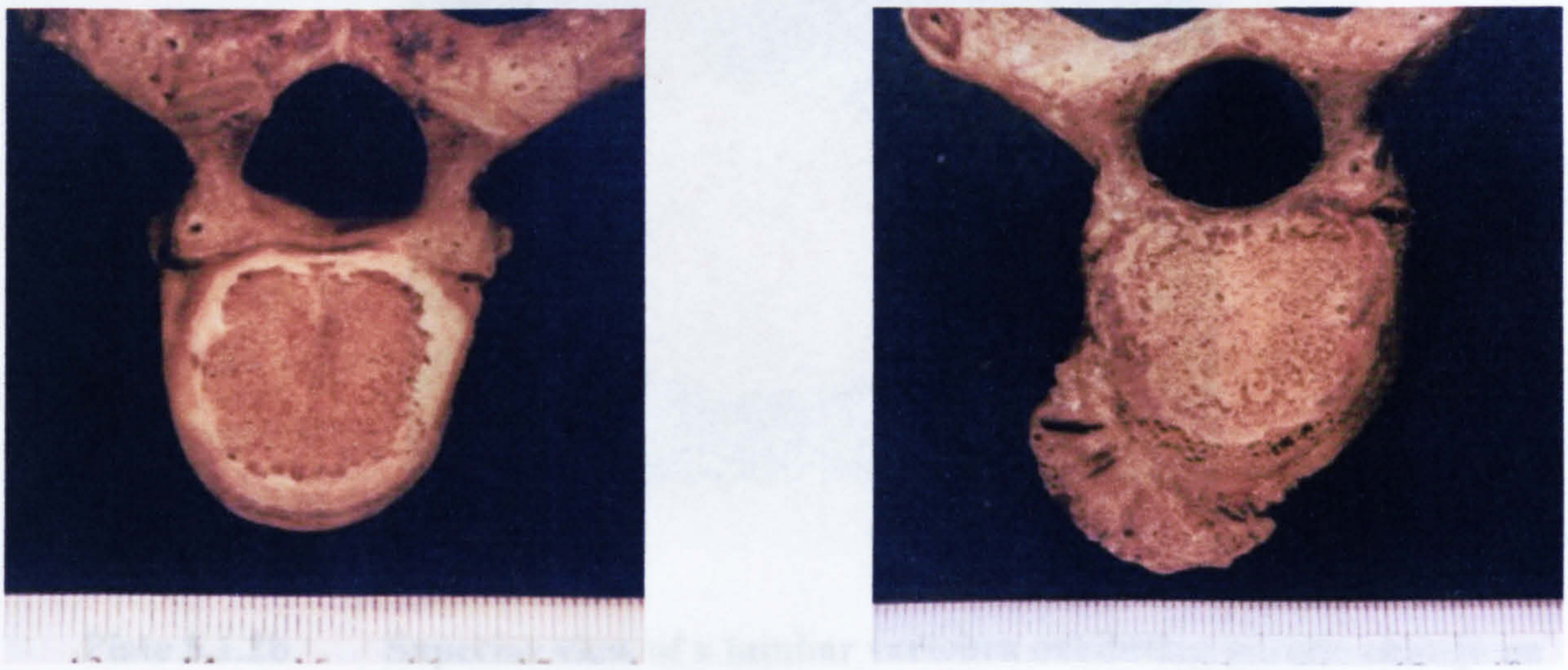
Diagnosis of joint disease in living individuals depends upon various clinical features (signs and symptoms), which have been previously discussed in section 5.1.1d, and which are not applicable to dry bone analysis (Rogers, 2000). Radiography, which is commonly employed in the clinical context may also be utilized for this application and is covered later in this particular section.

Criteria adopted for diagnostic purposes in the palaeopathological field are extremely important, but problems exist with the quantification and qualification of methods employed for identification of this condition (Aufderheide and Rodríguez-Martin, 1998; Ortner and Putschar, 1985). Essentially, five lesions can be observed in dry bone specimens, which may assist in the diagnostic process. These include:

**a)** ***Osteophytes***

Marginal proliferation of new bone is normally referred to as an osteophyte (Rogers *et al.*, 1987). Osteophytes are usually evident around joint and vertebral body margins (Plate 5.1.2a) and take several forms; thin rims of bone; flat ribbons; or large, florid and irregular bone fringes. These entities may manifest around part of or the entire joint margin and may also include "button" or "pancake" manifestation of the joint surface itself (Rogers, 2000). Alone, these entities are not diagnostic of osteoarthritis (Lagier, 1983) and indeed manifest as part of the normal degenerative process that affects joint margins generally. As such, they constitute the condition of osteophytosis and this will be described in further detail in section 5.2.1. As far as classification is concerned, osteophytes are referred to as marginal, central, periosteal or capsular (Doherty *et al.*, 1998; Resnick and Niwayama, 1981). In the case of the marginal and central types, these develop through endochondral ossification arising subsequent to the vascularization of subchondral bone marrow (*ibid.*). Periosteal osteophytes form as a result of stimulation of the periosteal membrane and form from a process resembling appositional bone growth (Doherty *et al.*, 1998; Resnick and Niwayama, 1981). Capsular osteophytes arise in response to capsular traction forces (Doherty *et al.*, 1998; Preidler and Resnick, 1996; Resnick and Niwayama, 1981). These types of osteophyte can all be imaged radiographically. Marginal entities appear as lips (outgrowths) of new bone around the periphery of the joint (Resnick and Niwayama, 1981). Central osteophytes produce a characteristic "bumpy" contour in the central aspect of the articular surface (*ibid.*). Periosteal developments are often seen as a thickening of the intra-

articular cortices that result in buttressing (*ibid.*) and capsular osteophytes appear as lips of bone extending along the direction of capsular pull (*ibid.*).



**Normal** **Abnormal**

**Plate 5.1.2a Superior view of a normal thoracic vertebra (*left*) compared to superior view of a thoracic vertebra exhibiting osteophyte development on right anterolateral margins (*right*).**
**Post medieval, London.**
**(Photos: Linda O'Connell, courtesy of the Natural History Museum).**

**b) *Porosity***

In dry bone specimens, irregular holes with sharp edges may be observed on joint surfaces and these manifestations are described as "porosity" (Plate 5.1.2b). Following the loss of articular cartilage, subchondral bone becomes exposed and ultimately will be subject to further abrasion and alteration. This process produces two types of pathological sequelae; chondrous tuft development (Milgram, 1983) and cyst formation, the latter of which eventually leads to extensive bone resorption. The former entities represent reparative cartilage tissue forming in the marrow of exposed articular bone (Storey and Landells, 1971; Vignon *et al.*, 1974).

Histological analysis has demonstrated that these lesions are continuous with underlying cysts in living tissue that contain proliferating myxomatous cells. The subchondral cysts themselves are sclerotically margined entities of between 2-20 mm in diameter which

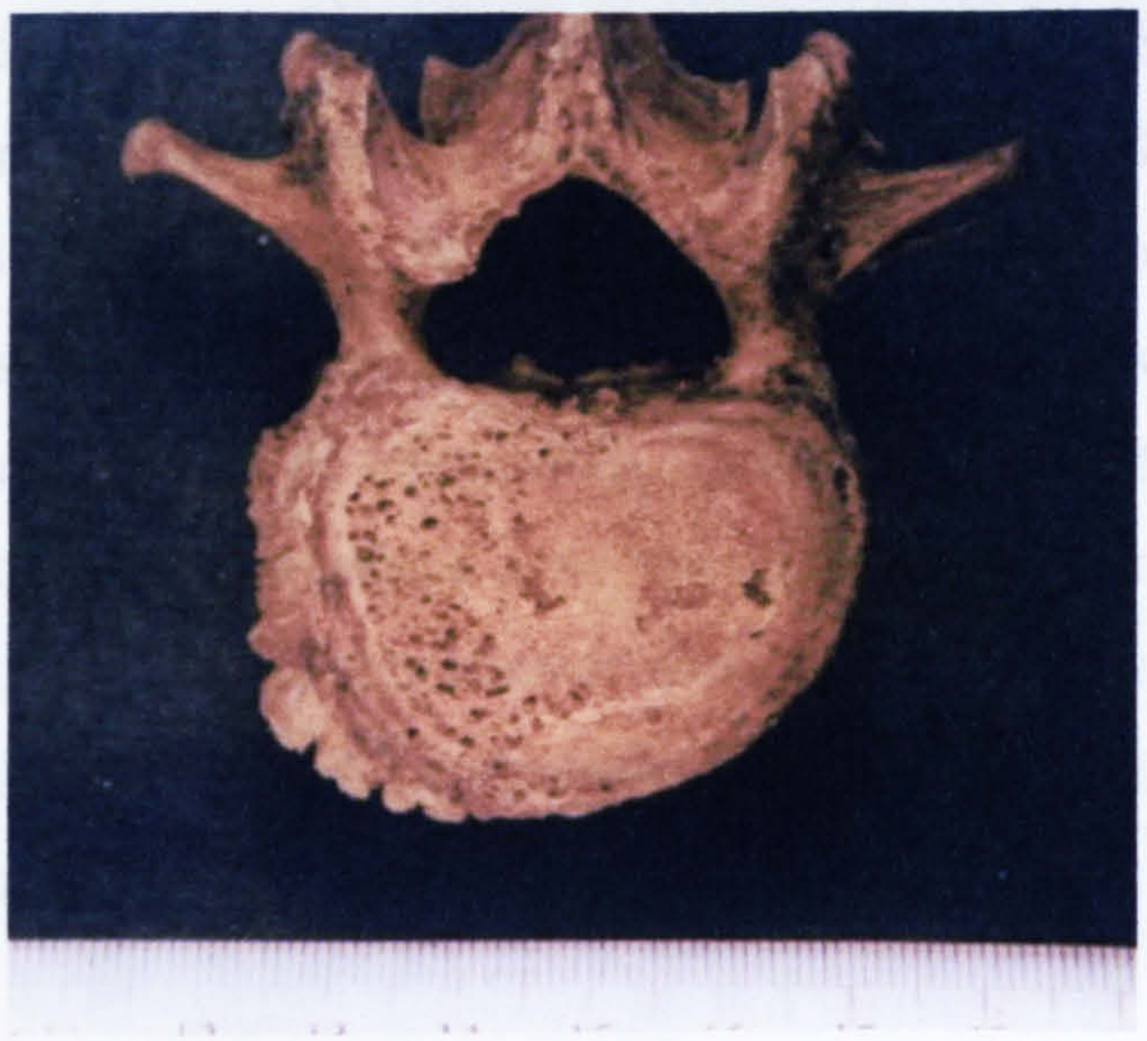


**Plate 5.1.2b Superior view of a lumbar vertebra exhibiting porotic change on right lateral aspect of body surface. Osteophyte development is also evident around the right half of the superior margin.**
**Post medieval, London.**
**(Photo: Linda O'Connell, courtesy of the Natural History Museum).**

represent focal areas of subarticular bone loss (Centeno, 1999). They are sometimes also referred to as geodes (Centeno, 1999; Spraycar, 1995) and typically develop as a result of increased biomechanical loading of bone subsequent to cartilage destruction and may communicate with pits on the surface of the bone (Rogers and Waldron, 1995).

However, it must be remembered that other forms of "holes" may be evident and these may result from a number of pathological processes, such as a) invasion of calcified cartilage by subchondral blood vessels (Brown *et al.,* 1980, 1983; Brown and Weiss, 1988; Hamerman, 1989); b) exposure of vascular channels subsequent to articular plate attenuation (Jurmain, 1999); c) perforation of the articular plate following eburnation (*ibid.*); and d) formation of conduits that permit fat to infiltrate and lubricate the joint (Ragsdale, 1991).

Differentiation between the causative agents may be problematical, although porosity attributed to angiogenesis tends to look more rounded in appearance (Jurmain, 1999). Furthermore, the relationship between eburnation and the development of porosity is also far from clear. Almost forty decades ago, a number of authors, including Ortner (1968), stated that these two entities always occurred in combination. This hypothesis has since been dispelled. In 1997, Rothschild undertook a study of the knee joint from 400 skeletons in the Hamman-Todd collection. Osteoarthritis was recognized by the presence of osteophytes or subchondral bone sclerosis. Porosity was also examined for, in order to

elucidate its relationship to osteoarthritis. Two hundred and thirty three (58.3%) of the specimens were found to be normal. Of the sample of 400, 29.5% demonstrated the presence of osteoarthritis, with 24.2% expressing no porotic change. Seventy (17.5%) joints exhibited porosity, and a further 12.2% were unaffected by osteoarthritis. Only 5.2% of specimens demonstrated the co-existence of these two entities, which led Rothschild (1997) to conclude that there was no relationship, therefore, between them. He further suggested that porosity "should be deleted as an identifier of osteoarthritis" (*ibid.*: 532). In consequence, therefore, it would thus seem sensible to record porosity independently of other lesions, a recommendation that is encouraged by a number of authors (Bridges, 1993; Buikstra and Ubelaker, 1994).

**c)** ***Eburnation***

In the developing osteoarthritic joint, loss of articular cartilage leads to direct bone to bone contact during movement. Remodelling of the subchondral bone ensues and leads to densification and polishing (Aufderheide and Rodriguez-Martin, 1998; Rogers, 2000) (Plate 5.1.2c), usually at points of maximum mechanical loading (Rogers and Waldron, 1995). This manifestation is termed eburnation and arises from the latin term *eburnea*, meaning ivory (*ibid.*). Grooves may subsequently develop parallel to the plane of motion in joints exhibiting singular planes of operation.

**d)** ***Loss of normal joint contour***

When the normal morphology of a joint is compromised by active remodelling, an alteration in the normal contour shape will eventuate (Rogers, 2000). Extreme changes will culminate in a marked distortion in the anatomical configuration. Subchondral bone change produces a flattening and/or enlargement of joint surfaces (Rogers *et al.*, 1987). Such change is particularly noted in the facet joints of the vertebral column (*ibid.*) and in the femoral head, which becomes flattened and widened and eventually comes to resemble a mushroom (Rogers and Waldron, 1995; Rogers *et al.*, 1987). Plate 5.1.2c demonstrates this change on the left superior articular facet of a thoracic vertebra. The marked change in anatomical morphology clearly contrasts with the normal appearance of the right superior articular facet.

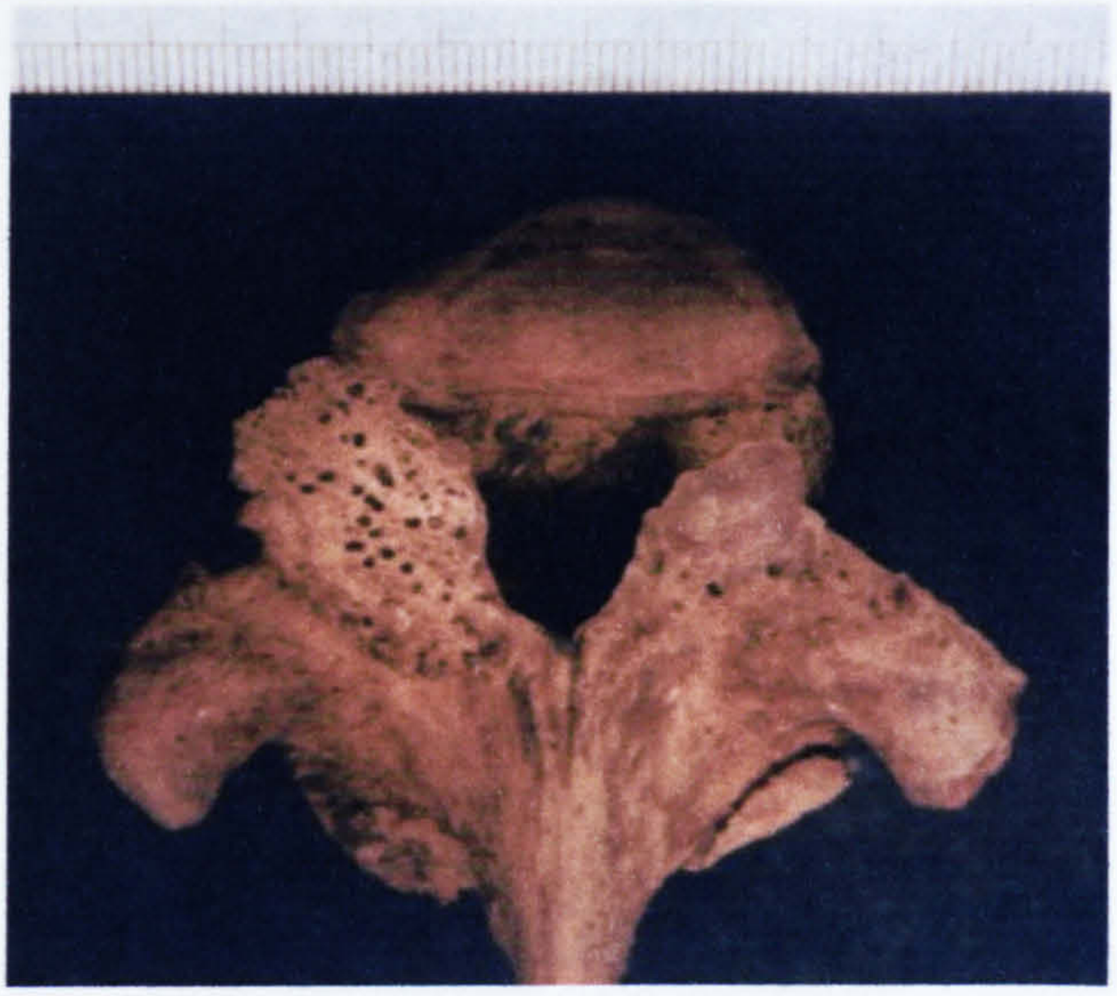


**Plate 5.1.2c Superoposterior view of a thoracic vertebra exhibiting osteophyte and porotic development on the left superior articular facet. Small areas of eburnation are discernible (shiny cream colour) within the central medial region of this articular surface. Post medieval, London. (Photo: Linda O'Connell, courtesy of the Natural History Museum).**

**e) *Ankylosis*.**

The term ankylosis is essentially an orthopaedic term that implies that a joint has decreased or absent motion and usually arises due to fusion of adjacent skeletal elements. Although ankylosis may be found associated with osteoarthritic change, it is not a feature of osteoarthritis alone (Hough, 1997), although bony bridges across joints may ultimately coalesce and unite (Plate 5.1.2e). This development, however, most likely transpires as a direct result of inherent limited mobility in these particular areas (*ibid.*).

Despite the presence of the aforementioned manifestations in bone, there still exists no standardized method for recording osteoarthritic change, a concern that researchers have been reiterating for over thirty years (Rogers, 1966; Waldron and Rogers, 1991). Some authors employ the presence of osteophytes alone (Bridges, 1991; Clark and Delmond, 1979) while others use eburnation solely (Cockburn *et al.*, 1979; Lim *et al.*, 1995; Rogers and Dieppe, 1994; Rogers *et al.*, 1987) or the combined presence of at least two of osteophytes, loss of normal joint contour and porosity (Rogers and Waldron, 1995; Rogers *et al.*, 1987; Waldron, 1992). Of all of these changes, however, eburnation is considered to

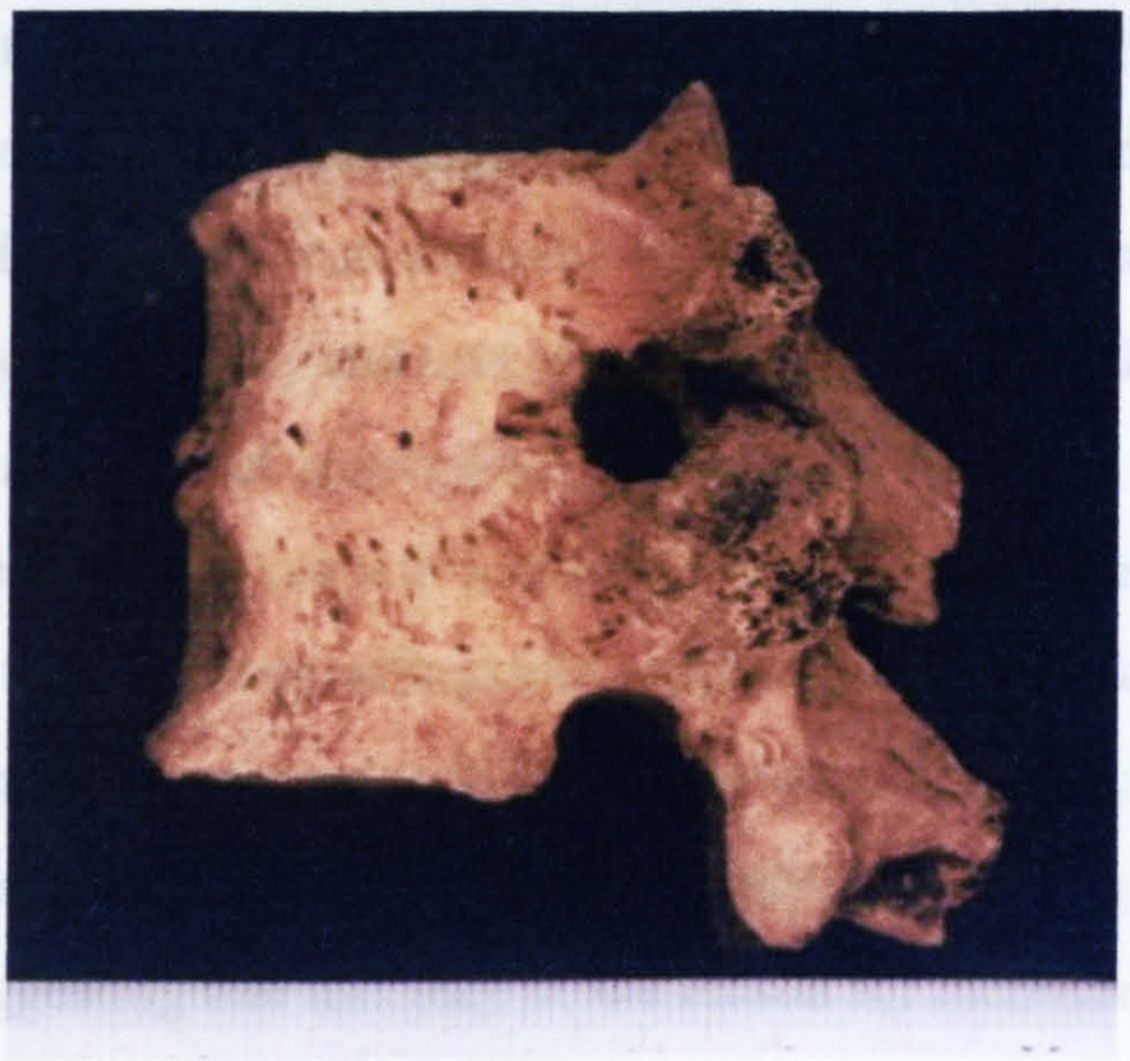


**Plate 5.1.2e Left lateral view of two ankylosed thoracic vertebrae. Post medieval, London. (Photo: Linda O'Connell, courtesy of the Natural History Museum).**

be pathognomonic by a number of authors (Jurmain, 1999; Ortner and Putschar, 1995; Rogers, 2000; Rogers and Waldron, 1995). However, because eburnation develops as a result of direct bone to bone contact in the absence of cartilage, a number of authorities quite rightly contend that such changes can arise subsequent to *other* forms of arthritis. In light of this, although they agree, therefore, that eburnation can be employed as a marker of severity of osteoarthritis, they do not include it as a form of diagnostic criteria (Altman *et al.*, 1986, 1990, 1991).

Osteoarthritis should only be applied to diarthrodial joints exhibiting subchondral bone remodelling and osteophytosis (Schwartz, 1995; Rogers, 2000). Employment of the presence of osteophytes, which may arise as a consequence of normal age related change, or as part of another disease process, as the sole identifier of osteoarthritis is probably the main reason for the wide variety in reported frequencies of the disease in the palaeopathological context (Rogers, 2000).

Radiographic features of osteoarthritis have previously been described in section 5.1.1e, but may also be employed in the analysis of skeletal specimens. Despite this facility, however, there exists a significant disparity between radiographic appearances and visual manifestations (Rogers and Waldron, 1995), with lesions appearing more obvious in the latter medium (*ibid.*). In 1990, Rogers and colleagues compared the visual and

radiographic detection of bone change in 24 knee joints from 14 skeletons. Of these, 33.3% were considered normal utilising both techniques. Sixteen joints exhibited visual changes - 45.8% of these demonstrated the presence of osteophytes alone, while the remaining 20.8% were diagnosed as osteoarthritic on the basis of a) eburnation, or b) the combination of osteophytes, porosity and loss of normal joint contour shape. Radiographic changes were noted in only 8.3% of specimens. Despite the very small sample, two areas of interest were identified. First, there was a remarkable discrepancy between the diagnosis of osteoarthritis using either visual or radiographic approaches. In this case, 20.8% were identified by visual means, as compared to 8.3% radiographically, thus suggesting that radiographic analysis is a poor tool for detecting osteoarthritis (in dry bone at least). The authors continued by suggesting that this may be the reason for inconsistencies between symptoms reported and radiographic change observed in epidemiological studies. The second point to note concerns the diagnosis of osteoarthritis by visual examination of dry bone. If eburnation, or a combination of osteophytes, porosity and loss of normal joint contour shape are utilized as identifying features, then 20.8% of the joints would be classified as osteoarthritic. However, if osteophyte presence on its own is also added to this equation, then the number of joints diagnosed with the disease would rise to 66.7%. This clearly demonstrates how variation in reported prevalence rates may arise, depending on the diagnostic criteria employed, although the very small sample employed in this research must also be recognized.

Naturally consistency is required if comparisons are to be made between archaeological and modern populations and samples. Unfortunately, there is still much disagreement among osteologists and palaeopathologists regarding this issue (Rogers, 2000; Waldron and Rogers, 1991) and such methodological inconsistencies will only be resolved when easily recognisable and appropriate criteria are identified and agreed upon.

The vertebral column is not an uncommon site for detection of such modification and is explained by considering the evolutionary biomechanics of this structure. The adoption of an erect bipedal posture in humans has led to the development of several specific skeletal adaptations, of which the spine is one example. The shape of this component is not a straight line but possesses four curves - cervical and lumbar regions are convex anteriorly, whilst thoracic and sacral elements are concave anteriorly (see Figures 3.1 and 3.6C). This curvature allow humans to balance their weight efficiently over their feet, but increases throughout the day as a result of fatigue. Points of maximum (C5, T8 and L4) and minimum (T1, T12 and L5/S1) stress occur within these curves and these are suggested as

agents responsible for the variation of pathological change observed in the spine (Aufderheide and Rodríguez-Martin, 1998; Bridges, 1992; Nathan, 1962). This hypothesis is certainly borne out in a number of anthropological studies, with the lower cervical, lower thoracic and lumbar regions (which experience maximal spinal motion [Moskovitz, 1997]), demonstrating greater affectation (Bridges, 1992, 1994; Dawson and Trinkaus, 1997; Merbs, 1983).

As a consequence, it can therefore be considered that the vertebral column, rather than reflecting occupational activity, tends to reflect biomechanical stresses placed on it by bipedalism and bipedal posture over extended periods (Knüsel, 2000). This fact is attested to by archaeological studies that have demonstrated that particular activities are not reflected in osteoarthritic change seen in the vertebral column (Bridges, 1994; Knüsel *et al.*, 1997; Waldron and Cox, 1989). In the latter paper, 24 cases of spinal osteoarthritis were appraised with respect to occupational status. Eight individuals were recorded as weavers, two were classified as manual workers, ten as non-manual and four were not known. It was discovered that a greater number of non-manual workers exhibited osteoarthritic changes in the spine, possibly suggesting that a lack of activity may have been the cause.

Proteoglycans synthesis is vital for sustaining cartilage health and it has been found that dynamic periodic and prolonged, or light loading will stimulate and impede this process respectively (Swanpoel *et al.*, 1995). It has certainly been observed that when lumbar apophyseal joints are distracted using orthopaedic Harrington instrumentation, they subsequently atrophy.

Significant loading of the upper lumbar apophyseal joints tends only to occur in the superoinferior orientation, particularly if the vertebral column is eliciting flexion or torsional movements. This has important ramifications for individuals with sedentary lifestyles and work patterns (Waldron and Cox, 1989). Spinal flexion experienced by such people will be static and postural in nature, rather than dynamic, and this predisposes the apophyseal joint cartilage to potential mechanical disruption. The articular cartilage and capsule of the joint are delineated by a fibrocartilaginous transition zone. In this area, the collagen fibres are orientated in line with stresses exerted through the capsule. The insertion points of the collagenous fibres of the joint capsule are also susceptible to developing fine splits as a result of this arrangement, and this, in turn, disrupts the load bearing properties of the cartilage, thus predisposing to osteoarthritic development.

When axial rotation is elicited in the lumbar vertebrae, the axis of rotation shifts toward the apophyseal joints in the direction of rotation. As a result, the capsule of the opposing joint should become tense and wrap round the inferior articular process. Previous studies have shown that these wrap-around ligaments are all fibrocartilaginous. Thoracic joints, on the other hand, are shielded from such loading and should therefore be purely fibrous. Boszcyk *et al.* (2001) undertook an immunohistochemical study of the posterior capsule of cadaveric thoracic and lumbar apophyseal joints, in order to analyse the molecular composition of the extracellular matrix to test this hypothesis. Both joint capsules immunolabelled for most glycosominoglycans and for type I, II and VI collagen. However, only the lumbar capsules immunolabelled for type II collagen, aggrecan, chondroitin-6-sulphate and link protein. This latter finding suggests that the lumbar joint capsule does indeed accommodate a fibrocartilaginous ligament that is able to withstand compression as well as tension during torsional movements, by wrapping itself around the inferior articular process as rotation occurred and thus limiting further movement.

Bilateral presentation of osteoarthritis of apophyseal joints (and osteophytosis of vertebral bodies) has been noted, particularly in the thoracic region of the spine (Merbs, 1983), but has not been extensively studied (Bridges, 1992). In the past, this variation, with greater expression favouring the right aspect, was sometimes attributed to the predominance of right handedness, despite the fact that some contemporary studies at the time (Culver and Pirson, 1956, Schorr *et al.*, 1956) found equal presentation of osteophytes on the right hand side in both right and left handed individuals. This patterning can, in fact, be attributed to the position of the descending aorta, which is intimately related to the left side of the thoracic vertebrae from the level of T4, until it traverses the posterior mediastinum and lies in the midline, anterior to T12 (Gosling *et al.*, 1996). The tendency for osteophytes to develop symmetrically in the lumbar region, which has been noted for about 40 years (Nathan 1962), also supports this theory.

## 5.2 INTERVERTEBRAL DISC DISEASE

### 5.2.1 Vertebral spondylosis (osteophytosis)

In order to fully appreciate the pathological manifestations associated with intervertebral disc degeneration, and the morphological factors predisposing to it, one needs to consider

embryological development. This is important, because changes taking place at this time can lead to what are perceived as structural 'weaknesses' in the developing vertebral body. Early on in this process, cleavage occurs and rapid cell division takes place. The cells (blastomeres) undergo compaction and form a solid ball of cells, called the morula (Brookes and Zeitman, 1998; Larsen, 2001; Moore and Persaud, 1998). The blastocoel/blastocyst cavity subsequently develops within this structure (Brookes and Zeitman, 1998; Larsen, 2001; Moore and Persaud, 1998) and the fluid contained therein increases and divides the blastomeres into two areas: the trophoblast and the inner cell mass. Together, these two areas constitute the blastocyst (*ibid.*).

In the third week after fertilization, gastrulation takes place (Brookes and Zeitman, 1998; Larsen, 2001; Moore and Persaud, 1998), as the blastocyst invaginates and mesenchymal cells continue to draw this newly formed cavity (the archenteron) inward. Pouches then bud off from the archenteron lining and generate the primary germ layers: endoderm (inner), mesoderm (middle) and ectoderm (outer). Around day 22-24, the dorsal or posterior part of the mesoderm above the archenteron then forms a temporary structure known as the notochord (Larsen, 2001). The ectoderm above the rudimentary notochord thickens and creates the neural plate (Moore and Persaud, 1998). This enlarges and develops a neural groove along the midline, and raised margins (the neural folds) (Scheuer and Black, 2000). These folds eventually meet over the top of the neural groove and fuse to form the hollow neural tube (Scheuer and Black, 2000; Moore and Persaud, 1998). This then detaches from the surface ectoderm and will eventually develop into the central nervous system. The notochord and developing neural tube are enclosed within a mesenchymal template (Scheuer and Black, 2000) and chondrification centres that appear in this structure by the sixth week of intrauterine life will go on to produce the centrum of the vertebra (*ibid.*). The notochord becomes increasingly compressed as ossification ensues. Finally, the notochord regresses and eventually disappears, although a remnant may remain in the intervertebral disc (Mankin and Radin, 1997; Resnick and Niwayama, 1978). In the spaces between the developing vertebrae, the notochord expands and forms the nucleus pulposus of the intervertebral disc (Larsen, 2001; Moore and Persaud, 1998; Peacock, 1951, 1952). Cells from the inner aspect of the annulus fibrosus replace the notochord cells within the nucleus pulposus and this degeneration continues until all of the cells of the notochord have disappeared, usually by the second decade of life (Scheuer and Black, 2000). The sclerotome is a structure that develops from the differentiation of blocks of segmented mesoderm known as somites (Larsen, 2001). The annulus fibrosus develops

from sclerotomal cells left in the region where the sclerotome splits during re-segmentation (Larsen, 2001; Moore and Persaud, 1998).
Failure of proper retroregression of the notochord creates a defect in the cartilaginous end plate and prolapse of the intervertebral disc into the vertebral body occurs, facilitating the formation of Schmorl's nodes (*ibid.*).

Within the adult intervertebral disc, three areas are distinguishable; an outer annulus fibrosus, an intermediate transition zone and an inner nucleus pulposus. The former two contain fibrochondrocyte cells derived from mesenchyme. The latter is initially formed from the notochord, but is later replaced by fibrochondrocyte cells (Oegema, 1993). This arrangement renders the intervertebral disc a highly heterogeneous structure and the cells within vary with anatomical region. Furthermore, they possess significant differences in their phenotypes. Gene expression levels of various constituents, including collagen type I and II and aggrecan, have been measured and demonstrate that the annulus fibrosus and transition zone can undergo reversible shifts in phenotype when cultured *in vitro* under different conditions (Wang *et al.*, 2001). This strongly suggests that culture systems play an important role in determining cell phenotype and in the response of these cells to *in vitro*, and therefore potentially *in vivo*, biophysical and biochemical stimuli.

Osteophytosis describes the degenerative disease of the superior and inferior vertebral body surfaces. Joints between these elements are not synovial (unlike the apophyseal joints between the vertebral arches), but cartilaginous. The articular surfaces are covered by a thin layer of hyaline cartilage and united by a plate of fibrocartilage. Stresses and damage to the fibres of this fibrocartilage provoke bone deposition along the anterior and lateral margins of the vertebral bodies. Although intervertebral disc degeneration is usually cited as the main cause for this manifestation (with local tears of the annulus fibrosus proving one of the usual factors [Renton, 1998]), traumatic and infectious processes also have a role to play in its aetiology (Clark and Delmond, 1979; Nathan, 1962). Technically speaking, the lipping that is observed on the vertebral bodies is referred to as spondylosis deformans. In this condition, the osteophytes extend from superior and inferior anterolateral aspects of the vertebral bodies (Hough, 1997), and extend across intervening intervertebral spaces. They are most often found in the mid and lower cervical regions (Aufderheide and Rodríguez-Martin, 1998; Rogers, 2000) and the lower lumbar area (Andersson, 1983; Aufderheide and Rodríguez-Martin, 1998; Rogers, 2000). The thoracic region is also affected, although there is some dispute as to specific area, with some authors

favouring the upper extremities (Rogers, 2000) and others, the lower aspects (Aufderheide and Rodríguez-Martin, 1998). The osteophytes tend to grow parallel to the vertebral end plate and project out from the vertebral body and curve towards neighbouring vertebrae. Ultimately, they may fuse or ankylose (Schwartz, 1995), uniting adjacent vertebral bodies and thus preventing movement.

In some cases, these osteophytes may be particularly prominent and extend along most of the length of the vertebral column, resulting in ankylosis. In 1969, Baker and associates noted that a spontaneous ankylosis of the associated apophyseal joints tended to accompany segmental fusion. In particularly marked cases of ankylosis, the term ankylosing hyperostosis (spondylosis hyperostotica, hyperostotic spondylosis) was coined to describe these particular marked cases (Lagier, 1983). Additional, associated extraspinal manifestations are considered indicative of "Forestier's Disease" or Diffuse Idiopathic Skeletal Hyperostosis (DISH). In this condition, the intervertebral disc and subchondral bone are normal and osteophytes arise from ossification of ligament insertions (Binder, 1998; Lagier, 1983). Differentiating between this condition and severe osteophytosis which is ankylosed, however, has proved problematical (Fournasier *et al.,* 1983; Resnick and Niwayama, 1976; Rogers *et al.,* 1985), but not impossible.

Resnick and Niwayama (1976) evaluated 215 cadaveric spines and 100 patients with DISH, both radiographically and histologically, and were able to differentiate both quantitatively and qualitatively between ossification associated with the latter condition and typical spondylosis. Fournasier *et al.* (1983) undertook morphological, radiological and histological examination of entheseal new bone formation in post mortem thoraco-lumbar (T3-L5) specimens. They also found that they were able to distinguish marginal osteophytic growth from ossification of entheses further down the vertebral body and away from the margin of the intervertebral disc.

Osteophytosis is an age related phenomenon (Nathan, 1962; Rogers *et al.,* 1997), which increases in severity with time (Clark and Delmond, 1979) and as such, has even been employed as an ageing technique for skeletal material (Stewart, 1957). Minimal lesions begin to manifest as early as the third decade (Ortner and Putschar, 1985) and almost all individuals are affected to some degree by 60 years (Clark and Delmond, 1979). Furthermore, this condition tends to occur earlier and with greater severity in men (*ibid.*). These factors are certainly attested to by Schmorl and Junghanns (1971), who examined over 4000 spines from post-mortem examinations. They discovered that spinal

osteophytosis was present in 60% of females and 80% of males by the age of 50 years, and that by 90 years, this value had risen to 100%.

Very little work appears to have been conducted on the effects of ethnicity on the development of osteophytosis. It has been noted that anterior osteophytes tend to affect whites more than Negroids, although the relationship is not significant. However, in both groups, males express a greater predilection than females, and this is significant (Nathan, 1962). If posteriorly developing osteophytes are considered, then once again, prevalence in whites is greater than in Negroids, but this time the relationship is significant. Males are also affected more than females, but this is not statistically significant (Nathan, 1962).

In 1979, Clark and Delmond forwarded three factors (in addition to the support strength of tissue surrounding the intervertebral disc) that governed osteophyte development. These comprised; a) degree of compression and shear force on the intervertebral disc, b) rate of disc degeneration and c) degree of spinal curvature. These areas will be discussed further.

a) ***The degree of compression and shear force on the intervertebral disc***

Osteophytes probably form in response to abnormal stresses on the joint margin (Moskowitz and Goldberg, 1987; Rogers *et al.,* 1997) as evidenced by Wolff's Law[1] of remodelling. They serve to both brace and deflect compressive and shear forces and thus act as a partial or complete natural arthrodesis for the vertebral column (Clark and Delmond, 1979; Schmorl and Junghans, 1971). As Nathan noted back in 1962, the morphology and location of the osteophytes resemble the capital and bases of architectural pillars, and these structures are employed in structural engineering to increase the pillar's resistance to compressional forces. The formation of an osteophyte also widens the surface area of the vertebral end plate and thus dissipates forces acting across the vertebral bodies, by deflecting them from the weaker central region to the stronger, compact bone of the peripheral and neighbouring osteophytes (Nathan, 1962). It is also worth noting at this point that enthesophytes, which are also regarded as a skeletal response to stress, were found to be positively correlated (r=0.65) with osteophytes in a study conducted by Rogers *et al.* in 1997.

[1] Wolff's Law (of bone transformation) essentially describes the unique and adaptive property of bone, whereby osteons are organised to lie along lines of mechanical stress in bones. If the stress pattern is altered, then the osteons will align to accommodate it accordingly (Steele and Bramblett, 1988).

b) ***The rate of disc degeneration***

The mechanism of intervertebral disc degeneration will be considered next. Both the cartilaginous end plate and the disc itself may contribute to this process. The cartilaginous end plate is responsible for four main functions (Antoniou *et al.,* 1996): a) involvement in vertebral body growth, b) intervertebral disc nutrition, c) partial absorption of the hydrostatic pressure dissipated by the intervertebral disc under loading, and d) prevention of bulging of the nucleus pulposus into the vertebral body. All of these functions depend upon the structural integrity of the matrix and the physiological balance between collagen, proteoglycans and water. Cartilaginous end plate degeneration transpires as a result of end plate matrix changes (Antoniou *et al.,* 1996; Gruber and Hanley, 2002). Such degeneration may eventually lead to an accelerated degenerative process (Pritzker, 1977; Oda *et al.,* 1988) and also contribute to intervertebral disc herniation (Kokubun *et al.,* 1996). Increased damage to the end plate matrix structure is demonstrable in the normal adult as compared to the child (Aoki *et al.,* 1987; Bernick and Calliet, 1982; Oda *et al.,* 1988). Three phases have been identified to explain this degeneration (Antoniou *et al.,* 1996):

*Phase I* (growth) – In the age group 0-15 years, active synthesis of matrix molecules, such as procollagen I and II and aggrecans, takes place. In addition, active denaturation of type II collagen also occurs.

*Phase II* (ageing and maturation) – Between 15-40 years, there is a noticeable decrease in the synthetic activity taking place and a reduction in denaturation of type II collagen.

*Phase III* (degeneration) – From 40-80 years, there is an increase in type I procollagen synthesis and type II collagen denaturation. These processes are both related to tissue degeneration.

It has been suggested that with age, the cartilaginous end plate thins, tears and then disappears (Coventry *et al.,* 1945; Eckert and Decker, 1947), changes which have been attributed to apoptosis[2] of chondrocytes. In a recent study, Ariga and colleagues (2001) demonstrated the presence of apoptosis in the cartilaginous end plate. They also noted that the percentage of apoptotic cells increased with age and was followed by tearing and

[2] Apoptosis is a morphologic pattern of cell death affecting single cells, marked by shrinkage of the cell, condensation of chromatin, formation of cytoplasmic blebs, and fragmentation of the cell into membrane-bound apoptotic bodies that are eliminated by phagocytosis (Dorland, 2000).

eventual disappearance of the end plate. They concluded that apoptosis was involved in the ageing process and preceded the development of intervertebral disc degeneration. Apoptosis can be induced by a variety of other factors other than age, including tumour necrosis factor, nitric oxide, growth/nutritional deprivation and irradiation (*ibid.*). Changes are also noted within the intervertebral disc with increasing age. From around 30 years of age, the disc gradually dehydrates (Ritchie and Fahrni, 1970) and proteoglycans chemistry also begins to alter (Urban and McMullin, 1988). There is a noticeable change in the total *in situ* content of both proteoglycans and water with further increasing age (Bishop and Pearce, 1993; Buckwalter *et al.,* 1985; Pedrini-Mille *et al.,* 1983). Essentially, the proteoglycan content of the intervertebral disc begins to decline (Adams and Muir, 1976; Buckwalter, 1995; Gower and Pedrini, 1969; Pearce *et al.,* 1987) and leads to loss of water and a decreased capacity to bear compressional loads (Adams *et al.,* 1996a). The additional loss of patterning/distribution of type I and II collagen fibres, together with an excess of type I fibres in both the annulus fibrosus and the nucleus pulposus (Herbert *et al.,* 1975) also compromises the mechanical efficiency of the intervertebral disc. The concomitant, age related calcification of the cartilaginous end plate (which has occurred prematurely with a mutation in the type II collagen gene in murine studies [Sahlman *et al.,* 2001]) inhibits diffusion of nutrients into the intervertebral disc.

Okuda and associates (2001) have documented age related changes in the expression of insulin like growth factor-1 (IGF-1) receptors and IGF binding proteins and have recorded how this may contribute to the decline in proteoglycan synthesis in intervertebral disc cells. Insulin like growth factor-1 is essentially a peptide that can activate proteoglycan synthesis and studies have shown that chondrocytes exhibit a reduced response to IGF-1 with age (Guerne *et al.,* 1995; Loeser *et al.,* 2000; Martin *et al.,* 1997) and in osteoarthritis (Dore *et al.,* 1994; Fernihough *et al.,* 1996; Loeser *et al.,* 2000).

Innervation and vascularization of the intervertebral disc are both age and disease related. In fetal and neonatal structures, the superficial layers of the annulus fibrosus contain dense accumulations of both nerves and blood vessels (Jackson *et al.,* 1966), but these gradually disappear during postnatal development (Bogduk *et al.,* 1981; Palmgren *et al.,* 1996) until only the outermost lamellae of the annulus demonstrate their presence. Here they lie between the layers and parallel to the orientation of the collagen fibres (Palmgren *et al.,* 1996). The nucleus pulposus, however, appears to be devoid of nerves at all stages of development (Palmgren *et al.,* 1996). Despite this, vascular and neural tissue has been

seen to reappear in degenerated and herniated intervertebral discs (Coppens *et al.,* 1997, 1990; Freemont *et al.,* 1997; Johnson *et al.,* 2001; Kauppila, 1995; Palmgren *et al.,* 1996), sometimes with nerves (Coppens *et al.,* 1997, 1990; Johnson *et al.,* 2001) and blood vessels (Freemont *et al.,* 1997; Johnson *et al.,* 2001) penetrating deep into the inner third of the annulus fibrosus or the nucleus pulposus and others just infiltrating outer areas (Ashton *et al.,* 1994). Melrose and colleagues (2002) found such changes associated with a depletion of proteoglycans in an ovine annular lesion model of experimental disc degeneration. Unfortunately, little is known about the specific factors governing this innervation, although studies on other tissues have identified a number of important regulatory influences, including activity of specialized nerve support cells called glia. Peripheral glia, or Schwann cells, regulate mature peripheral nerve growth (Brandt *et al.,* 1999; Son and Thompson, 1995) through a number of mechanisms including Schwann cell derived neurotrophic factors, cell bridging effects, or synthesis of matrix molecules that either stimulate or inhibit the growth of nerves. Johnson *et al.* (2001) demonstrated the presence of Schwann cells, in association with nerves, in degenerate intervertebral discs, although this co-localization is not exclusive.

In intervertebral disc degeneration, there is also an alteration in degradative enzymes (Ng *et al.,* 1986). Extensive vascular ingrowth (as previously noted), followed by further internal disc disruption and angiogenic factors associated with this blood vessel proliferation are capable of activating degradative enzymes (Weiss and McLaughlin, 1993), thus potentially initiating intervertebral disc degeneration.

Other potential risk factors include familial predisposition (Sambrook *et al.,* 1999; Simmons *et al.,* 1996), inadequate sports activities and night work shifts (Elfering *et al.,* 2002). However, it must be remembered that the relationship between occupational risk and disc degeneration is extremely complex and difficult to quantify. A number of authors have also suggested that facet tropism (coronal and/or sagittal asymmetry) predisposes to the development of degenerative disc disease (Broberg, 1993; Carrera *et al.,* 1980; Farfan and Sullivan, 1967; Farfan *et al.,* 1972; Ishihara *et al.,* 1997; Ko and Byung, 1997; Noren *et al.,* 1991). Some authorities dispute this theory, however, based on the results of both animal (Stokes *et al.,* 1989; Sullivan *et al.,* 1971; Vanharanta *et al.,* 1993) and human studies (Cassidy *et al.,* 1992; Hagg and Wallner, 1990; Malmivaara *et al.,* 1987; Vanharanta *et al.,* 1993). Such discrepancies in the literature can be explained a number of ways. In the first instance, study groups and methodologies for data collection (cadaveric, photographic, radiological, axial CT scanning) were extremely variable. Secondly, definitions of facet tropism varied between authors. In some cases, differences between

facet angles (used to denote tropism) were set as high as 5° or as low as 1°. Finally, the criteria employed to determine degenerative disc disease were also multifaceted, and included anatomical dissection, clinical evaluation, surgical examination, myelographic appearance, plain CT, and MRI scans.

No single standardized method for recording intervertebral disc degeneration currently exists, although a number of authors have recorded changes by MRI (Modic *et al.*, 1988; Pearce *et al.*, 1991; Sether *et al.*, 1990) and a recent publication by Pfirrmann (2001) has presented one potential grading system, utilising the MRI approach.

**c)** ***The degree of spinal curvature***

The third category of factors governing osteophyte development (as noted by Clark and Delmond, 1979) concerns the degree of spinal curvature and may be alluded to by the term "wedging". Wedging has been defined as the difference between the posterior (P) and anterior (A) longitudinal heights of the vertebral body (termed the [P-A] value) (Allbrook, 1956). Positive wedging is defined where P is greater than A and provides a measure of relative kyphosis. Negative wedging relates to lordosis and occurs when P is less than A. Men possess a relatively greater defined kyphosis in the lumbar region of the spine than women and this dramatically increases with age (Clark and Delmond, 1979). The extent to which each individual vertebra contributes to curvature was considered by Clark and Delmond in 1979. They found that L4 was the point of contraflexure, that is to say, the point at which the curvature changes from a kyphotic arc to a lordotic one, and which presented the point of greatest stress in the lumbar segment. Not surprisingly, the fourth lumbar vertebra also exhibited the greatest amount of osteophytosis in their study. As a result they concluded that wedging may potentially provide a means for normal degenerative change predictability. On a similar note, Manns *et al.* (1996) noted that age related kyphosis is a function of both vertebral morphology and intervertebral disc integrity. Eventually this will result in the development of localized areas of increased stress within the annulus fibrosus (McNally and Adams, 1992) and thus predispose it to disruption and damage (Johnstone *et al.*, 1992; Urban and McMullin, 1988).

Pathological manifestations of both vertebral spondylosis and spinal osteoarthritis are indeed similar. Fibrillary disintegration of the cartilaginous end plate, through which the intervertebral disc is attached to the vertebral body, cannot be histologically distinguished from changes in apophyseal osteoarthritis (Lagier, 1983), and eburnation of subchondral

bony plates also develop in a similar manner. This essentially means that the two processes of degeneration are not unrelated despite the fact that many authors make a distinction between the degenerative changes affecting the intervertebral discs and vertebral bodies (spondylosis) and those affecting the apophyseal joints (classified as osteoarthritis). Lagier (1983) has even suggested that the term spinal osteoarthritis should not be limited to apophyseal joints alone

It is a fact that the intervertebral discs shift a greater amount of compressive and torsional loads onto the apophyseal joints (Broberg, 1983; Mankin and Radin, 1997) and thus contribute to further degenerative change there (Andersson, 1983; Moskovitz, 1997). Changes in the facet joint after chemonucleolysis-induced disc space narrowing were examined in animal models (Gotfried *et al.*, 1986) and results suggested that there is a cause and effect relationship between the disc pathology and facet pathology and that this can affect the adjacent disc facet joint biology. Initial facet lesions appeared to be potentially reversible with reconstitution of the disc height as opposed to the marked changes seen with the long term/permanent loss of disc height (Lipson and Muir, 1981), which might be expected to cause irreversible osteoarthritic-like changes in the adjacent facet joint.

With respect to human clinical studies, Butler *et al.* (1990) noted that intervertebral disc degenerative change tended to precede apophyseal joint degeneration, although Swanpoel *et al.* (1995) noted that of the two methods (MRI and CT scans) utilized to examine each of these areas respectively, the former may have been better at detecting change. Furthermore, Swanpoel and colleagues (1995) reported a weak correlation ($r^2$ =0.29) between intervertebral disc degeneration and apophyseal joint damage themselves. They also noted that fibrillation of apophyseal joint cartilage did occur in the absence of intervertebral degeneration. Previously, Malmivaara *et al.* (1983) had also documented that these two processes were unrelated, at least at the levels of T10-L1. In fact, several authors have long since stated that degeneration of the intervertebral disc cannot explain all types of apophyseal joint degeneration (Ingelmark, 1959; Lewin, 1964).

### 5.2.2 Intervertebral disc herniation

The most dramatic clinical effect of disc degeneration is disc herniation and the incidence of this closely follows the increasing incidence of disc degeneration up to the age of 45

years (Hakelius and Hindmarsh, 1972; Sprangfort, 1971) and occurs mainly in the lower three lumbar segments (Andersson, 1983; Casey and Weinstein, 2001; Johnson, 1995). Studies on cadavers (Jayson and Barks, 1973) and MRI scans of patients (Powell *et al.*, 1986) have shown that disc degeneration, when present, increases the risk of this occurring. Genetic factors may play a role in this, in additional to environmental ones. Familial predisposition in individuals less than 21 years (Matsui *et al.*, 1992) and of all ages (Varlotta *et al.*, 1991) have been noted and the fact that females show a greater predilection than males has led to the suggestion that this may be via a sex-linked genetic transfer (Simmons *et al.*, 1996). Other predisposing factors have included smoking (Bigos *et al.*, 1992) and occupational activity (Bigos *et al.*, 1986, 1992). Truck driving (Kelsey *et al.*, 1984) has been forwarded as one example of the latter. Height, weight and body mass have not demonstrated any relationship to date (Harrington *et al.*, 2001) and neither has biochemical ageing changes (Gordon *et al.*, 1991).

Rupture of the intervertebral disc begins at the periphery through the effects of rotation and forward flexion of the vertebral column (Lu *et al.*, 1996; Mundt *et al.*, 1993; Oshina *et al.*, 1995), rather than through compression or compression coupled with flexion (Adams and Hutton, 1982; Jayson, 1998). On flexion of the vertebral column, the nucleus pulposus tends to move posteriorly within the intervertebral disc (Fennell *et al.*, 1996). Extension tends to be accompanied by anteriorly directed migration (*ibid.*). Such changes had also been previously recorded in cadavers (Shepperd, 1991). However, Fennell and associates (1996) did point out that such cadaveric studies did not truly replicate the correct bending geometry of the spine. The intervertebral discs were bisected, and this effectively altered the normal internal swelling pressure that plays an important role in the intervertebral disc's response to axial compression (Hukins, 1992; Urban and Maroudas, 1979). Despite this, experiments on cadaver spines have demonstrated abnormal patterns of movement (Shepperd, 1991). Fennell and colleagues (1996) undertook their study on living individuals, but only on a very small sample of three subjects. They employed MRI to study the position of the nucleus pulposus in lumbar intervertebral discs in flexed, extended and neutral postures. Results showed that the extent of migration of the nucleus pulposus was correlated with the flexion-extension angle. In two of the subjects, abnormal movements were noted in the L4-L5 disc, with the nucleus pulposus moving in the opposite direction to that anticipated. Fennell *et al.* (1996) explained that this could be accounted for by the fact that these two individuals had a previous history of back pain, and may therefore, have had an abnormal L4-L5 disc.

Pressure within the intervertebral disc increases with upright posture and load bearing. The load on the lumbar spine is increased by the contraction of the paravertebral muscles stabilising the vertebral column, and reduced by the lumbar lordosis (Jayson, 1998). The prolapse of intervertebral discs has been linked with the sudden loading of the vertebral column, while in the flexed position (Nachemson, 1960, 1981; Simunic *et al.,* 2001), and indeed Kelsey and colleague's (1984) epidemiological study suggested a 300% to 600% increased risk of acute lumbar intervertebral disc prolapse in those individuals whose work involved repetitive bending and lifting.

Flexion of the spine stretches and thins the posterior annulus fibrosus in the axial direction, thus rendering the intervertebral disc more vulnerable to prolapse if hydrostatic pressure in the nucleus pulposus is increased simultaneously. Furthermore, in 2000, Race *et al.* demonstrated a strong dependence of the intervertebral disc's modulus on both the level of hydration and the loading rate. Simunic *et al.* (2001) employed an animal model in their study and demonstrated that the nucleus pulposus is at greatest risk of damage when the vertebral column is fully flexed and the intervertebral disc fully hydrated, irrespective of loading rate.

The stress distribution is not uniform within the intervertebral disc. Adams *et al.* (1996b) examined 87 intervertebral discs obtained from 53 lumbar spines taken from individuals between 16-87 years. No actual breakdown of absolute numbers of individuals of specific ages or sex of those individuals were presented, although tables and figures did refer to these parameters indirectly. Adams and colleagues found that intradiscal stresses measured were not highest in the nucleus pulposus, as is commonly believed, but in the inner and middle annulus fibrosus, especially posterior to the nucleus. The outermost 2-4 mm of the annulus fibrosus has practically no resistance to compressive stresses. Essentially, a large central region, representing the functional nucleus pulposus and the inner annulus fibrosus, exhibited equal and unvarying vertical and horizontal stresses, irrespective of direction or location of the pressure transducer. In this area, the intervertebral disc behaved like a pressurized fluid. In front and behind this functional area, the stresses registered differed from one another and varied with distance. This reflected the solid behaviour of the annulus fibrosus. The only exception was the outermost 2-4 mm, which behaved like a tensile skin.

Although the highest peak stresses occur in the annulus fibrosus (Adams *et al.,* 1996a, b), most recent work has shown that regions in the posterolateral annulus, near to the intervertebral foramen, demonstrate the highest pressure (Edwards, 2001). The mid-sagittal stress values are greatest with combined bending and compression movements,

rather than compression alone (Adams *et al.,* 1994, 1996a, b; McNally and Adams, 1992). Although these studies are mostly conducted *in vitro*, it has to be noted that the areas identified do correspond with the most frequently recorded locations for intervertebral disc degeneration. Older intervertebral discs exhibit more irregular stress profiles (McNally and Adams, 1992).

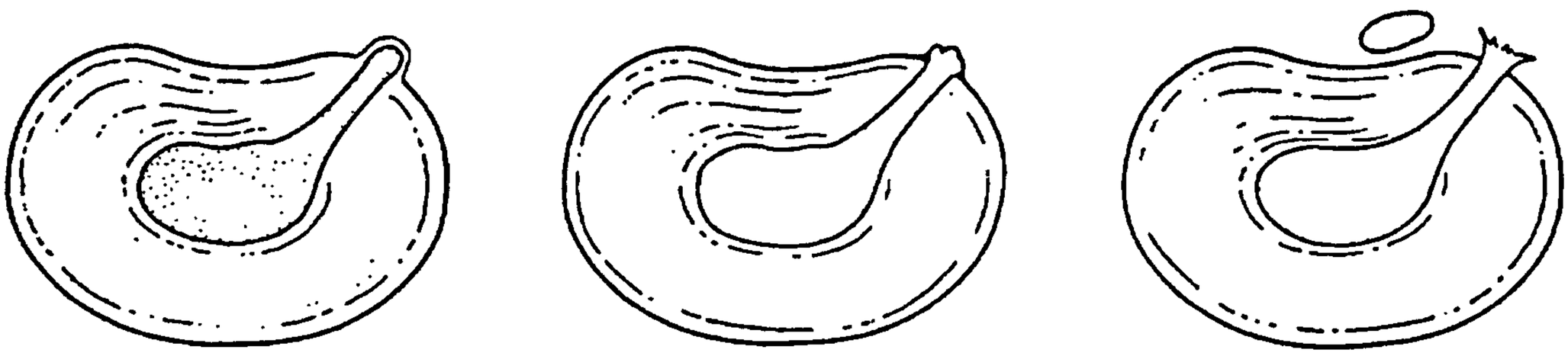
Magnetic resonance imaging has been employed to examine relaxation times and water diffusion within different regions and under different loads in the intervertebral discs. Results suggest that this approach can be utilized to measure significant changes occurring in the discs and therefore inform on changes transpiring with degeneration (Chiu *et al.,* 2001).

An elevation in the tensile stress in the annulus fibrosus can lead to annular tears and thus predispose to subsequent intervertebral disc herniation (Brinckmann and Porter, 1994; Kelsey *et al.,* 1990). As a consequence of this, if the intervertebral disc is considered as a fluid filled cylinder, then annular failure could be related to end plate morphology through Laplace's[3] law. This law states that wall tension is equal to the radius/wall thickness multiplied by the transferal pressure, or put as a corollary, wall tension anywhere in an oval tube is proportional to the radius of curvature. It thus follows that end plates that are rounder, will therefore exert a greater tension in the posterior aspect of the annulus fibrosus, due to the radius in that area being relatively longer per total area of the end plate. The greater amounts of tension arising there will potentially lead to more frequent failure in that area (Harrington *et al.,* 2001), particularly at the levels of L4-L5 and L5-S1. Actual overall size of the end plate is less of a factor governing intervertebral disc herniation overall, although the L4-L5 disc gave the most significant results of the whole. Likewise, overall end plate area only appears to be significant in males, but if this is divided down into specific areas in the vertebral column, then neither sex shows any significance (*ibid.*).

The three degrees of herniation are known as protrusion, extrusion and sequestration (Figure 5.5) and are identified according to extent and whether the herniated material retains contact with the disc (Jayson, 1998). The pathogenesis of protrusion has not been experimentally demonstrated in humans, although animal models have been employed for this purpose (Kuga and Kawabuchi, 2001) and have demonstrated that this type of herniation results from disorganization of ruptured lamellae in the annulus fibrosus and not from focal compression of the nucleus pulposus. Herniation of the intervertebral disc most

[3] Pierre Simon de Laplace (1749-1827) was a French mathematician and physicist (Dorland, 2000).

often occurs at the level of L4/5 and L5/S1, and tends to be directed in a posterolateral direction (Jayson, 1998).



a) Protrusion b) Extrusion c) Sequestration

**Figure 5.5 Types of intervertebral disc herniation.**
**a) In the protruding disc, the nucleus pulposus is confined by the outer fibres of the annulus fibrosus. b) In the extruded disc, the nucleus pulposus breaks through and comes to lie under the posterior longitudinal ligament. c) In the sequestrated disc, a free fragment of nuclear material comes to lie in the spinal canal.**
**(Adapted from Johnson, 1995: 768. Original Figure No. 22.4).**

The effects of herniation are variable, and depend upon the direction of displacement. Generally speaking, they may damage surrounding structures, such as nerve roots, meninges, periosteum, blood vessels and ligaments (*ibid.*). More specifically, posterior displacement/prolapse can affect the spinal cord and its roots (Hough, 1997) and produce neurological symptoms and signs (Resnick and Niwayama, 1978). The cervical (particularly C5/6 [Bland, 1983; Hardin and Halla, 1997]) and lumbar regions show the greatest predilection for this development clinically and may cause spinal stenosis (Andersson, 1983) to develop in either area. In the lumbar region this develops with encroachment of osteophytes on the spinal canal and is due to degenerative spondylolisthesis associated with osteoarthritis of the apophyseal joint.

Anterior and lateral displacement/prolapse is associated with spondylosis deformans (Resnick and Niwayama, 1978) as previously described in section 5.2.1. Anterior intervertebral disc herniation may produce a "limbus" vertebra, where the displaced disc tissue obliquely traverses the vertebral trabeculae and exits on, more commonly, the exterior anterior aspect (and less commonly the lateral surface) of the vertebral body, thus producing a small bone fragment. Lateral disc protrusion is more common in the cervical region and less so in the thoracic region (Binder, 1998).

Effects of these manifestations are largely threefold and include the development of trabecular sclerosis in surrounding bone, calcification and ossification of the protruded disc, and extrusion of granulation tissue from the bone marrow into the intervertebral disc. All of these produce radiographic correlates (Resnick and Niwayama, 1978).
Superior or inferior displacement/prolapse produces an abnormality in the discovertebral junction and causes Schmorl's nodes in the vertebral body (Resnick and Niwayama, 1978). Hilton *et al.* (1976) report how these lesions were first independently documented by Schmorl (1927) and Putschar (1927) and are also sometimes referred to as cartilaginous nodes or intraspongious discal herniae. They may develop as a result of vascular channel regression, producing weak areas into which intervertebral discs herniate (Chandraraj *et al.*, 1998) or when the cartilaginous end plate is disrupted in some other manner (Hamanishi *et al.*, 1994; Resnick and Niwayama, 1978). Such disruption may manifest due to a number of reasons:

a) an abnormality in the end plate, such as juvenile kyphosis (Scheuermann's disease), trauma, metabolic disease, neoplasia or intervertebral osteochondrosis.

b) an abnormality in the underlying subchondral bone.

c) a weakness in the area adjacent to the nucleus pulposus, which arises as a result of the indentation left during notochord regression or where blood vessels were transmitted during infancy (Renton, 1998)

d) a noticeable perforation in the cartilaginous end plate, sometimes referred to as the "ossification gap" (Hamanishi *et al.*, 1994; Resnick and Niwayama, 1978). This is only found in children.

e) perforation and subsequent embedding of vascular channels within the vertebral body into the cartilaginous end plate (Hamanishi *et al.*, 1994; Hassler, 1970; Resnick and Niwayama, 1978).

All of the above manifestations present a weakened area that is unable to resist the pressure of the adjacent nucleus pulposus. In young patients, herniations tend to occur vertically, due to the resistance of the intact annulus fibrosus and the turgidity of the nucleus pulposus (Resnick and Niwayama, 1978). The pressure is greatest at this stage and may be accountable for the rapid formation of Schmorl's nodes at that time, whereas, with

increasing age, turgor decreases (due to a decrease in fluid) and herniation occurs more slowly (*ibid.*). In fact, in older individuals, particularly after the fourth decade, the annulus fibrosus begins to degenerate and becomes more associated with transverse intervertebral disc herniation.

The depressions resulting from these vertical herniations are often irregular in shape and have a lining of intact cortical bone. They tend to be central in the vertebral body (Hilton *et al.*, 1976), probably where the vestigial remnants of the notochord have left a focus of weakness, but may be found in any position and are most common in the lower thoracic and upper lumbar regions (Hilton *et al.*, 1976; Saluja *et al.*, 1986; Rogers, 2000). The mid thoracic and lower lumbar areas are less affected (*ibid.*). Lesions are more frequent in males than in females at all intervertebral disc levels, but especially in the mid to lower lumbar region. In many cases the specific aetiology of these nodes is unknown (Saluja *et al.*, 1986), although factors including trauma (Kornberg, 1988), underlying infection, neoplastic disease, and osteoporosis may also play a part in their production.

Hamanishi *et al.* (1994) studied 506 individuals, 400 of which were subjects reporting to a specific lumbar clinic and aged 11-84 years, and the other 106, a control group who, with the exception of one person, were all greater than 50 years of age. Schmorl's nodes were examined for using MRI and were identified in 10 (9.4%) of the control group and 76 (19%) of the lumbar group. Associated intervertebral disc herniations were noted in 30 (39.4%) cases from the lumbar group and mostly occurred at the L4-L5 level. Hamanishi and associates further documented that the older the patient with Schmorl's nodes, the greater the incidence of posterior disc herniation, especially in the lower disc levels.

A number of authors have reported cases of spontaneous regression of a herniated intervertebral disc (Komori *et al.*, 1996; Postacchini, 1999; Saal *et al.*, 1990). When such discs have been biochemically, histologically and immunohistochemically evaluated after surgical resection, inflammatory granulation tissue has found to be present (Doita *et al.*, 1996; Grönblad *et al.*, 1994; Habtemariam *et al.*, 1998; Ito *et al.*, 1996; Rothoerl *et al.*, 1998; Saal *et al.*, 1990) and has been associated with infiltrating macrophages and matrix metalloproteinases (Doita *et al.*, 2001; Grönblad *et al.*, 1994). These inflammatory mediators may induce neovascularization and persistence of inflammation (Doita *et al.*, 2001), two processes which may potentially lead to phagocytosis and resorption of herniated intervertebral discs. The inflammatory process itself has been attributed to one of two processes. In the first instance, to the direct chemical irritation of the nucleus pulposus (Kawaguchi *et al.*, 2001; Kikuchi *et al.*, 1998; Koch *et al.*, 1998; Olmarker *et al.*, 1995;

Rand *et al.,* 1997) and in the second, to an autoimmune response to the nucleus pulposus (Bobechko and Hirsch, 1965; Habtemariam *et al.,* 1996; Kanerva *et al.,* 1997).

### 5.2.3 Diagnosis of intervertebral disc herniation in dry bone

Diagnosis of intervertebral disc herniation in dry bone specimens largely depends on the direction of the herniation. Vertical herniation produces Schmorl's nodes, which are readily identified because they produce characteristic deformations. The intervertebral disc protrudes and impinges upon the vertebral surface facing it and then extends into the trabecular bone of the vertebral body, thus producing depressions on the superior and/or inferior vertebral body surface. The resulting entities are often very irregular in appearance/shape (Collins, 1949; Coughlan and Holst, 2000) and size (*ibid.*; Schwartz, 1995). They can manifest in any area, but tend to exhibit a predilection for the centre of the body, for reasons previously explained in section 5.2.2. They are lined with a layer of intact cortical bone, and this allows them to be differentiated from other lesions that can affect this part of the vertebral body. The defect can be anything between 5 mm (Aufderheide and Rodríguez-Martin, 1998) to 1 cm in diameter (Collins, 1949) and may reach depths of up to an almost implausible 1-1.5 cm (Aufderheide and Rodríguez-Martin, 1998). In the case of anterior or lateral herniation, osteophytosis develops. This manifestation has previously been described in dry bone in section 5.1.2a. Posterior manifestations produce osteolytic lesions of the posterior margin of the vertebral body surface.

# CHAPTER 6 MATERIALS AND METHODS

## 6.1 ARCHAEOLOGICAL SAMPLES INVESTIGATED

Generally speaking, there are two types of archaeological skeletal material that can be investigated; that which represents a documented sample, and that which does not. The former consists of individuals where certain parameters, such as sex and age at death, are known from coffin plates and associated documentary evidence. This type of sample represents an extremely important resource for human osteologists and palaeopathologists for many reasons. For example, it allows demographic profiling, comparison with contemporary material, not to mention an appropriate instrument for testing the validity and reliability of osteological methods (Scheuer, 1998; Scheuer and Bowman, 1995). Within the context of this thesis, documented material was mandatory - without it, it would be impossible to make any valid assessment regarding any relationships that may have existed between the various parameters under study. Naturally, it is preferable to have a large, statistically viable sample for analysis, but this requisite was partially tempered by the fact that the material under examination had to be documented.

The material that was studied, therefore, essentially heralded from four English post-medieval sites:

1) Christ and All Saints Church Spitalfields (hereafter known as Christ Church), London.
2) St. Bride's Church, Fleet Street, London.
3) St. Nicholas Church, Sevenoaks, Kent.
4) The Quaker Burial Ground, London Road, Kingston-upon-Thames.

The individuals buried at these sites, and the subsequent sample derived (for which interment dates occurred between 1741 and 1850), thus represent an eighteenth to nineteenth century, North-west European, middle-class documented population. Samples 1-3 were recovered from crypts beneath churches and sample 4 heralded from a burial ground. Socio-economic status in the Christ Church individuals had been established by an examination of occupation (and position within occupational structure), wills, land tax returns, insurance policies and company membership (Cox, 1996; Molleson and Cox, 1993). There were difficulties with this approach, but results actually reflected modern historiography (Molleson and Cox, 1993). Socio-economic status was consequently

divided into six categories: artisan, master craftsman, professional, merchant, wholesaler and the independently wealthy (Cox, 1996; Molleson and Cox, 1993). The status of the named sample was therefore described as a mix between two of Daniel Defoe's[1] groups: the "middling sort, who live well" and "the working trades, who labour hard but feel no want" (*ibid.*: 68, 98).

Socio-economic status in the St. Bride's individuals was difficult to assess as occupation was only recorded for 27 % of the adult males (Scheuer, 1998; Scheuer and Bowman, 1995) and interpretation of occupation in a historical context may prove difficult (*ibid.*). Furthermore, information contained within trade directories, land tax returns and church records was incomplete (Scheuer, 1998). However, Scheuer (*ibid.*) does state that that the socio-economic status of those buried in the crypt was higher than those interred in the cemetery.

At St. Nicholas, Sevenoaks, the majority of the eighteenth and nineteenth century vault burials were found in distinctive and elaborate coffins (Boyle and Keevill, 1998) and this relates to the assertion that burial within the church was normally reserved for individuals of high status, who were financially comfortable (Boyle, 1999; Boyle and Keevill, 1998). At the Quaker burial ground in Kingston-upon-Thames, coffin types were found to be noticeably different, possibly reflecting the social status of the individual. However, caution must be exercised here as it is normally assumed that the most ostentatious burials will be those contained within brick burial vaults (as was the case with the Barnard family at this site). Furthermore, it was believed that this attested to the prominence of this family within the community (Bashford and Pollard, 1998), thus implying a degree of prosperity. However, although Quakers were considered to avoid ostentatious burial practices (Stock, 1998), this attitude did not seem to be in complete accord with those coffins recovered from Kingston-upon-Thames (Bashford and Pollard, 1998). As an additional point, suppositions regarding social status and coffin furniture tend to be based on surviving material effects that fare far better within a vault context than those that would have been interred within general cemetery in an acidic sandy soil.

Further information pertaining to each of these sites is detailed in sections 6.1.1 to 6.1.4.

Material for analysis from each of the sites was selected according to the relative state of preservation of the skeletal elements under examination. Burials that were poorly preserved, lacked appropriate elements, exhibited prohibitive pathological change and did

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[1] Daniel Defoe (1660-1731) was a versatile and prolific writer who produced over 560 books, journals and pamphlets (Drabble, 1995).

not have a recorded age at death were omitted. Where fragmentary remains were encountered, then at least two-thirds of the vertebral column and pelvis had to be present. If one of these areas was complete, then selection depended upon at least 50% of the other area surviving. In the case of the vertebral column, percentages applied only to the observable areas of the elements examined and not to the whole specimen. With respect to the pelvis, although re-articulation was desirable, it was not mandatory if two-thirds of measurements taken from each innominate and the sacrum were achievable.

In a number of cases, data could not be recorded due to a variety of reasons and these have been listed in Table 6.1.

**Table 6.1 Reasons for missing data**

| |
|---|
| ***Metrical data*** |
| Post-mortem erosion of area |
| Indistinct boundary/margin |
| Anatomical restraints |
| Soft tissue adherence |
| Degenerative changes evident |
| Unable to calculate because of other missing values |
| ***Non-metrical data*** |
| Post-mortem erosion of area |
| Soft tissue adherement |

### 6.1.1 Christ Church, Spitalfields

Over 1000 individuals were buried in the crypt of Christ Church, Spitalfields, between 1729, when the church was consecrated, until this practice was prohibited in 1857 (Cox, 1998; Molleson and Cox, 1993). Nine hundred and eighty three sets of human remains were recovered during the excavation of the site, which began in November 1984 (Cox, 1996; Reeve and Adams, 1993) and concluded 22 months later (Cox, 1996) in September 1986. Of these, 968 were skeletonized (Molleson and Cox, 1993) and comprised 623 adults (aged 17 years or over), of which 312 were female and 311 male; 130 adults where sex was undetermined for a variety of reasons; and 215 juveniles (*ibid.*). For 383 of these individuals, sex and age at death were known (*ibid.*) from associated coffin plates, and these became known as the "named sample". These people had been buried between 1729 and 1852 (Cox, 1996; Molleson and Cox, 1993) and had dates of birth ranging from 1646

until 1844 (*ibid.*). Twenty five individuals (6.5%) had been born before 1700, 57 (14.9%) after 1800, and 301 (78.6%) in the intervening century.

Documentary research revealed that the place of residence at the time of death had been recorded for all but 20 of these cases, the latter of which were not noted in the burial register (Cox, 1996). Of those that were chronicled, 38.5% heralded from Spitalfields; 38.7% from neighbouring parishes; 21.7% from other London parishes; and 1.3% from other areas external to London (Cox, 1996; Molleson and Cox, 1993). The names of these individuals also hinted at their origins: 41.6% were French; 33.1%, English; and 25.3%, ambiguous or unknown (*ibid.*). The large proportion of French persons is attributed to the Protestant refugees, who travelled to London from the late sixteenth century until the middle of the eighteenth century (*ibid.*). These individuals were Huguenot Protestants, escaping religious intolerance that was prevalent in France during that period.

From this remarkable collection of human remains, which is currently housed at the Natural History Museum, London, 70 individuals were selected for examination. The remaining individuals were omitted from the study on account of four factors: poor preservation (including a lack of appropriate skeletal elements), the presence of prohibitive pathological change, juvenile status and a missing record of an age at death. The examination was undertaken at the aforementioned museum. The composition of this sample, by sex and age at death, is presented in Table 6.2.

**Table 6.2 Composition of the sample from Christ Church, Spitalfields, by sex and age at death**

| Age (years) | Female | Male | Total |
|---|---|---|---|
| 17 - 19 | 2 | 0 | 2 |
| 20 - 29 | 4 | 2 | 6 |
| 30 - 39 | 6 | 3 | 9 |
| 40 - 49 | 6 | 4 | 10 |
| 50 - 59 | 7 | 5 | 12 |
| 60 - 69 | 9 | 11 | 20 |
| 70 - 79 | 4 | 3 | 7 |
| 80 - 89 | 4 | 0 | 4 |
| **Total** | **42** | **28** | **70** |

### 6.1.2 St. Brides, Fleet Street

The seventh church to stand at St. Brides was opened in 1675, and replaced an earlier one which had perished in the Great Fire of London (Harvey, 1968; Scheuer, 1998; Scheuer and Bowman, 1994, 1995). Unfortunately, this edifice was also destroyed (apart from the steeple), some 265 years later during the air-raids launched on London during World War II (*ibid.*). In advance of the rebuilding and re-dedication of the present church, in 1957, an excavation had been undertaken of the crypts and revealed a medieval charnel house as well as almost 300 burials dating to the eighteenth and nineteenth centuries (Harvey, 1968; Scheuer, 1998; Scheuer and Bowman, 1995).

The current collection, which comprises 227 individuals (Scheuer, 1998) and resides in the crypt, actually represents less than half of those buried there; the fate of the remaining interments is not known. These surviving burials eventually became the subject of a conservation and re-evaluation programme conducted between 1990 and 1995 (Scheuer, 1998; Scheuer and Bowman, 1995).

Each of the 227 interments was associated with a coffin plate, which detailed the occupant's name (from which sex was deduced), age at death and date of death (Harvey, 1968; Scheuer, 1998; Scheuer and Bowman, 1994). This sample comprised 212 adults (103 female, 109 male) and 15 juveniles of less than 19 years (three female, 12 male). These individuals had been buried between 1740 and 1852 and their dates of birth varied from 1679 to 1840 (*ibid.*).

Material from this collection was examined in the crypt of St. Bride's church. The juvenile remains were excluded from the study. With regard to the adult specimens, poor preservation and prohibitive pathological change precluded examination of all but 23 individuals.

The composition of this sample, by sex and age at death, is shown in Table 6.3.

**Table 6.3 Composition of the sample from St. Brides, Fleet Street, by sex and age at death**

| Age (years) | Female | Male | Total |
|---|---|---|---|
| 17 - 19 | 0 | 0 | 0 |
| 20 - 29 | 2 | 1 | 3 |
| 30 - 39 | 2 | 2 | 4 |
| 40 - 49 | 2 | 2 | 4 |
| 50 - 59 | 2 | 0 | 2 |
| 60 - 69 | 3 | 3 | 6 |
| 70 - 79 | 3 | 1 | 4 |
| Total | 14 | 9 | 23 |

### 6.1.3 St Nicholas, Sevenoaks

The proposal to establish a suite of parish rooms as an undercroft below the existing floor of St. Nicholas' church, precipitated a 12 week excavation there, between September and December 1993 (Boyle, 1999; Boyle and Keevill, 1998). A total of 256 burials, dating to the period 1550-1875, were recovered (Boyle and Keevill, 1998). Sixteen of these remained un-examined, and a further 48 (which had been identified by name) were reburied due to extensive soft tissue survival (Boyle, 1999; Boyle and Keevill, 1998). Of the residual 192 skeletonized remains, 175 (61 female, 55 male, 59 unknown sex) were adult and 17 were juvenile. Thirty six of these (22 female, 11 male, three juvenile) represented individuals with associated coffin plates and were interred between 1648 and 1854.

At the time of analysis, 19 of the named individuals were retained by the Oxford Archaeological Unit in Oxford. Only five individuals could be examined from the sample due to a variety of reasons: six were poorly preserved or lacked appropriate elements; three were juvenile; two exhibited prohibitive pathological change; one did not have a recorded age at death; and two had actually been reburied.

The details of their sex and ages at death are tendered in Table 6.4.

**Table 6.4 Composition of the sample from St. Nicholas, Sevenoaks, by sex and age at death**

| Age (years) | Female | Male | Total |
|---|---|---|---|
| 17 - 19 | 0 | 0 | 0 |
| 20 - 29 | 0 | 0 | 0 |
| 30 - 39 | 0 | 1 | 1 |
| 40 - 49 | 0 | 0 | 0 |
| 50 - 59 | 2 | 1 | 3 |
| 60 - 69 | 0 | 0 | 0 |
| 70 - 79 | 1 | 0 | 1 |
| **Total** | **3** | **2** | **5** |

### 6.1.4 Quaker Burial Ground, London Road, Kingston-upon-Thames

In Autumn 1996, a vacant piece of land on London Road in Kingston-upon-Thames was required for residential redevelopment (Bashford and Pollard, 1998; Kirk and Start, 1999). This ground had been leased to the Quakers in 1663 and had witnessed many burials between 1664 and 1814 (Bashford and Pollard, 1998) - interments that were subsequently excavated over a ten-week period in 1996. Surviving Quaker documents recorded a total of 497 burials, of which 364 were located (*ibid.*) and 360 subsequently excavated (Start and Kirk, 1998). These individuals comprised 295 adult and 65 juvenile remains (*ibid.*). Ten burials were located within the Barnard family vault, representing three generations of the family (Kirk and Start, 1999), and included nine adults (five female, three male, one of unknown sex) and one infant (unknown sex), who were buried between 1716 and 1792 (Bashford and Pollard, 1998). Coffin plates, informing of age at death were associated with 16 interments and of these, seven heralded from the Barnard family. The School of Conservation Sciences at Bournemouth University currently curates the latter seven individuals, and five of these were selected for examination at that institution. The two specimens that were omitted from the study included one juvenile and an adult that was too poorly preserved to successfully examine.

Sex and age at death of this sample is submitted in Table 6.5.

**Table 6.5 Composition of the sample from Quaker Burial Ground, London Road, Kingston-upon-Thames, by sex and age at death**

| Age (years) | Female | Male | Total |
|---|---|---|---|
| 17 - 19 | 0 | 0 | 0 |
| 20 - 29 | 2 | 0 | 2 |
| 30 - 39 | 0 | 1 | 1 |
| 40 - 49 | 1 | 0 | 1 |
| 50 - 59 | 0 | 0 | 0 |
| 60 - 69 | 0 | 0 | 0 |
| 70 - 79 | 0 | 1 | 1 |
| 80 - 89 | 0 | 0 | 0 |
| **Total** | **3** | **2** | **5** |

### 6.1.5 The total sample

When the above 'subsamples' are combined, the overall total for remains analysed amounts to 103. These individuals represent 62 females and 41 males and are presented by age composition in Table 6.6.

**Table 6.6 Composition of the total sample analyzed by sex and age at death.**

| Age (years) | Female | Male | Total |
|---|---|---|---|
| 17 - 19 | 2 | 0 | 2 |
| 20 - 29 | 8 | 3 | 11 |
| 30 - 39 | 8 | 7 | 15 |
| 40 - 49 | 9 | 6 | 15 |
| 50 - 59 | 11 | 6 | 17 |
| 60 - 69 | 12 | 14 | 26 |
| 70 - 79 | 8 | 5 | 13 |
| 80 - 89 | 4 | 0 | 4 |
| **Total** | **62** | **41** | **103** |

In summary, this sample therefore comprises 103 adults, who were born between 1672 and 1820 and died between 1741 and 1850. They were most likely born in England and lived and died in the South-east of the country during a period of climactic decline and at a time witnessing rapid industrialization and urbanization (Molleson and Cox, 1993; Roberts and Cox, 2003). At this time living conditions for the majority of individuals were worsening and the country was affected by epidemics of smallpox, typhus, diphtheria and cholera

(Roberts and Cox, 2003). Most likely the individuals comprising this sample were, to a greater extent, cushioned against these events by virtue of their socio-economic status.

## 6.2 METHODOLOGY

Metrical and non-metrical data were collected from the sample of 103 specimens, detailed in the previous sections, and undertaken at the place of storage/curation. Basic demographic parameters were recorded first, in the following order:

1) Burial Number
2) Type of burial
3) Date of interment
4) Sex
5) Age at death
6) Parity status, if known

Of the above list, only two (3, 5) represent examples of continuous variables and could therefore be recorded directly. The burials were listed first according to a specific site order (Christ Church, Spitalfields; St. Brides, Fleet Street; St. Nicholas, Sevenoaks; Quaker burial ground, London Road) and then in ascending order of specific identification number. In this way, each of the burials examined was assigned a number between one and 103. The type of burial and sex were each numerically coded as shown in Tables 6.7 to 6.8. Where known, parity status was recorded as the number of births documented for a particular individual.

**Table 6.7 Numerical coding for type of burial**

| Type of burial | Numerical code |
|---|---|
| Crypt | 0 |
| Cemetery | 1 |

**Table 6.8 Numerical coding for sex of individual**

| Sex of individual | Numerical code |
|---|---|
| Female | 0 |
| Male | 1 |

The skeletal analysis itself was then undertaken by adhering to a specific examination procedure, whereby skeletal elements were analysed, as follows:

1) Sacrum
2) Left innominate
3) Right innominate
4) Articulated pelvis
5) First cervical to fifth lumbar vertebrae (non-metrical data)
6) Right femur
7) Left femur

The measurement of human skeletal remains has been an important part of anthropological analyses for describing individuals and comparing groups. Measurements include dimensions and calculated indices that are commonly employed by anthropologists as indicators of shape or morphology. These may subsequently be employed to describe differences in both cranial and post-cranial form, as well as evaluating temporal and geographical variation. The metrical data collected for this thesis consisted of various measurements, including those previously defined in the literature, and others devised by the author. Each of these will be discussed in turn in sections 6.2.1 (the sacrum), 6.2.2 (the innominate) and 6.2.3 (the articulated pelvis). The equipment employed to obtain this data is recorded after each measurement's description and was the same throughout the study. The non-metrical information concerned the degenerative change observed in the vertebral column, and described the extent and degree of osteophytosis, porosity and eburnation. This is detailed further in section 6.2.4. Standardization, with respect to body size, was effected by utilization of the maximum length of the femur, as recorded in section 6.2.5.

### 6.2.1 The sacrum

The number of sacral segments was first noted before a total of 15 individual measurements were taken. The measurements are individually detailed below and illustrated in Figures 6.1 to 6.3.

**A)** ***Maximum superior sacral width (Maximum anterior breadth)***

This describes the greatest distance across the alae of the first sacral vertebra (Buikstra and Ubelaker, 1994; Schwartz, 1995; Segeberth-Orban, 1980; Steele and Bramblett, 1988). See Figure 6.1A.
Equipment: Digital sliding callipers.

**B)** ***Maximum inferior sacral width***

The width of the anterior sacrum at a level determined by the inferior extremity of the auricular surface (Cox, 1989). See Figure 6.1B.
Equipment: Digital sliding callipers.

**C)** ***Maximum transverse diameter of S1***

The maximum transverse width of the body of the first sacral vertebra, measured to the external aspect of the epiphyseal ring (Buikstra and Ubelaker, 1994; Schwartz, 1995). See Figure 6.2C.
Equipment: Digital sliding callipers.

**D)** ***Maximum anteroposterior (A-P) diameter of S1***

The maximum anteroposterior (A-P) width of the first sacral vertebra measured from the sacral promontory to the sacral canal (Schwartz, 1995). See Figure 6.2D.
Equipment: Digital sliding callipers.

**E)** ***Height of body of first sacral vertebra***

The distance, in the midsagittal plane, from the sacral promontory to the inferior-most border of the first sacral vertebra (Cox, 1989). See Figure 6.1E.
Equipment: Digital sliding callipers.

**F)** ***Promontorium angle***

The angle between the superior surface of the body of the first sacral vertebra and the anterior sacral surface (Cox, 1989). See Figure 6.3F.
Equipment: Profile gauge and protractor. The contour of the sacral promontory was profiled and then traced onto a piece of paper. The promontorium angle was then measured from this using a protractor.

**G)** ***Mid-ventral curved length***

The midsagittal anterior curved length, extending from the sacral promontory to the sacral apex (Schwartz, 1995). See Figure 6.3G.
Equipment: Opisometer

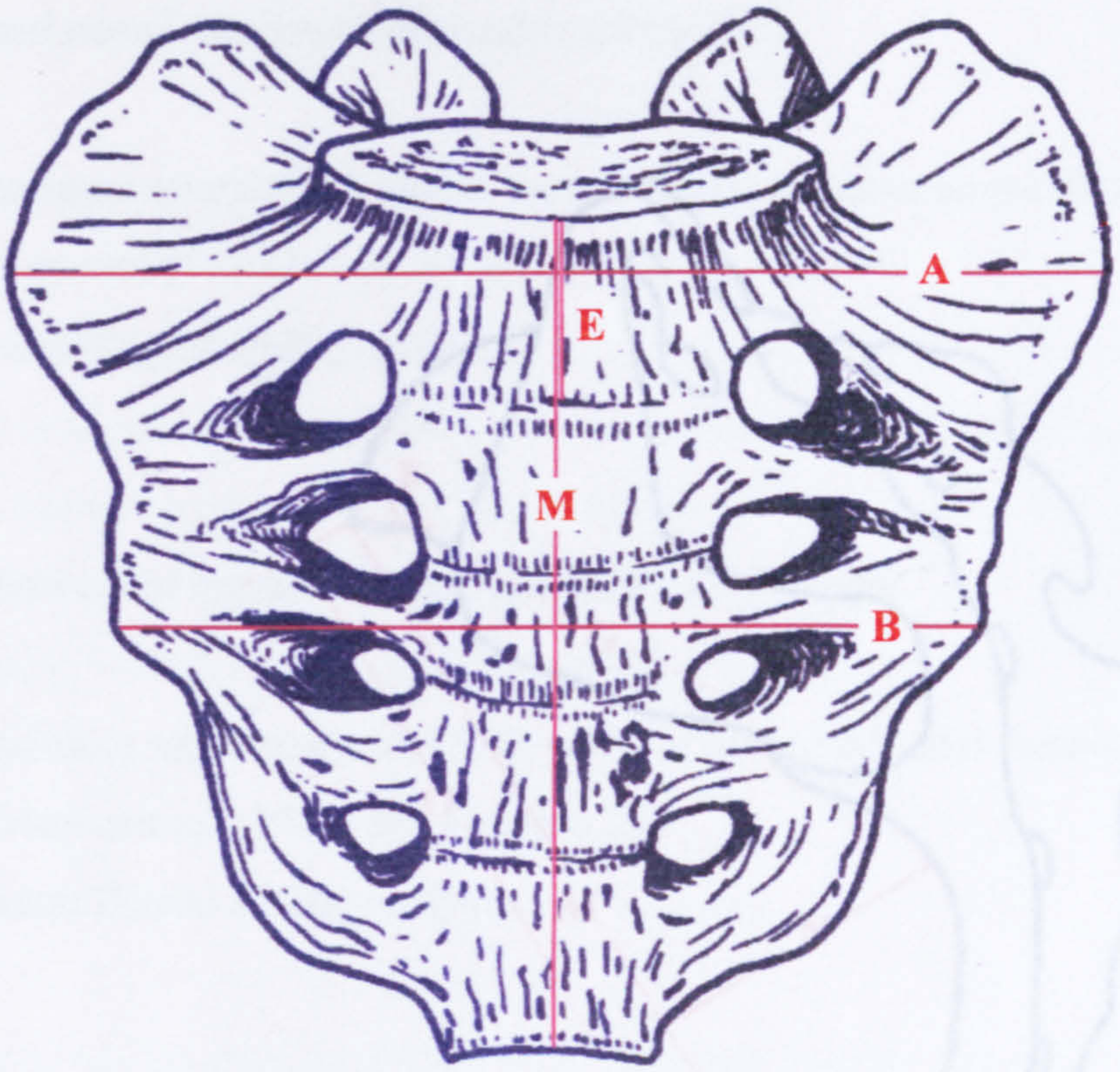



**Figure 6.1 Anterior view of sacrum**
**The measurements E and M are both taken from the sacral promontory, but for clarification purposes, have been separated slightly in this diagram, to allow differentiation between them.**
**(Adapted from Snell, 1986: 308. Original Figure No. 6-9A)**

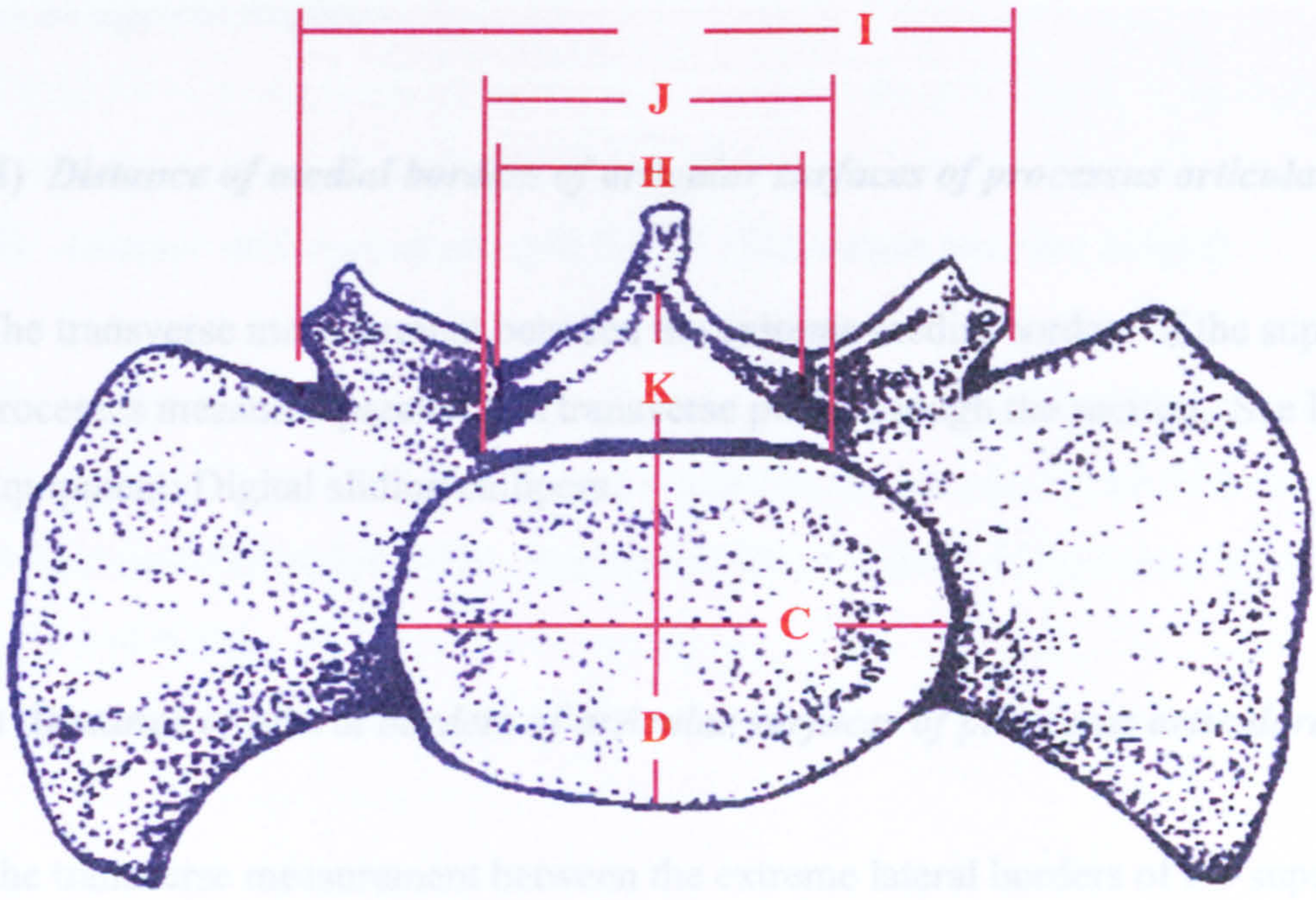



**Figure 6.2 Superior view of sacrum**
**(Adapted from Schwartz, 1995: 91. Original Figure No. 3-9)**

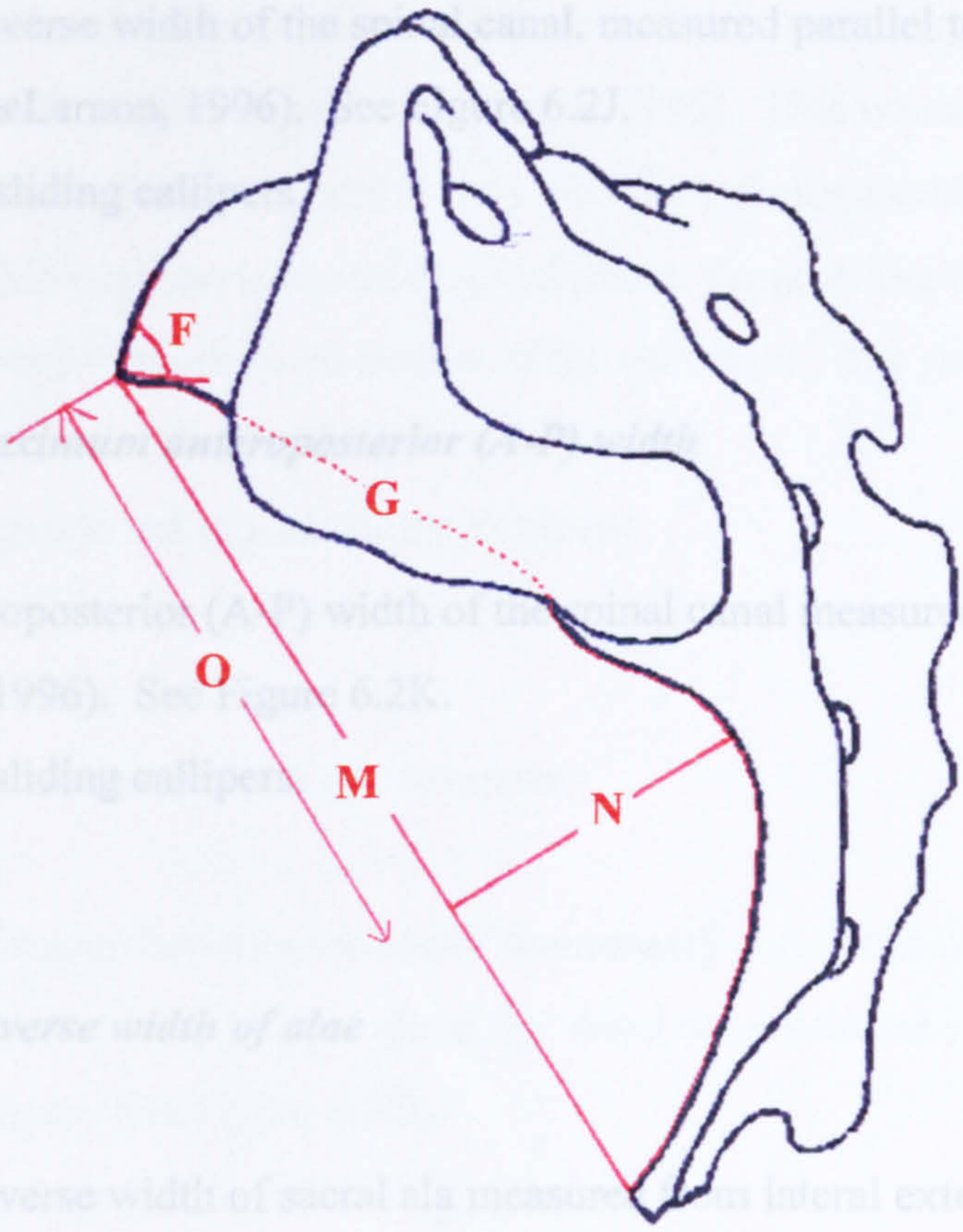



**Figure 6.3 Left lateral view of sacrum**
**(Adapted from Gunn, 1996: 112. Original Figure No. 9.11)**

**H)** ***Distance of medial borders of articular surfaces of processus articulares superiores***

The transverse measurement between the extreme medial borders of the superior articular processes measured parallel to a transverse plane through the sacrum. See Figure 6.2H.
Equipment: Digital sliding callipers.

**I)** ***Distance of lateral borders of articular surfaces of processus articulares superiores***

The transverse measurement between the extreme lateral borders of the superior articular processes measured parallel to a transverse plane through the sacrum. See Figure 6.2I.
Equipment: Digital sliding callipers.

**J)** ***Spinal canal maximum transverse width***

The maximum transverse width of the spinal canal, measured parallel to a transverse plane through sacrum (MacLarnon, 1996). See Figure 6.2J.

Equipment: Digital sliding callipers.

**K)** ***Spinal canal maximum anteroposterior (A-P) width***

The maximum anteroposterior (A-P) width of the spinal canal measured in the midsagittal plane (MacLarnon, 1996). See Figure 6.2K.

Equipment: Digital sliding callipers.

**L)** ***Combined transverse width of alae***

The maximum transverse width of sacral ala measured from lateral extremity of first sacral vertebra to superolateral border of the ala (Schwartz, 1995). This was calculated by subtracting the maximum transverse diameter of S1 from the maximum superior sacral width (6.1A-6.2C).

No equipment required.

**M)** ***Anterior mid ventral straight length (Maximum anterior height)***

A measurement taken in the midsagittal plane from the middle of the anterior border of the sacral promontory to the middle of the anteroinferior border of the fifth sacral vertebra (Buikstra and Ubelaker, 1994; Schwartz, 1995; Steele and Bramblett, 1988). See Figures 6.1M and 6.3M.

Equipment: Digital sliding callipers.

**N)** ***Maximum depth of curvature (Sacral depth)***

The maximum distance of the anterior surface from a chord connecting the two anterior-most points to the midline of the sacrum (Schwartz, 1995). This was achieved by placing one end of the profiler on the sacral promontory, and the inferior aspect against the sacral apex. Maintaining this position in the midsagittal plane, the profiling bars were then pushed against the bone to produce an outline of the curvature. The greatest depth of the profile was then measured. See Figure 6.3N.

Equipment: Profile gauge and digital sliding callipers.

**O)** ***Position of the maximum depth of curvature***

This describes the distance between the sacral promontory and the point at which the maximum depth of curvature is located along the chord connecting the aforementioned point and the sacral apex. See Figure 6.3O.

Equipment: Profile gauge and digital sliding callipers.

### 6.2.2 The Innominate

A total of 31 measurements were taken from first the left, and then the right, innominate bones. These are detailed below and presented in Figures 6.4 to 6.6.

**A)** ***Maximum innominate length***

The maximum distance between the most superior point on the iliac crest and the most inferior point on the ischial tuberosity (Buikstra and Ubelaker, 1994; Schwartz, 1995). See Figure 6.4A.

Equipment: Osteometric board.

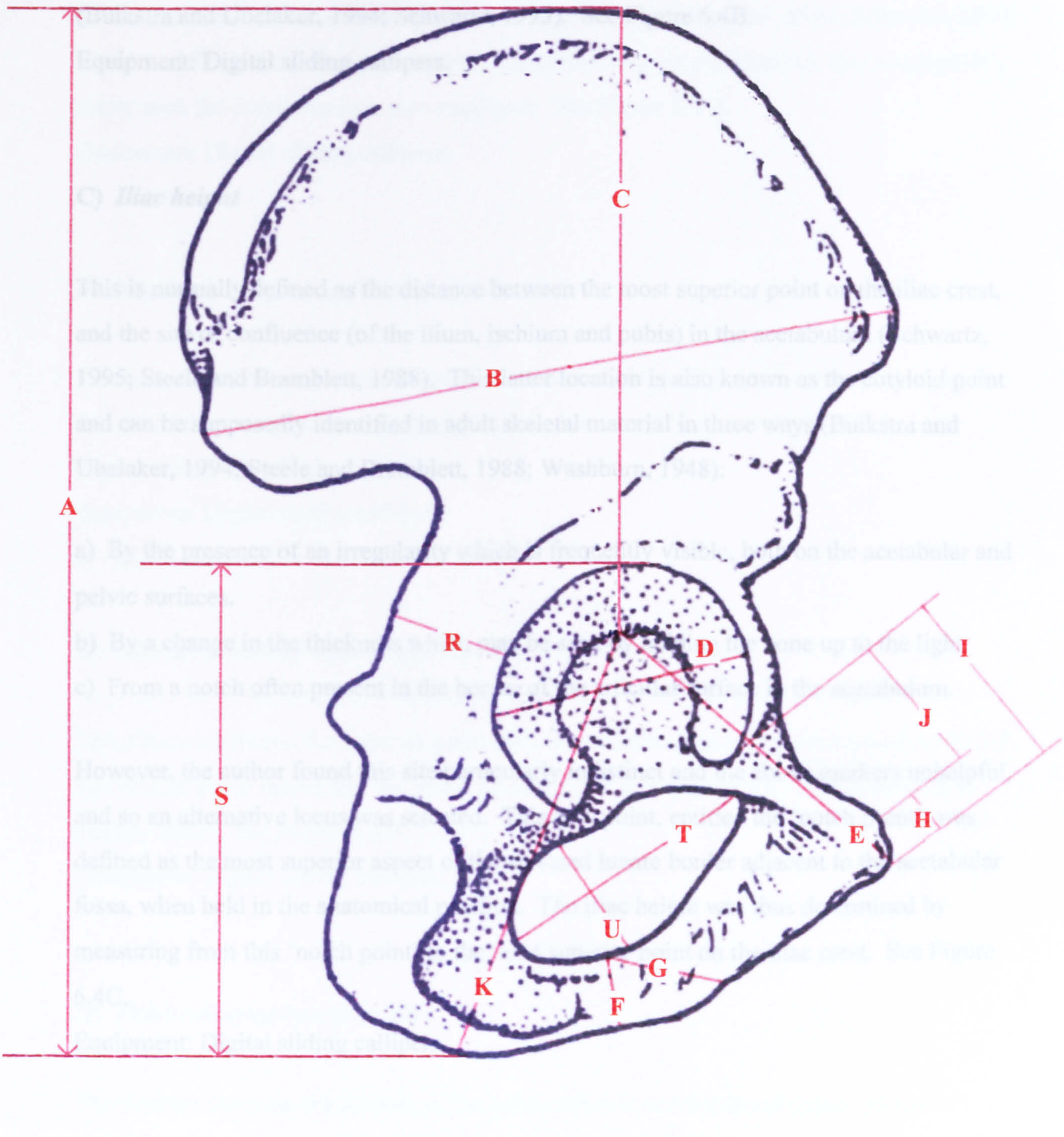



**Figure 6.4 Lateral view of right innominate**
**(Adapted from Snell, 1986: 311. Original Figure No. 6-12B)**

**B)** ***Innominate breadth***

The distance between the anterior-superior iliac spine and posterior-superior iliac spine (Buikstra and Ubelaker, 1994; Schwartz, 1995). See Figure 6.4B.
Equipment: Digital sliding callipers.

**C)** ***Iliac height***

This is normally defined as the distance between the most superior point on the iliac crest, and the site of confluence (of the ilium, ischium and pubis) in the acetabulum (Schwartz, 1995; Steele and Bramblett, 1988). This latter location is also known as the cotyloid point and can be supposedly identified in adult skeletal material in three ways (Buikstra and Ubelaker, 1994; Steele and Bramblett, 1988; Washburn, 1948):

a) By the presence of an irregularity which is frequently visible, both on the acetabular and pelvic surfaces.
b) By a change in the thickness which may be seen by holding the bone up to the light.
c) From a notch often present in the border of the articular surface in the acetabulum.

However, the author found this site particularly indistinct and the above markers unhelpful, and so an alternative locus was selected. This new point, entitled the 'notch point', was defined as the most superior aspect of the elevated lunate border adjacent to the acetabular fossa, when held in the anatomical position. The iliac height was thus determined by measuring from this 'notch point' to the most superior point on the iliac crest. See Figure 6.4C.
Equipment: Digital sliding callipers.

**D)** ***Acetabulum diameter***

The diameter measured on the internal aspect of the acetabulum parallel with the long axis of the ischium (Schwartz, 1995; Steele and Bramblett, 1988; Taylor and DiBennardo, 1984). See Figure 6.4D.
Equipment: Digital sliding callipers.

**E)** ***Pubis length***

This is normally defined as the measurement taken from the most superior point on the face of the symphysis pubis to the cotyloid point (Buikstra and Ubelaker, 1994; Schwartz, 1995; Steele and Bramblett, 1988). However, for reasons already pertained to, the 'notch point', rather than the cotyloid point, was employed. See Figure 6.4 E.
Equipment: Digital sliding callipers.

**F)** ***Minimum height of inferior pubic ramus***

This describes the maximum constriction on the inferior pubic ramus between the lower margin of the obturator foramen and the lower border of the ramus (DiBennardo and Taylor, 1983). See Figure 6.4F.
Equipment: Digital sliding callipers.

**G)** ***Oblique length of inferior pubic ramus***

The distance between the superior point used in measuring the minimum vertical height of the inferior pubic ramus and the inferior point of the pubic symphysis (DiBennardo and Taylor, 1983). See Figure 6.4G.
Equipment: Digital sliding callipers.

**H)** ***Tubercolusymphyseal height***

The distance between the summit of the pubic tubercle and the symphysion, measured parallel to the long axis of the tubercle-symphysis chord (DiBennardo and Taylor, 1983). See Figure 6.4H.
Equipment: Digital sliding callipers.

**I)** ***Pubic acetabular length***

The distance between the most superior aspect of the symphysis pubis and the nearest rim of the acetabulum, along the long axis of the pubis length. The tips of the callipers were used to measure this, taking care to keep the instrument parallel to the axis of the pubis. See Figure 6.4I.
Equipment: Digital sliding callipers.

**J)** ***Pubic tubercle-acetabular length***

The distance measured from the summit of the pubic tubercle to the nearest point on the acetabulum, parallel to the long axis of the pubis length. Figure 6.4J.
Equipment: Digital sliding callipers.

**K)** ***Ischium length***

This is normally defined as the greatest distance between the ischial tuberosity and the cotyloid point (Buikstra and Ubelaker, 1994; Schwartz, 1995). Once again, the 'notch point' was used in preference to this (See Figure 6.4K) and the site thus located on the ischial tuberosity was defined as the 'ischio-acetabular point'. This latter site was employed for subsequent measurements (see 6.2.2S, 6.2.3F, J-K).
Equipment: Digital sliding callipers.

**L)** ***Pubo-sacroiliac diameter***

The distance from the symphysion to the point where the anterior auricular point of the arcuate line intersects the anterior border of the auricular surface (Segeberth-Orban, 1980). See Figure 6.5L.
Equipment: Digital sliding callipers.

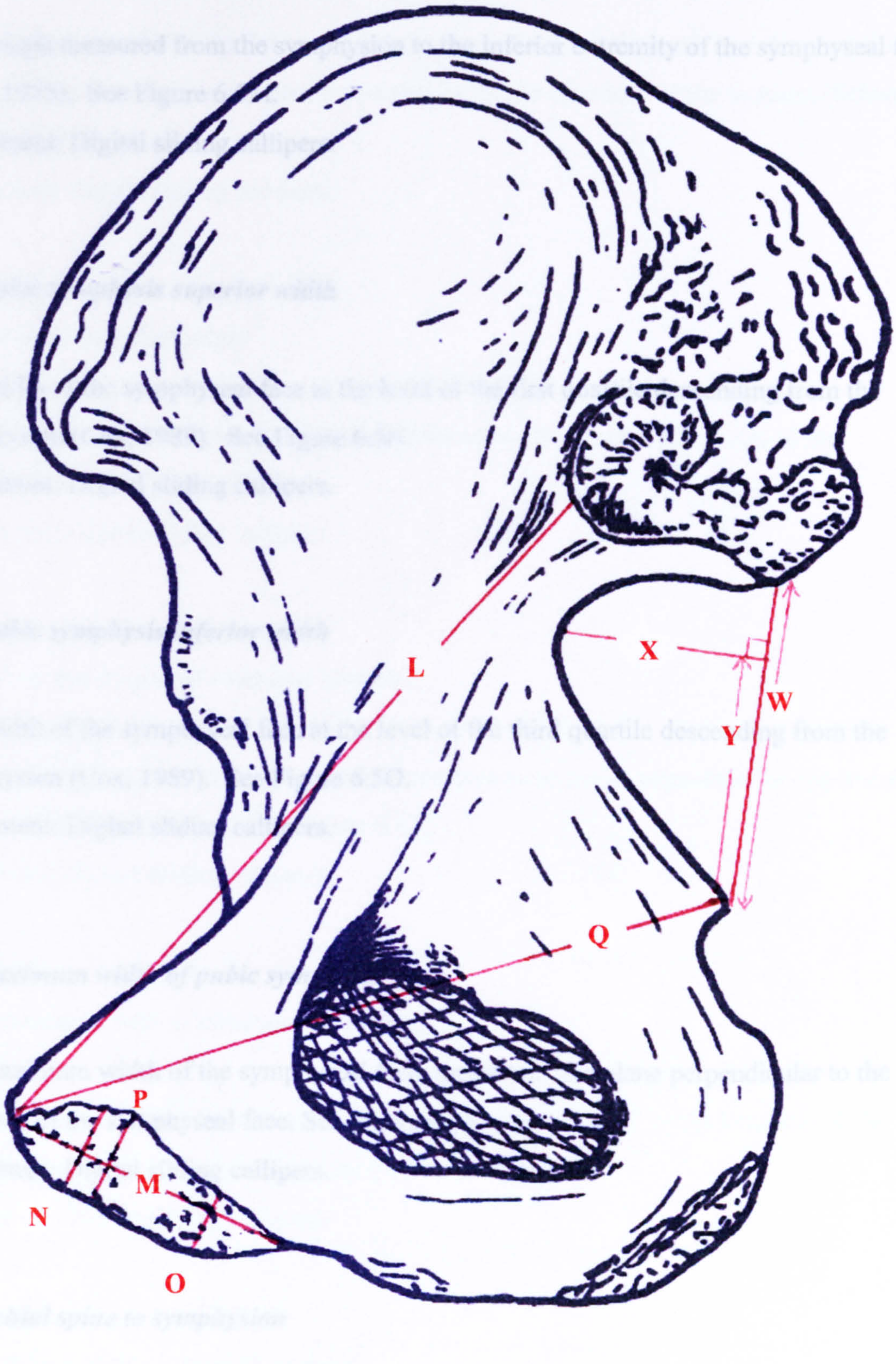



**Figure 6.5 Medial view of right innominate**
**(Adapted from Snell, 1986: 311. Original Figure No. 6-12A)**

**M)** ***Pubic symphysis depth***

The length measured from the symphysion to the inferior extremity of the symphyseal face (Day, 1975). See Figure 6.5M.

Equipment: Digital sliding callipers.

**N)** ***Pubic symphysis superior width***

The width of the symphyseal face at the level of the first quartile descending from the symphysion (Cox, 1989). See Figure 6.5N.

Equipment: Digital sliding callipers.

**O)** ***Pubic symphysis inferior width***

The width of the symphyseal face at the level of the third quartile descending from the symphysion (Cox, 1989). See Figure 6.5O.

Equipment: Digital sliding callipers.

**P)** ***Maximum width of pubic symphysis***

The maximum width of the symphyseal face, measured on a plane perpendicular to the long axis of the symphyseal face. See Figure 6.5P.

Equipment: Digital sliding callipers.

**Q)** ***Ischial spine to symphysion***

The distance from the medial point of the ischial spine to the symphysion. See Figure 6.5Q.

Equipment: Digital sliding callipers.

**R)** ***Acetabulosciatic breadth***

Distance between the midpoint on the inferior part of the sciatic notch and the posterior margin of the acetabular rim taken perpendicular to the long axis of the ischium (Schwartz, 199). See Figure 6.4R.
Equipment: Digital sliding callipers.

**S)** ***Ischial acetabular height***

The distance measured from the 'ischio-acetabular point' to the farthest rim of the acetabulum. See Figure 6.4S.
Equipment: Digital sliding callipers.

**T)** ***Maximum length of obturator foramen***

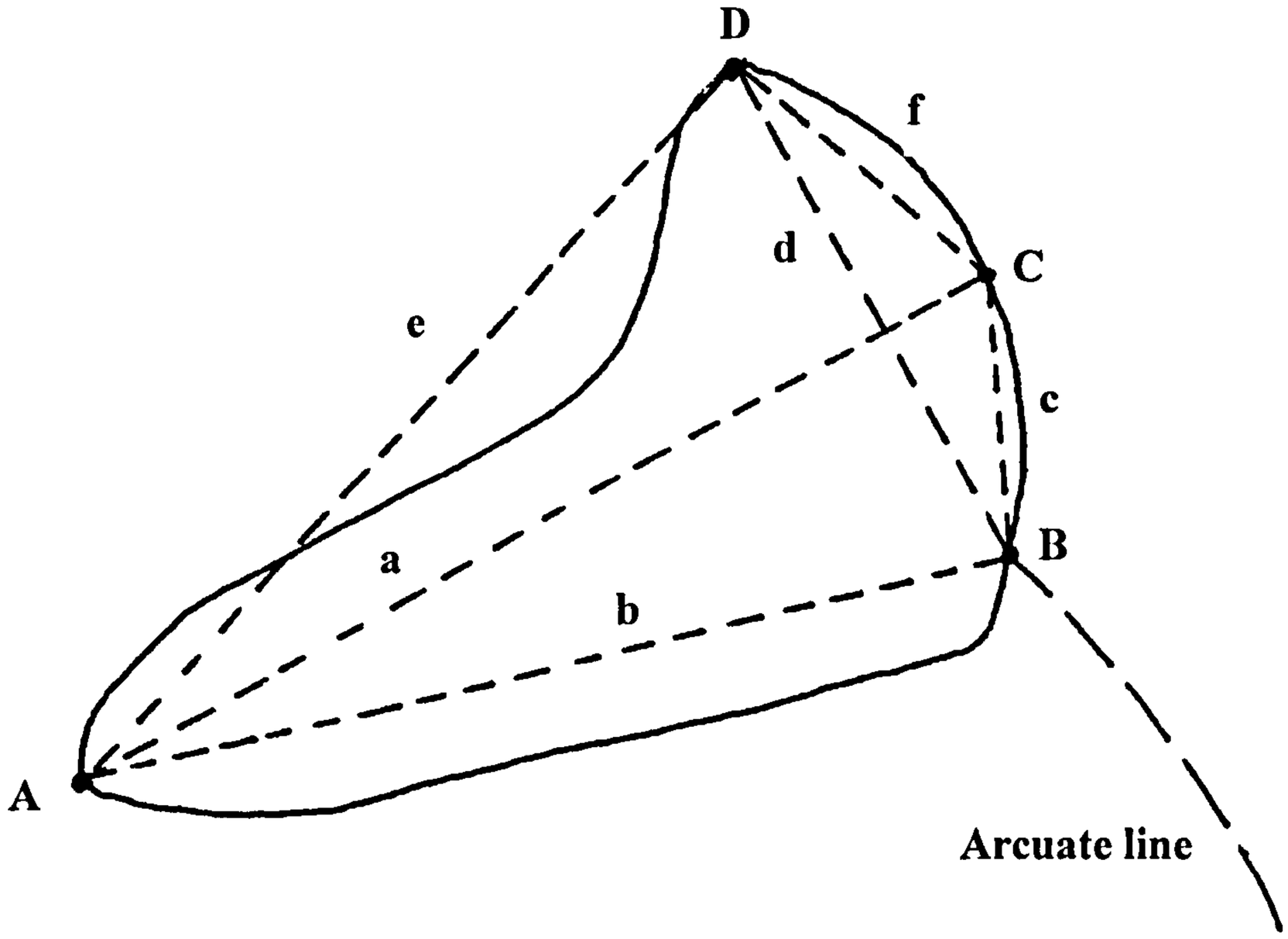
The maximum length of the obturator foramen measured in the anteroinferior-superolateral plane on the lateral surface. See Figure 6.4T.
Equipment: Digital sliding callipers.

**U)** ***Maximum width of obturator foramen***

The maximum width of the obturator foramen measured parallel to the long axis of the pubis length, on the lateral surface. See Figure 6.4U.
Equipment: Digital sliding callipers.

**V)** ***Profiling of the auricular surface***

The auricular surface was mapped by means of six defined lines (Figure 6.6). These measurements were devised by the author to be employed, not only as descriptive linear parameters, but also to enable calculation of associated angles and areas.




**Key:**

| | | | |
|---|---|---|---|
| **A** | Posterior inferior iliac spine (PIIS) | **a (AC)** | PIIS-MLP length (Maximum length) |
| **B** | Arcuate bisection (AB) | **b (AB)** | AB-PIIS length (Arcuate length) |
| **C** | Max-lateral point (MLP) | **c (BC)** | AB-MLP length |
| **D** | Max-posterosuperior (MPSP) | **d (BD)** | AB-MPSP length (Maximum width) |
| | | **e (AD)** | PIIS-MPSP length (Maximum oblique length) |
| | | **f (CD)** | MLP-MPSP length |

**Figure 6.6 Stylised view of left auricular surface**

The posterior inferior iliac spine and the site where the arcuate line bisects the margin of the auricular surface are defined by the points A and B respectively. The chord that joins these two locations (b) was designated the arcuate length. Ali and MacLauglin (1991) describe a similar chord as the maximum length of the caudal limb. However, their measurement was the maximum one obtained by extending callipers from the arcuate bisection and did not involve use of the posterior inferior iliac spine. The maximum length (a) describes the greatest length measurable across the auricular surface, and extends from the posterior inferior iliac spine to its terminus, the max-lateral point (C). The arcuate bisection (B) was employed to delineate the maximum width of the surface (d) and was found by measuring to the opposite extremity. Ali and MacLaughlin (*ibid.*) also measured this length and designated it the maximum length of the cranial limb. In this study, the point thus defined on the postero-superior aspect was called the max-posterosuperior point (D). Once this position was known, the maximum oblique length (e) could be measured, as

well as the short chord (f) extending from the max-lateral point. The length between the arcuate bisection and the latter mentioned point described the final short chord (c).

W) ***Profiling the greater sciatic notch***

In order to present a profile of the greater sciatic notch, three measurements were recorded. These included the sciatic notch width, sciatic notch height and sciatic notch position.

***Sciatic notch width***

The width of the greater sciatic notch measured between the posterior inferior iliac spine and the tip of the ischial spine (Schwartz, 1995; Steel and Bramblett, 1988). See Figure 6.5W.
Equipment: Digital sliding callipers.

***Sciatic notch height***

The perpendicular distance from deepest point of sciatic notch to bisection of line demarcating sciatic notch width (Cox, 1989). See Figure 6.5X.
Equipment: Profile gauge and digital sliding callipers.

***Sciatic notch position***

The distance from the tip of the ischial spine to the intersection of the line of the notch height by perpendicular dropped to it from the deepest point in the notch (Schwartz, 1995; Taylor and DiBennardo, 1994). See Figure 6.5Y.
Equipment: Profile gauge and digital sliding callipers.

### 6.2.3 Articulated pelvis

The sacrum and right and left innominates were temporarily re-articulated, once all measurements had been completed on the individual bones. This process was achieved by securing the three elements in their correct anatomical position with two elastic bands (Iscan and Cotton, 1985; Tague, 1989) (Plate 6.2.3). This arrangement is far less damaging

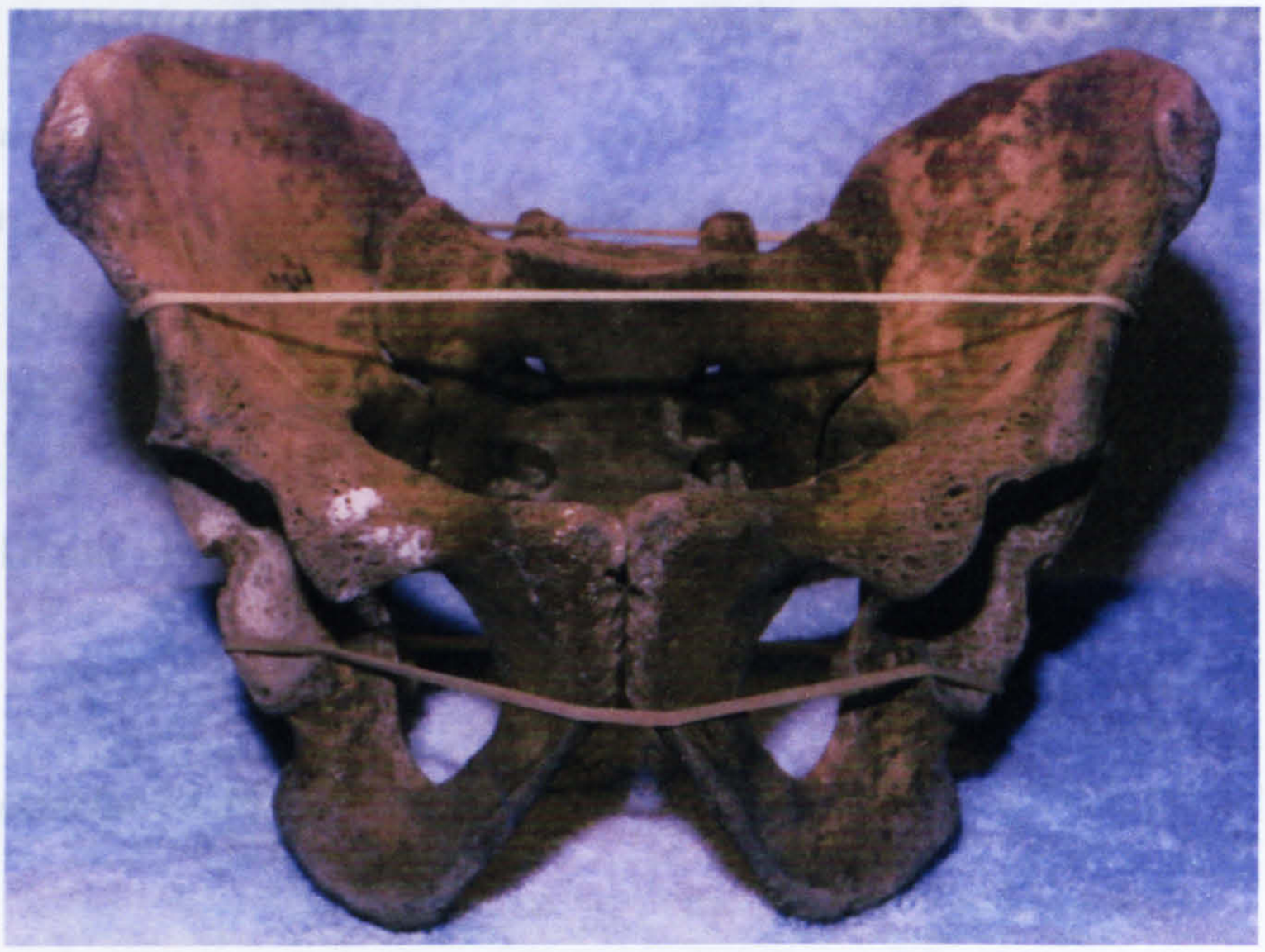


**Plate 6.2.3 Anterosuperior (A-P) view of re-articulated pelvis (Photo: Linda O'Connell)**

to the material than the application of adhesives and was quick and easy to accomplish. One concern with this approach is that re-articulation of the dry bone, where soft tissue is absent, will produce a loss in size. Iscan and Cotton (1985) do not discuss this issue in their work. Of those authors that do, Tague (1989) made no compensation for absence of the symphyseal disc in his research, whereas Schroeder and colleagues (1997) did note that an absence of cartilage would compromise true articulation and thus produce inaccuracies in anatomical positioning. In order to address this issue, they suggested that the isolated skeletal components, comprising the sacrum and innominates, should always be examined independently as well as after re-articulation. This approach was adopted with this study. As one final point, although it is clear that a decrease in size will be affected by dry re-construction, it is very difficult to assess whether this reduction will be constant throughout the sample. However, in order for appropriate analyses to be subsequently undertaken on data collected, it was assumed that it would be.

Once re-articulated, a total of 16 measurements were taken. These are detailed below and displayed in Figures 6.7 to 6.12.

A) *Anteroposterior (A-P) superior diameter of the pelvis*

This describes the distance from the medial sacral promontory to the posterior extremity of the pubic symphysis (measured to the right and left pubic crest and averaged) (Gunn, 1996; Schwartz, 1995; Steele and Bramblett, 1988). This is also known as the sagittal, true conjugate or obstetric conjugate diameter (Bennett and Brown, 1999; Cunningham *et al.*, 1997; Sweet and Tiran, 1999). See Figures 6.7A and 6.8A.
Equipment: Digital sliding callipers.

B) *Anteroposterior (A-P) inferior diameter of the pelvis*

This describes the distance from the medial anterior apex of the fifth sacral vertebra to the inferior posterior extremity of the pubic symphysis (measured to left and right inferior posterior aspect of the symphysis pubis and averaged) (Centeno, 1999; Gunn, 1996). This is also known obstetrically as the anteroposterior (A-P) and sacropubic diameter (Bennett and Brown, 1999; Cunningham *et al.*, 1997; Sweet and Tiran, 1999). See Figure 6.8B and 6.9B.
Equipment: Digital sliding callipers.

C) *Transverse diameter of the pelvis*

The maximum transverse diameter between the arcuate lines of the pelvic inlet (Bennett and Brown, 1999; Cunningham *et al.*, 1997; Gunn, 1996; Schwartz, 1995; Steele and Bramblett, 1988; Sweet and Tiran, 1999). See Figure 6.7C.
Equipment: Inside spring callipers and digital sliding callipers. The spring callipers were placed at the level of the pelvic brim in the transverse plane. They were then slowly released until the tips touched the innominates at their maximum extremities. Their removal was effected by careful compression and the resultant diameter measured using the digital sliding callipers.

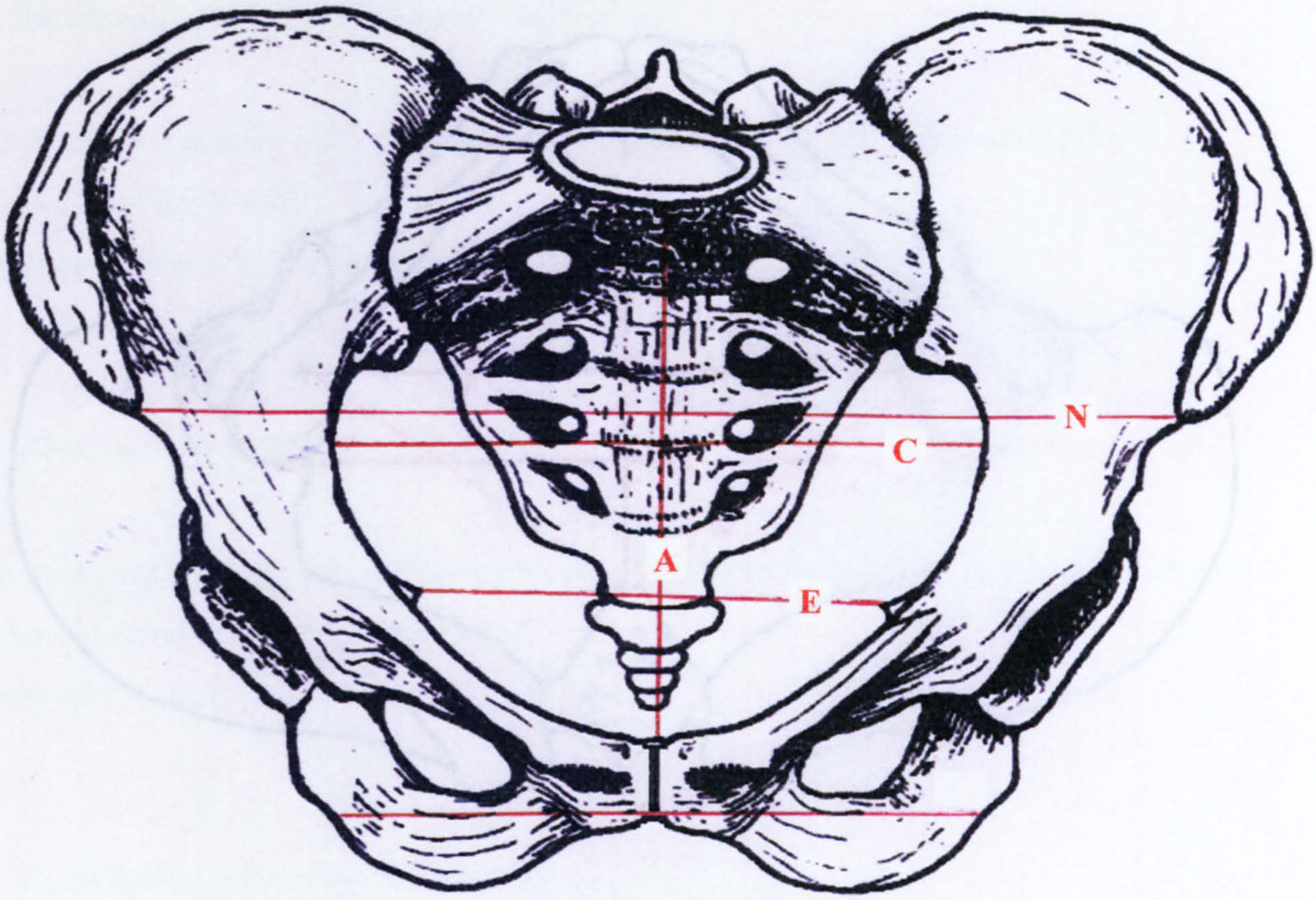



**Figure 6.7 Anterior view of pelvis**
**(Adapted from Snell, 1986: 304. Original Figure No. 6-5B)**

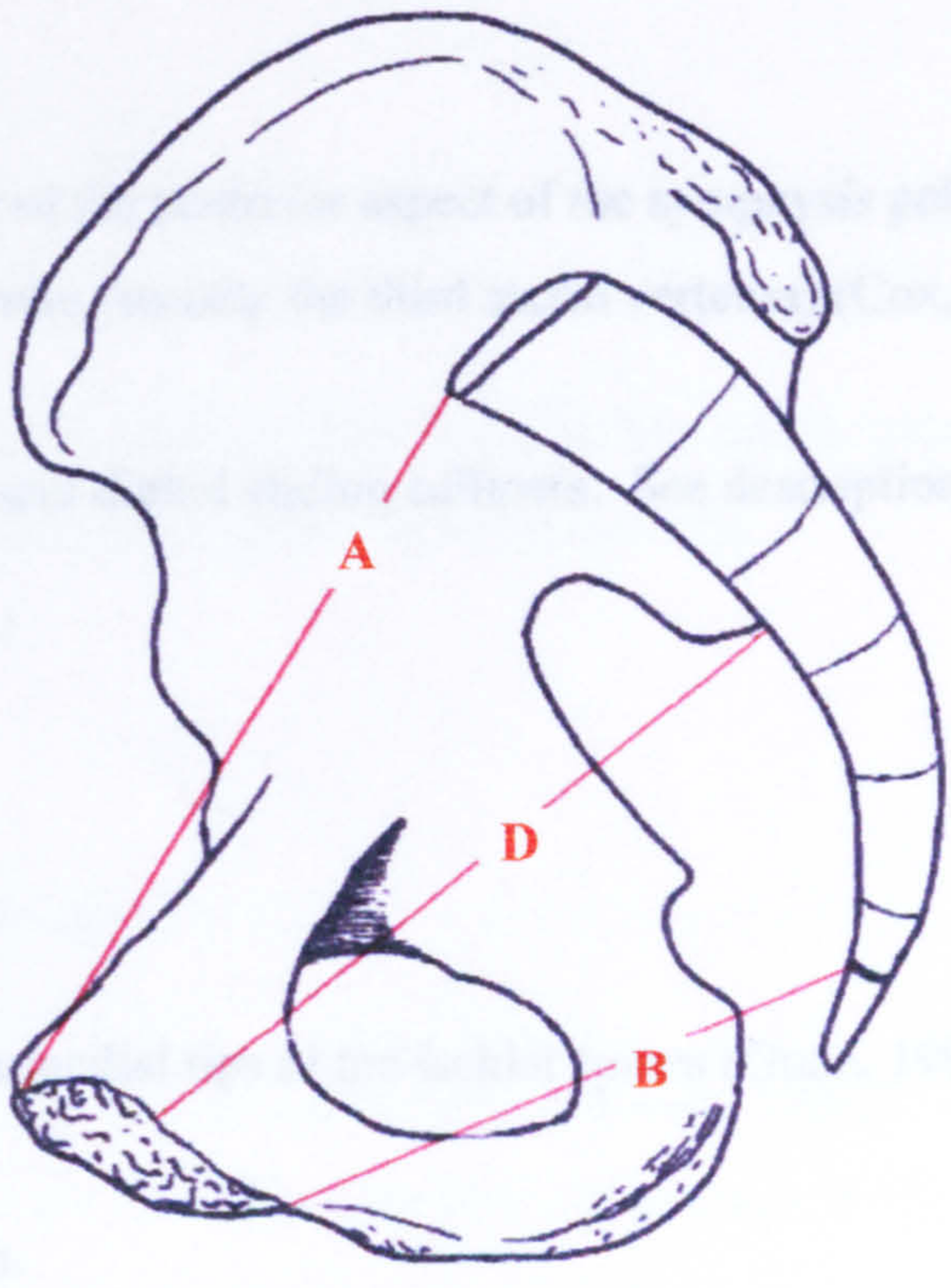



**Figure 6.8 Lateral view of the right half of the pelvis**
**(Adapted from Snell, 1986: 323. Original Figure No. 6-20)**

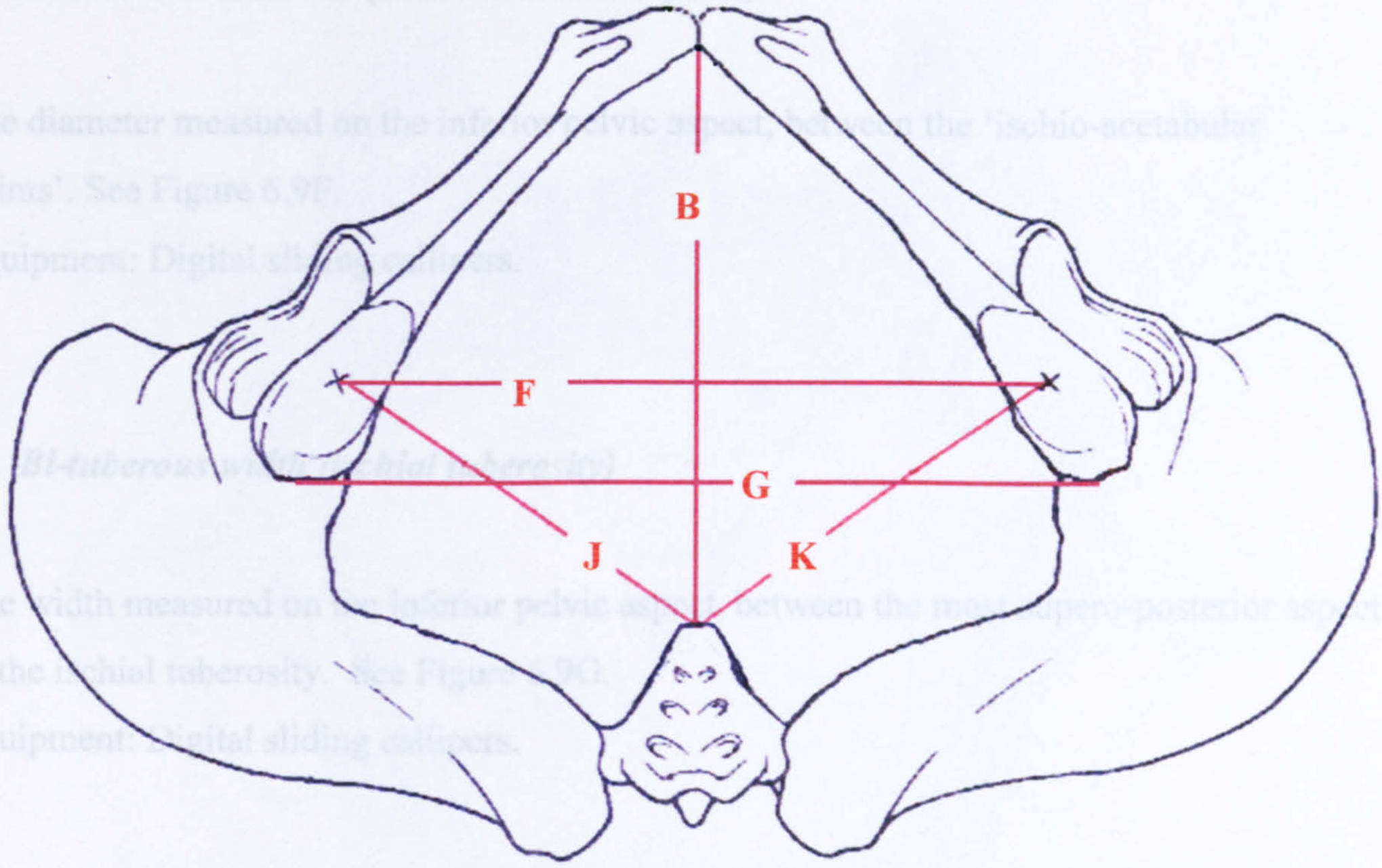



**Figure 6.9 Inferior view of pelvis**
**The X on the ischial tuberosity marks the position of the ischio-acetabular point**
**(Adapted from Gosling *et al.*, 1996: 5.3. Original Figure No. 5.3)**

**D) *Greatest pelvic diameter***

The distance from the medial point of the posterior aspect of the symphysis pubis to the point of maximum depth of the sacrum (usually the third sacral vertebra) (Cox, 1989). See Figure 6.8D.
Equipment: Inside spring callipers and digital sliding callipers. See description of use under section 6.2.3C above.

**E) *Bispinous breadth***

The distance measured between the medial tips of the ischial spines (Gunn, 1996; Sweet and Tiran, 1999). See Figure 6.7E.
Equipment: Digital sliding callipers.

**F)** ***Bi-tuberous diameter (ischio-acetabular point)***

The diameter measured on the inferior pelvic aspect, between the 'ischio-acetabular points'. See Figure 6.9F.
Equipment: Digital sliding callipers.

**G)** ***Bi-tuberous width (ischial tuberosity)***

The width measured on the inferior pelvic aspect, between the most supero-posterior aspect of the ischial tuberosity. See Figure 6.9G.
Equipment: Digital sliding callipers.

**H)** ***Right ischial spine to sacral apex***

The distance measured from the medial aspect of the tip of the right ischial spine to the mid-sagittal point of the apex of the fifth sacral vertebra. See Figure 6.10H.
Equipment: Digital sliding callipers.

**I)** ***Left ischial spine to sacral apex***

The distance measured from the medial aspect of the tip of the left ischial spine to the mid-sagittal point of the apex of the fifth sacral vertebra. See Figure 6.10I.
Equipment: Digital sliding callipers.

**J)** ***Right ischial tuberosity to sacral apex***

The distance measured from the 'ischio-acetabular' point of the right ischial tuberosity to the mid-sagittal point of the apex of the fifth sacral vertebra. See Figure 6.9J.
Equipment: Digital sliding callipers.

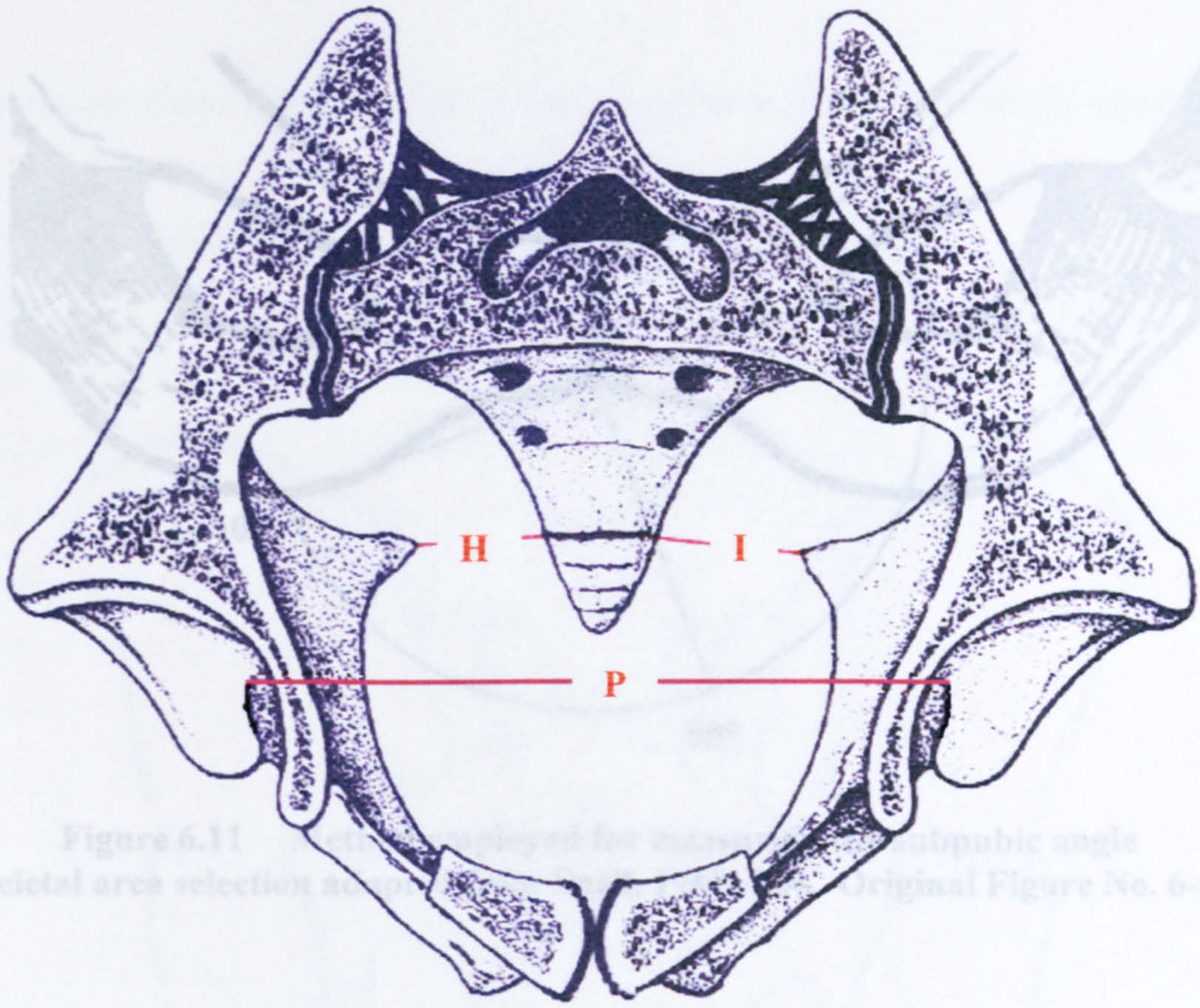



**Figure 6.10 Horizontal; section through the pelvis**
**(Adapted from Snell, 1986: 321. Original Figure No. 6.19)**

**K)** ***Left ischial tuberosity to sacral apex***

The distance measured from the 'ischio-acetabular' point of the left ischial tuberosity to the mid-sagittal point of the apex of the fifth sacral vertebra. See Figure 6.9K.
Equipment: Digital sliding callipers.

**L)** ***Subpubic angle***

The subpubic angle was measured by placing the central point of the horizontal edge of a protractor at the inferior aspect of the anterior symphysis pubis. The zero degrees mark was placed level with the ischiopubic ramus of the right innominate bone and the angle measured where the curved edge of the protractor dissected the ischiopubic ramus of the left innominate bone. In this manner, the subpubic angle was measured at a designated 50mms along the ischiopubic rami (Cox, 1989). See Figure 6.11.
Equipment: Protractor

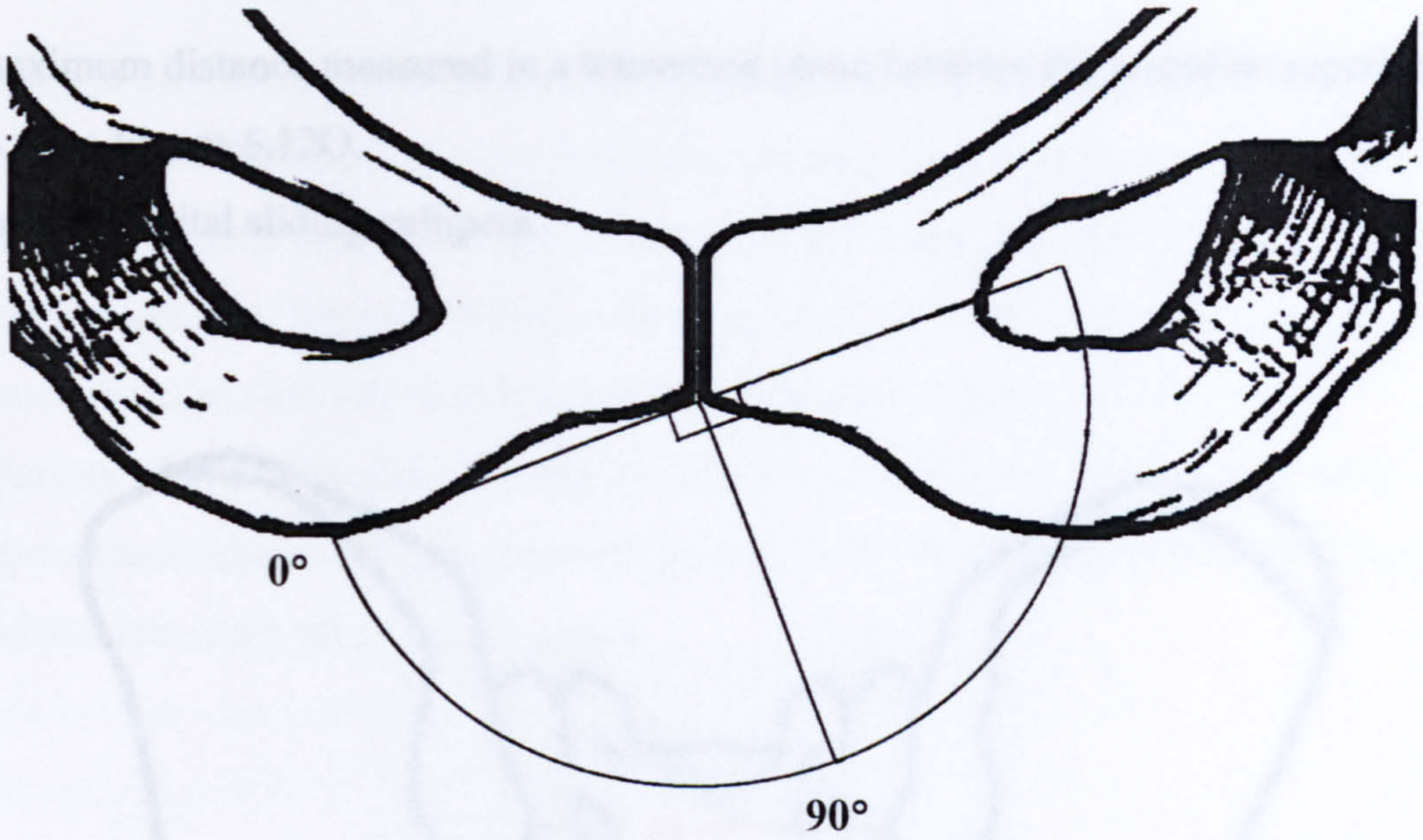



**Figure 6.11 Method employed for measuring the subpubic angle (Skeletal area selection adapted from Snell, 1986: 304. Original Figure No. 6-5B)**

**M)** ***Inlet circumference***

The inlet circumference was measured by tracing the circumference of the superior pelvic inlet (bounded anteriorly by the symphysis pubis, laterally by the iliopectineal lines and posteriorly by the sacral promontory) with an opisometer (Cox, 1989). This measurement was always conducted from the right symphyseal margin, around the pelvic inlet, to the left symphyseal margin.

Equipment: Opisometer.

**N)** ***Superior-anterior bi-iliac breadth of pelvis***

The maximum distance measured in a transverse plane between the most inferior, tapering points of the anterior superior iliac spines (Schwartz, 1995; Steele and Bramblett, 1988). See Figure 6.7N.

Equipment: Digital sliding callipers.

**O)** ***Inferior-posterior bi-iliac breadth of pelvis***

The maximum distance measured in a transverse plane between the posterior superior iliac spines. See Figure 6.12O.

Equipment: Digital sliding callipers.

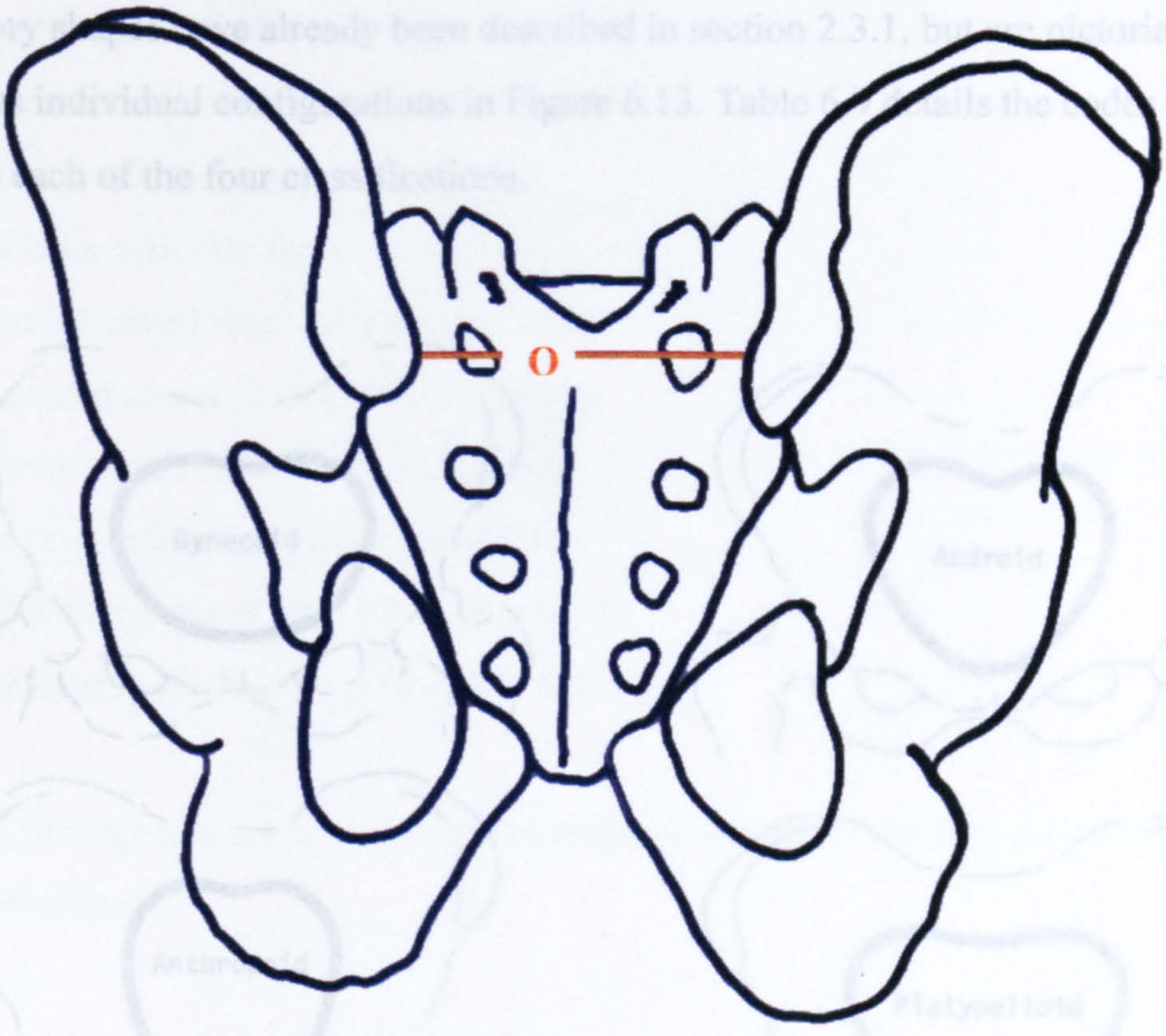



**Figure 6.12 Antero-inferior view of the pelvis**
**(Adapted from Campbell, 1998: 170. Original Figure No. 7.3C)**

**P)** ***Bi-acetabular breadth***

The breadth measured in a transverse plane between the inferior-most medial part of the acetabulum where the semi-lunar surface rises above the bone surface. This point was selected for measurement because it represented a more precise and locatable reference than that of the acetabular fossa in general. See Figure 6.10P.

Equipment: Spreading callipers.

## Q) *Pelvic inlet shape*

In addition to the above measurements, the shape of the pelvic inlet was also described according to Caldwell and Moloy's (1933) classification. This particular system was adopted, not only because it is the one that is regularly employed in modern obstetrical practice (Bennett and Brown, 1999; Cunningham *et al.*, 1997; Sweet and Tiran, 1999), but also due to the ease with which pelves could be allocated a type. The four basic classificatory shapes have already been described in section 2.3.1, but are pictorially presented as individual configurations in Figure 6.13. Table 6.9 details the codes that were ascribed to each of the four classifications.

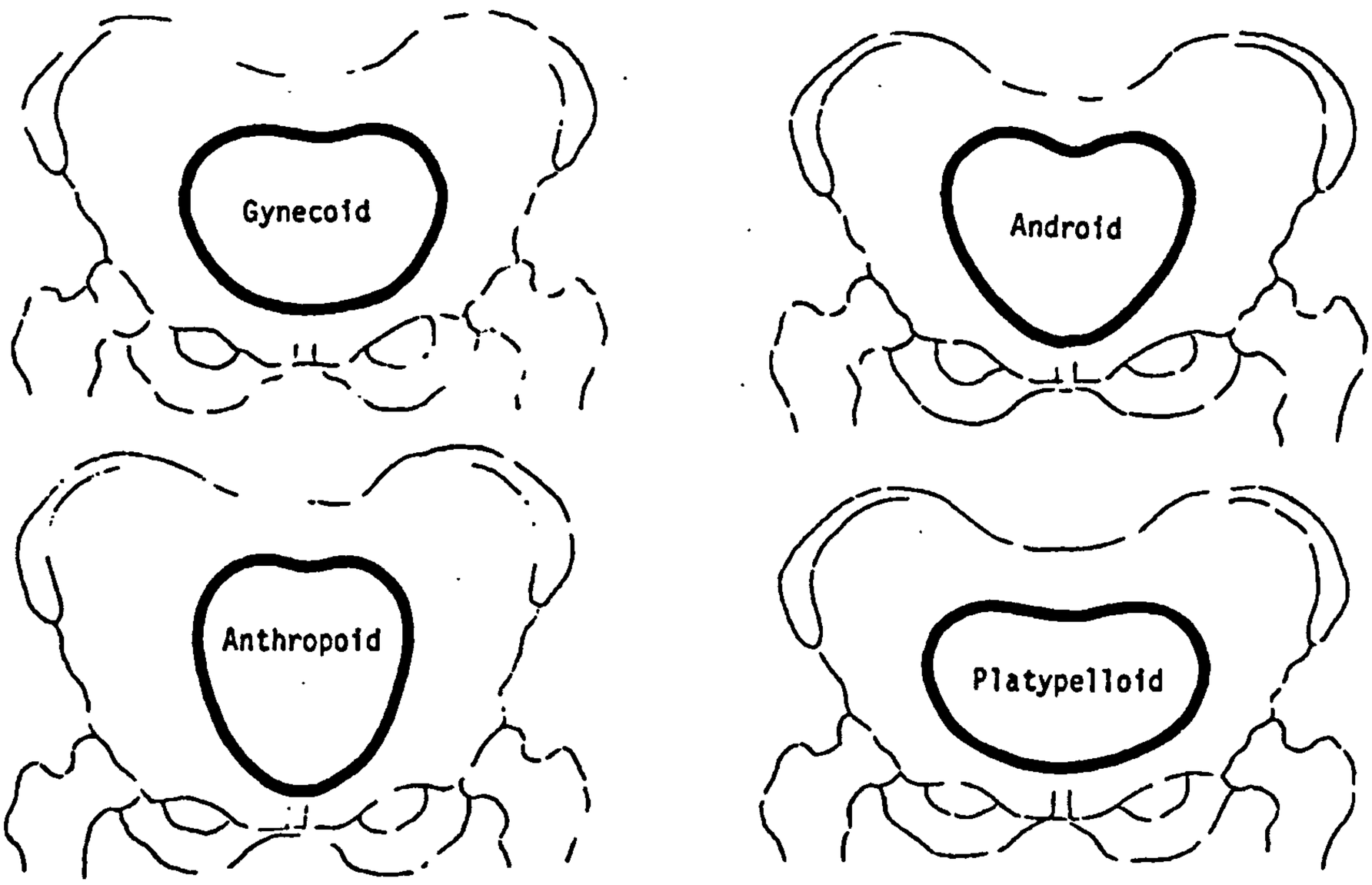



**Figure 6.13 Pelvic inlet classification according to Caldwell and Moloy (1933) (From Snell, 1986: 325. Original Figure No. 6-21C)**

**Table 6.9 Codes employed to designate pelvic classification**

| Code | Classification |
|---|---|
| 1 | Gynaecoid |
| 2 | Android |
| 3 | Anthropoid |
| 4 | Platypelloid |

### 6.2.4 The vertebral column (non-metrical data)

Degenerative joint change within the spine was recorded in all of the presacral vertebrae. The areas examined included, in the following order:

1) Vertebral body - superior surface
2) Vertebral body - inferior surface
3) Left superior articular facet
4) Right superior articular facet
5) Left inferior articular facet
6) Right inferior articular facet
7) Left superior costal facet (thoracic region)
4) Right superior costal facet (thoracic region)
5) Left inferior costal facet (thoracic region)
6) Right inferior costal facet (thoracic region)
7) Left transverse process facet (thoracic region)
8) Right transverse process facet (thoracic region)

In addition, the superior articular facets and superior surface of the first sacral vertebra were also examined.

The vertebrae were individually assessed for three indicators of degenerative disease:

a) Osteophytes
b) Porosity
c) Eburnation

The severity and extent of the osteophytes, porosity and eburnation were graded according to the standards proposed by Buikstra and Ubelaker (1994). These descriptions, together with the ascribed numerical codes, are detailed in Tables 6.10 to 6.12 respectively.

**Table 6.10 Numerical codes employed to designate severity and extent of osteophyte development**

| Code | Classification |
|---|---|
| ***Severity*** | |
| * | Unrecorded |
| 0 | No osteophytes |
| 1 | Barely discernible |
| 2 | Elevated ring or sharp ridge, possibly with curled spicules |
| 3 | Curved spicules/extensive spicule formation |
| 4 | Ankylosis present |
| ***Extent*** | |
| * | Unrecorded |
| 0 | None |
| 1 | $<^1/_3$ of the circumference affected |
| 2 | $^1/_3 - ^2/_3$ of the circumference affected |
| 3 | $>^2/_3$ of the circumference affected |

**Table 6.11 Numerical codes employed to designate severity and extent of porosity**

| Code | Classification |
|---|---|
| ***Severity*** | |
| * | Unrecorded |
| 0 | No porosity |
| 1 | Slight (pinpoint) |
| 2 | Moderate (coalesced) |
| 3 | Severe (pinpoint and coalesced) |
| ***Extent*** | |
| * | Unrecorded |
| 0 | None |
| 1 | $<^1/_3$ of surface affected |
| 2 | $^1/_3 - ^2/_3$ of surface affected |
| 3 | $>^2/_3$ of surface affected |

**Table 6.12 Numerical codes employed to designate severity and extent of eburnation**

| Code | Classification |
|---|---|
| ***Severity*** | |
| * | Unrecorded |
| 0 | No eburnation |
| 1 | Barely discernible/specks |
| 2 | Polishing only |
| 3 | Polishing with grooving |
| ***Extent*** | |
| * | Unrecorded |
| 0 | None |
| 1 | $<^1/_3$ of surface affected |
| 2 | $^1/_3 - ^2/_3$ of surface affected |
| 3 | $>^2/_3$ of surface affected |

### 6.2.5 The femur

The maximum lengths of the right and left femora were obtained by measuring from the most superior point on the femoral head to the most inferior aspect of the medial femoral condyle (Buikstra and Ubelaker, 1994; Steele and Bramblett, 1988). See Figure 6.14. Equipment: Osteometric board.

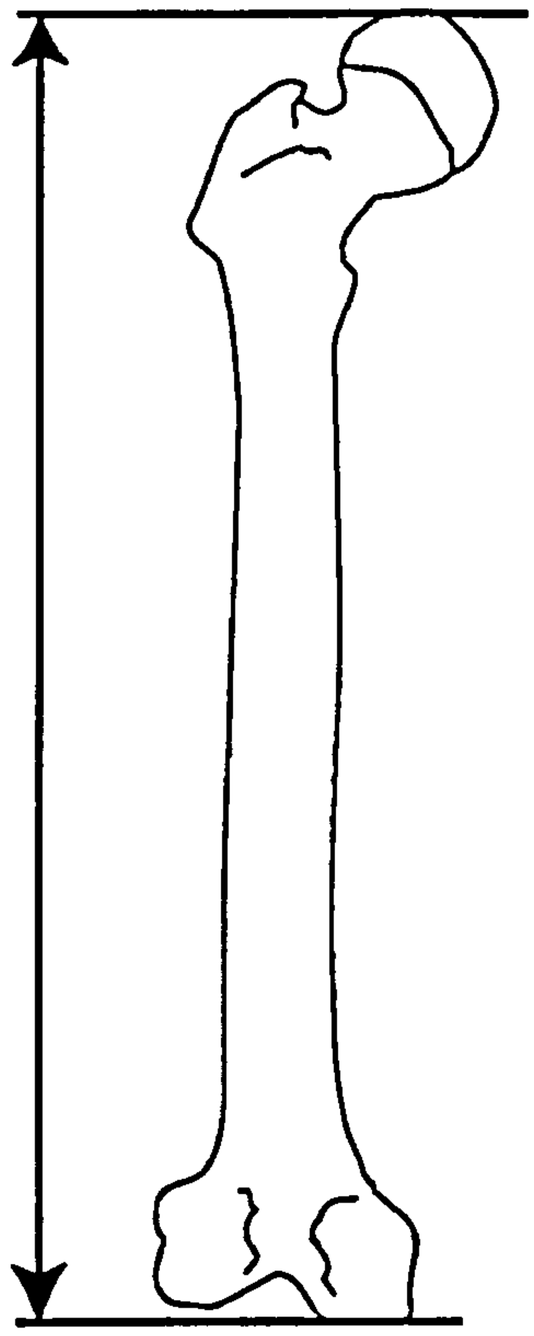


**Figure 6.14 Method for measuring the maximum length of the (left) femur (Adapted from Buikstra and Ubelaker, 1994: 83. Original Figure No. 54))**

### 6.2.6 Data collection and storage

All data was originally collected and documented onto specifically designed recording sheets (Appendix 2). These records form the hard copy of the archive and have been retained by the author. The data contained therein was subsequently entered into a spreadsheet using Microsoft Excel. Each row of the spreadsheet corresponded to one burial and columns represented the various parameters examined. This data was imported into a SPSS (version 10) package for statistical analyses and the final 'SPSS data editor for PhD' file is presented on the accompanying CD in Appendix CD1. Due to the length of

some of the variables names, the original column codes from the excel spreadsheet were employed in the data editor and these are defined in Volume 2, Appendix 3.

### 6.2.7 Assessment of intraobserver error

All of the measurements recorded above were repeated in a randomly selected number of specimens from each sample. These comprised twenty specimens from Christ Church, Spitalfields; twenty from St. Brides, Fleet Street; and three each from St. Nicholas, Sevenoaks and The Quaker Burial Ground, London Road. These repeated measurements were taken after the initial documentation of values for each complete subsample had been achieved. An estimate of repeatability was subsequently obtained by performing a statistical test, known as the measurement error or technical error of the measurement. In this test, the square root of the sum of the squared differences between repeated measurements is divided by twice the sample size, and the resulting value is the standard deviation of the measurement.

### 6.2.8 Statistical analyses

Statistical techniques employed were dictated by the nature of the data amassed and these consisted of the four accepted levels – nominal, ordinal, interval and ratio. The discrete or categorical data comprising the former two classifications included burial type, sex and pelvic inlet classification (all nominal variables) and pathology grading (all ordinal). The continuous variables were recorded as either interval data, consisting of the date of death, age at death and parity status; or as ratio values, which included all of the measurements that were taken.

Various statistical analyses were conducted on the data and these tests have been described below. Techniques employed for investigating attributes of the continuous variables (consisting mainly of the metrical data) have been described first, followed by those used to examine the discrete types (mainly comprising the pathology gradings). All of these analyses were carried out using a Statistical Package for the Social Sciences (SPSS) version 10 package, unless otherwise stated.

## a) Descriptive statistics

### i) Mean

The arithmetic mean is the most common form of average. The notation for the mean of a variable is $\bar{x}$ and is calculated from the following equation (Fletcher and Lock, 1994):

$$\bar{x} = \frac{\sum x}{n}$$

where:

$\sum$ = the sum of

$n$ = total number of values

### ii) Standard deviation

The standard deviation is a statistic employed to describe the spread of data and describes the "average" amount by which all values deviate from the mean (Rowntree, 1981). The formula used to calculate this value is (Glantz, 1987; Swinscow, 1983):

$$\sqrt{\frac{\sum(x-\bar{x})^2}{n-1}}$$

where:

$\sum$ = the sum of

$x$ = the individual value

$\bar{x}$ = the mean of the values

$n$ = total number of values

iii) Variance

This is defined as the square of the standard deviation (Glantz, 1987; Rowntree, 1981). It is denoted as $s^2$ and has the following formula (Glantz, 1987; Swinscow, 1983):

$$s^2 = \frac{\sum(x-\bar{x})^2}{n-1}$$

where:

$\sum$ = the sum of

$x$ = the individual value

$\bar{x}$ = the mean of the values

$n$ = total number of values

iv) Confidence intervals

The confidence interval (or limit) is a statistical convention for stating the confidence for an estimate based on a particular probability value (Glantz, 1987) (usually 90%, 95% or 99%). The 95% value has been selected for all computations. The 95% confidence limits are calculated using the following equation (Fletcher and Lock, 1994):

$$\bar{x} \pm 1.960 \frac{s}{\sqrt{n}}$$

where:

$\bar{x}$ = the mean of the values

$s$ = the standard deviation

$n$ = total number of values

**b) Kolmogorov-Smirnov test of normality**

This test compares the observed cumulative percentages with those that would be expected if the population from which the sample is taken has a normal distribution (Fletcher and Lock, 1994).

The null hypothesis ($H_0$) stated that the data has a normal distribution.
The alternative hypothesis ($H_1$) stated that the data does not have a normal distribution.

Statistics required: number in sample (n), mean ($\bar{x}$), standard deviation (s) and cumulative percentages.

Test statistic generated: D (the maximum absolute difference between observed and expected cumulative percentages) (*ibid.*).

Once the D value was calculated, it was compared with the value stated for a level of significance where p = 0.05, in a Kolmogorov-Smirnov single sample table. If the calculated value was less than this, then the null hypothesis was accepted and the data was deemed to have a normal distribution. If, on the other hand, the calculated value exceeded the stated one, then the null hypothesis was rejected and the alternative one accepted. That is to say that the data was not normally distributed.

**c) Test of difference in means/medians of two independent samples**

(Independent-samples t-test and Mann-Whitney U test)

The means/medians obtained from the female and male continuous data sets were compared to each other to investigate whether these two groups came from the same population. Data sets that were examined consisted of two types; normally distributed values and variances that were approximately equal, and non-normally distributed data. In the case of the former, an independent-samples t-test was undertaken to compare means (Glantz, 1987; Pallant, 2001). For the latter, the Mann-Whitney U test was employed to compare medians (*ibid.*).

For the independent-samples t-test, the null and alternative hypotheses were constructed in the following ways:

The null hypothesis ($H_0$) states that these two samples come from the same population

$$\bar{x}_1 = \bar{x}_2$$

(where $\bar{x}_1$ is the mean for the female group and $\bar{x}_2$ is the mean for the male group)

The alternative hypotheses take on one of three forms:

- $H_1$ states that these two samples come from different populations (TTT)

$$\bar{x}_1 \neq \bar{x}_2$$

- $H_2$ states that the mean of the female group is greater than that of the male (OTT)

$$\bar{x}_1 > \bar{x}_2$$

- $H_3$ states that the mean of the female group is less than that of the male (OTT)

$$\bar{x}_1 < \bar{x}_2$$

The first of these alternative hypotheses was adopted for the test, as absolute differences in means were being sought, and not the direction of that difference.

Statistics required: number in each sample ($n_1$ and $n_2$), mean ($\bar{x}_1$ and $\bar{x}_2$), standard deviation ($s_1$ and $s_2$).

Test statistic generated is (Fletcher and Lock, 1994):

$$\frac{|\bar{x}_1 - \bar{x}_2|}{\hat{s}\sqrt{\left(\frac{1}{n_1}+\frac{1}{n_2}\right)}}, \quad \text{where } \hat{s}^2 = \frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1+n_2-2}$$

where:

$\bar{x}$ = the mean of the values (of samples 1 and 2)

$n$ = total number of values (of samples 1 and 2)

$s$ = the standard deviation (of samples 1 and 2)

The test statistic is then compared to the value presented in the tables for either one sided tests, or two sided ones, where p=0.05 and the degrees of freedom (df) are equal to $n_1 + n_2 - 2$.

Effect size statistics were also employed to provide an indication of the magnitude of difference between the female and male groups (Pallant, 2001). This was accomplished by calculating the eta squared value. If this value is then multiplied by 100, the resulting percentage provides an indication of how much variance in the variable under study is explained by sex. SPSS does not provide eta squared values, but they were calculated from the following formula (Fletcher and Lock, 1994; Pallant, 2001):

$$\text{Eta squared} = \frac{t^2}{t^2 + (n_1 + n_2 - 2)}$$

The Mann-Whitney U test assumes that a sample size of ten or greater is under examination and this criteria was fulfilled. In this case, the medians of the female and male groups were compared and analysed as detailed in the previous test statistic.

**d) Test of association for discrete or categorical data**

(Chi-squared ($\chi^2$) test for independence)

This test is employed to investigate the relationship between categorical/nominal data (Fletcher and Lock, 1994; Pallant, 2001; Rowntree, 1981) (i.e. sex and pelvic shape). This test allows a comparison to be carried out between observed frequencies and those expected if the null hypothesis of no association holds. The Chi-squared test needs to have all expected frequencies at values of five or greater.

The null hypothesis states that there is no association between the variables

The alternative hypothesis states that there is a significant association between the variables

Test statistic is (Glantz, 1987; Fletcher and Lock, 1994):

$$\chi^2 = \sum \frac{(O-E)^2}{E} \qquad \text{degrees of freedom} = (r-1)(c-1)$$

where:

O = the observed cell counts

E = the expected cell counts

r = number of rows

c = number of columns

The calculated $\chi^2$ value is then compared to tabulated values at 5%, 1% and 0.01% level. If the former is greater than the latter, then the null hypothesis is rejected and the alternative one accepted.

The strength of any association demonstrated can be further explored by calculating Cramer's V statistic (Fletcher and Lock, 1994). This is defined as:

$$V = \sqrt{\frac{\chi^2}{(n)(m)}}$$

where:

$\chi^2$ = Chi-squared value

$n$ = the total of all the counts (the total number of cases or objects)

$m$ = the smaller of (c-1) and (r-1), where c is the number of columns, and r, the number of rows.

Yule's Q can also be calculated to measure association (and is only applicable to a 2x2 table). It is defined as (Bishop *et al.*, 1975):

$$Q = \frac{ad-bc}{ad+bc}$$

where a, b, c and d refer to the cell counts of a table labelled as:

| | |
|---|---|
| a | b |
| c | d |

SPSS does not provide values for Cramer's V and Yule's Q, and so they were calculated, with the use of a calculator, using the above formulae.

**e) Test of correlation between two continuous variables**

(Pearson product moment correlation coefficient and Spearman's rank correlation coefficient)

The Pearson product moment correlation coefficient was employed to measure the amount of correlation between two continuous variables that were normally distributed (Fletcher and Lock, 1994; Glantz, 1987; Rowntree, 1981; Pallant, 2001). Spearman's rank correlation coefficient was employed as the non-parametric alternative (*ibid.*). These tests produced a correlation coefficient, termed r and $r_s$, respectively.

Statistics required: n (number) and x and y (pairs of observations).

Test statistic (Fletcher and Lock, 1994; Glantz, 1987): =

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{\left[n\sum x^2 - (\sum x)^2\right]\left[n\sum y^2 - (\sum y)^2\right]}}$$

The value r lies between the range +1 and –1, which respectively represent perfect positive and perfect negative correlation. The measure of the strength of the relationship between the two variables can be determined by calculating the square of the correlation. This value ($r^2$ or $r_s^2$) is termed the coefficient of determination and provides a means of demonstrating how much variance each of the two variables in question share, and consequently quantifying the value (Fletcher and Lock, 1994; Glantz, 1987; Pallant, 2001). If this value is then multiplied by 100, the percentage of variance is produced.

### f) Discriminant function analysis

The discriminant function analysis is employed to explore the predictive ability of a combination of independent variables, on one categorical dependant one (Pallant, 2001). With this test, two variables ($X_1$ and $X_2$) are capable of differentiating between three groups. In order to do this, a linear combination (known as a discriminant function) is examined for in the discriminating variables ($X_1$ and $X_2$) in such a way that the three groups are maximally distinguished. The test statistic can be represented as follows (Tacq, 1997):

$$T - \overline{T} = k_1 (X_1 - \overline{X}_1) + k_2 (X_2 - \overline{X}_2) + k_3 (X_3 - \overline{X}_3) \ldots\ldots k_p (X_p - \overline{X}_p)$$

or

$$t = k_1 x_1 + k_2 x_2 + k3 x_3 + \ldots\ldots\ldots + k_p x_p$$

where:

$t$ and $x_1$ = deviations of the mean

$k$ = discriminant weight

$x_1$ to $x_p$ = discriminating variables

$_p$ = number of discriminating variables

## 6.2.9 Graphical presentation of correlation between two continuous variables

An appropriate mechanism was required to effectively (visually) display the relationship between each individual pelvic measurement and the three specific pathological manifestations. For each pelvic measurement taken, there were basically four separate pieces of information to display: the vertebral level examined and, at each of these, the presence/absence of the three pathological manifestations (osteophytes, porosity and eburnation). A 'signpost' representation was conceived to facilitate this, with four axes (representing the aforementioned pieces of information) contributing to its structure. The single vertical axis represented the vertebral levels, extending from the occipital condyles down to the superior aspect of the first sacral vertebra. The three axes in the horizontal

plane (spaced at 120°) represented each of the pathologies examined. In effect, a fifth dimension was added by interleaving severity and extent data along the vertical axis (so, for each vertebral level, a severity and then an extent value was plotted). Only data that was statistically significant, at either the 0.05 or 0.01 probability level, was employed in the construction of these graphs, with the horizontal axes being created from the significant correlation coefficients generated. Figure 6.15 gives an example of such a graph using contrived data.

The software programme to present data in this manner was created by Mr A. R Coshan of Pinegrove Technology. This versatile package, developed using the Open GL graphics library, allows the graph to be viewed from various angles in order to gain an appreciation of the interrelationship between the variables under study.

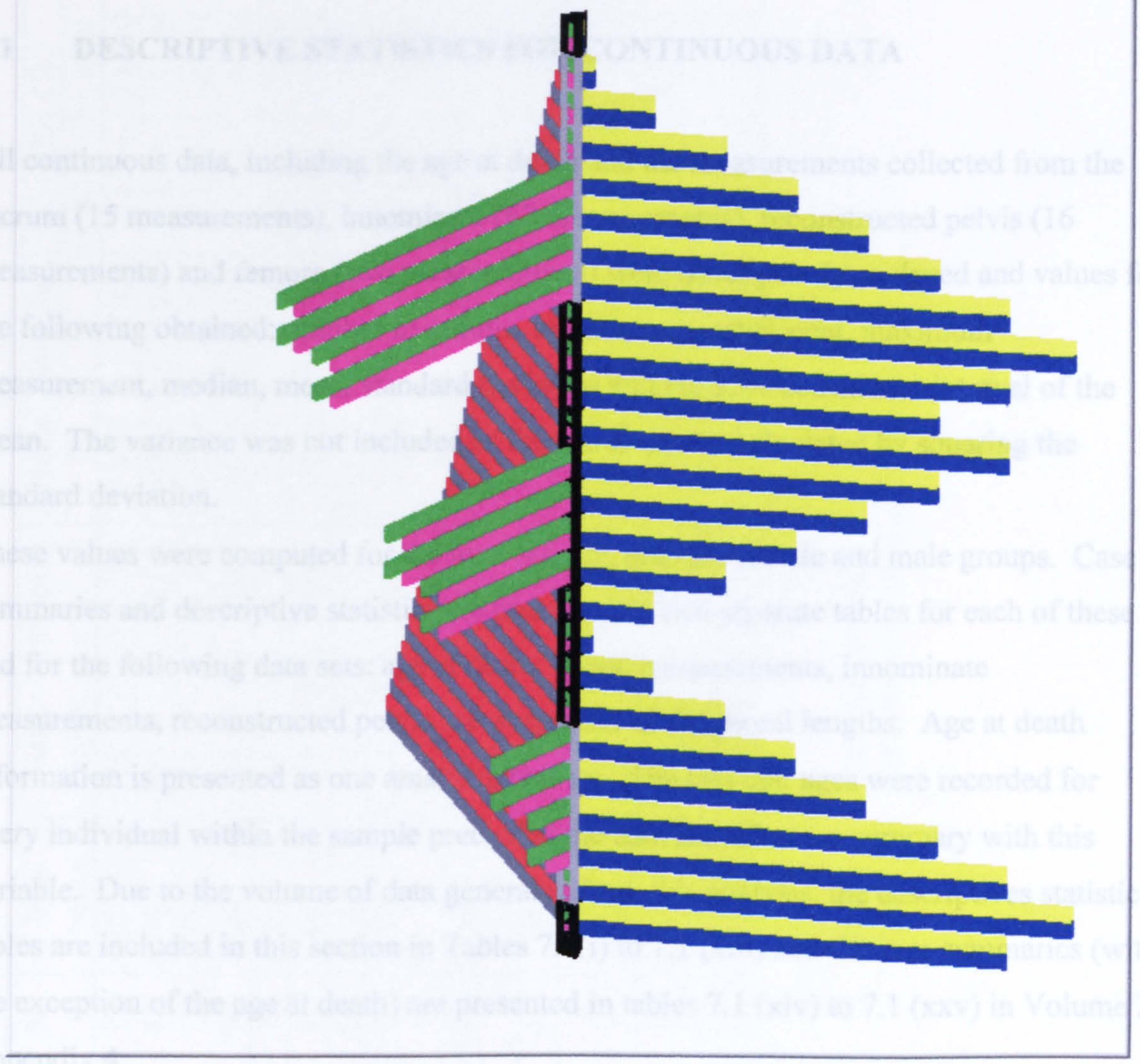


**Figure 6.15**
**Signpost graph example using contrived data**

The black and grey vertical axis represents the vertebral column and extends from the occipital condyles at the top of the structure to the superior aspect of the first sacral vertebra at the lower aspect. The occipital condyles, thoracic and sacral regions of the spine are coloured black. The cervical and lumbar areas are coloured grey.

The three dually coloured horizontal axes represent the three pathological manifestations that were examined for and are detailed as below:

Osteophytes (Severity, Extent)

Porosity (Severity, Extent)

Eburnation (Severity, Extent)

# CHAPTER 7 RESULTS AND DISCUSSION

## 7.1 DESCRIPTIVE STATISTICS FOR CONTINUOUS DATA

All continuous data, including the age at death and the measurements collected from the sacrum (15 measurements), innominate (62 measurements), reconstructed pelvis (16 measurements) and femora (two measurements) were descriptively analysed and values for the following obtained: number in sample, minimum measurement, maximum measurement, median, mean, standard deviation and the 95% confidence interval of the mean. The variance was not included as this value can be calculated by squaring the standard deviation.

These values were computed for the total sample, plus the female and male groups. Case summaries and descriptive statistics are presented in two separate tables for each of these and for the following data sets: age at death, sacral measurements, innominate measurements, reconstructed pelvis measurements and femoral lengths. Age at death information is presented as one amalgamated set. The fact that ages were recorded for every individual within the sample precluded the addition of a case summary with this variable. Due to the volume of data generated from this analysis, the descriptives statistics tables are included in this section in Tables 7.1(i) to 7.1 (xiii) and the case summaries (with the exception of the age at death) are presented in tables 7.1 (xiv) to 7.1 (xxv) in Volume 2, Appendix 4.

**Table 7.1(i) Case summary and descriptive statistics for age at death in total sample and female and male groups**

| Sample/ group | N | Min value | Max value | Median | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Min | Max |
| Total | 103 | 17 | 87 | 56.00 | 52.31 | 16.87 | 49.01 | 55.61 |
| Females | 62 | 17 | 87 | 55.00 | 52.08 | 18.24 | 47.45 | 56.71 |
| Males | 41 | 25 | 75 | 58.00 | 52.66 | 14.77 | 48.00 | 57.32 |

**Key:**

| | | | |
|---|---|---|---|
| N | Number of values | Std.Dev. | Standard deviation |
| Min | Minimum | CI | Confidence interval of the mean |
| Max | Maximum | | |

**Table 7.1(ii) Descriptive statistics for sacral measurements for total sample**

| Variable | N | Min value | Max value | Median | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Min | Max |
| Maximum superior sacral width | 97 | 102 | 133 | 114.58 | 114.48 | 6.02 | 113.28 | 115.67 |
| Maximum inferior sacral width | 83 | 78 | 103 | 90.10 | 90.01 | 5.93 | 88.73 | 91.28 |
| Maximum transverse diameter of S1 | 75 | 36.0 | 59.4 | 44.30 | 45.08 | 5.11 | 43.92 | 46.24 |
| Maximum A-P diameter of S1 | 90 | 24.3 | 38.3 | 30.09 | 30.24 | 3.00 | 29.62 | 30.86 |
| Height of body of first sacral vertebra | 72 | 21.2 | 41.2 | 32.24 | 32.49 | 3.53 | 31.68 | 33.31 |
| Promontorium angle | 92 | 44 | 74 | 57.00 | 57.02 | 5.24 | 55.95 | 58.09 |
| Mid-ventral curved length | 55 | 8.8 | 14.2 | 11.50 | 11.42 | 1.15 | 11.11 | 11.72 |
| Distance of medial borders of processus articulares superiores | 95 | 19.6 | 34.4 | 25.26 | 25.62 | 3.42 | 24.93 | 26.30 |
| Distance of lateral borders of processus articulares superiores | 91 | 46.7 | 68.8 | 58.21 | 58.12 | 4.80 | 57.13 | 59.10 |
| Spinal canal maximum transverse width | 98 | 23.9 | 38.3 | 30.21 | 30.38 | 2.95 | 29.80 | 30.96 |
| Spinal canal maximum A-P width | 8 | 12.5 | 16.2 | 13.42 | 13.80 | 1.22 | 12.95 | 14.65 |
| Combined transverse width of alae | 71 | 53.4 | 86.6 | 69.30 | 68.62 | 7.57 | 66.86 | 70.38 |
| Anterior mid-ventral straight height of sacrum | 58 | 69 | 128 | 101.0 | 100.49 | 11.77 | 97.46 | 103.52 |
| Maximum depth of curvature of sacrum | 48 | 11.7 | 34.3 | 24.32 | 24.26 | 4.92 | 22.87 | 25.66 |
| Position of maximum depth of curvature of sacrum | 48 | 26.2 | 79.9 | 60.08 | 59.68 | 9.56 | 56.97 | 62.38 |

**Key:**

| | | | |
|---|---|---|---|
| N | Number of values | Std.Dev. | Standard deviation |
| Min | Minimum | CI | Confidence interval of the mean |
| Max | Maximum | | |

**Table 7.1(iii) Descriptive statistics for sacral measurements for female group**

| Variable | N | Min value | Max value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| Maximum superior sacral width | 58 | 102.38 | 128.63 | 115.58 | 5.605 | 114.10 | 117.05 |
| Maximum inferior sacral width | 45 | 77.78 | 103.22 | 90.42 | 6.216 | 88.56 | 92.29 |
| Maximum transverse diameter of S1 | 44 | 36.00 | 51.72 | 42.26 | 3.548 | 41.19 | 43.34 |
| Maximum A-P diameter of S1 | 56 | 24.33 | 33.89 | 28.96 | 2.372 | 28.33 | 29.60 |
| Height of body of first sacral vertebra | 42 | 21.15 | 41.24 | 31.41 | 3.675 | 30.27 | 32.56 |
| Promontorium angle | 57 | 44.00 | 69.00 | 56.65 | 4.995 | 55.32 | 57.97 |
| Mid-ventral curved length | 28 | 8.75 | 14.20 | 11.06 | 1.134 | 10.62 | 11.50 |
| Distance of medial borders of processus articulares superiores | 54 | 20.00 | 33.00 | 25.17 | 3.183 | 24.30 | 26.04 |
| Distance of lateral borders of processus articulares superiores | 53 | 46.74 | 67.90 | 56.93 | 4.476 | 55.69 | 58.16 |
| Spinal canal maximum transverse width | 57 | 23.90 | 38.30 | 29.97 | 2.869 | 29.21 | 30.73 |
| Spinal canal maximum A-P width | 4 | 12.50 | 14.60 | 13.24 | 0.963 | 11.71 | 14.77 |
| Combined transverse width of alae | 42 | 58.55 | 86.63 | 72.67 | 6.384 | 70.68 | 74.66 |
| Anterior mid-ventral straight height of sacrum | 30 | 68.52 | 127.54 | 97.91 | 12.808 | 93.13 | 102.69 |
| Maximum depth of curvature of sacrum | 27 | 16.59 | 32.82 | 22.64 | 4.499 | 20.86 | 24.42 |
| Position of maximum depth of curvature of sacrum | 27 | 26.23 | 72.33 | 57.85 | 10.152 | 53.84 | 61.87 |

**Key:**

| | | | |
|---|---|---|---|
| N | Number of values | Std.Dev. | Standard deviation |
| Min | Minimum | CI | Confidence interval of the mean |
| Max | Maximum | | |

**Table 7.1(iv) Descriptive statistics for sacral measurements for male group**

| Variable | N | Min value | Max value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| Maximum superior sacral width | 39 | 101.53 | 133.28 | 112.84 | 6.307 | 110.79 | 114.88 |
| Maximum inferior sacral width | 38 | 78.79 | 102.24 | 89.51 | 5.613 | 87.67 | 91.35 |
| Maximum transverse diameter of S1 | 31 | 41.01 | 59.37 | 49.07 | 4.277 | 47.51 | 50.64 |
| Maximum A-P diameter of S1 | 34 | 25.24 | 38.29 | 32.35 | 2.752 | 31.39 | 33.31 |
| Height of body of first sacral vertebra | 30 | 28.94 | 38.43 | 34.00 | 2.726 | 32.98 | 35.02 |
| Promontorium angle | 35 | 48.00 | 74.00 | 57.63 | 5.631 | 55.69 | 59.56 |
| Mid-ventral curved length | 27 | 9.90 | 14.00 | 11.79 | 1.062 | 11.37 | 12.21 |
| Distance of medial borders of processus articulares superiores | 41 | 19.55 | 34.36 | 26.20 | 3.668 | 25.04 | 27.36 |
| Distance of lateral borders of processus articulares superiores | 38 | 51.24 | 68.78 | 59.78 | 4.803 | 58.20 | 61.36 |
| Spinal canal maximum transverse width | 41 | 25.25 | 37.96 | 30.94 | 3.000 | 30.00 | 31.89 |
| Spinal canal maximum A-P width | 4 | 13.20 | 16.16 | 14.37 | 1.314 | 12.27 | 16.46 |
| Combined transverse width of alae | 29 | 53.38 | 70.27 | 62.77 | 4.837 | 60.93 | 64.61 |
| Anterior mid-ventral straight height of sacrum | 28 | 80.20 | 122.71 | 103.26 | 10.052 | 99.36 | 107.16 |
| Maximum depth of curvature of sacrum | 21 | 11.72 | 34.27 | 26.35 | 4.734 | 24.20 | 28.51 |
| Position of maximum depth of curvature of sacrum | 21 | 45.50 | 79.94 | 62.02 | 8.405 | 58.20 | 65.85 |

**Key:**

| | | | |
|---|---|---|---|
| N | Number of values | Std.Dev. | Standard deviation |
| Min | Minimum | CI | Confidence interval of the mean |
| Max | Maximum | | |

**Table 7.1(v) Descriptive statistics for innominate measurements for total sample**

| Variable | N | Min value | Max value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| LEFT Maximum innominate length (cm) | 90 | 17.60 | 24.10 | 20.34 | 1.396 | 20.05 | 20.64 |
| RIGHT Maximum innominate length (cm) | 93 | 17.60 | 23.80 | 20.41 | 1.455 | 20.11 | 20.71 |
| LEFT Innominate breadth (cm) | 81 | 12.90 | 17.50 | 15.27 | 0.918 | 15.07 | 15.47 |
| RIGHT Innominate breadth (cm) | 81 | 13.30 | 17.60 | 15.30 | 0.964 | 15.09 | 15.51 |
| LEFT Iliac height | 96 | 98.07 | 140.33 | 119.34 | 8.902 | 117.54 | 121.14 |
| RIGHT Iliac height | 96 | 98.62 | 137.61 | 119.08 | 8.954 | 117.27 | 120.90 |
| LEFT Acetabulum diameter | 91 | 41.09 | 56.58 | 48.00 | 3.681 | 47.23 | 48.76 |
| RIGHT Acetabulum diameter | 95 | 39.34 | 56.00 | 48.17 | 3.959 | 47.36 | 48.98 |
| LEFT Pubis length | 61 | 78.60 | 109.59 | 92.19 | 5.623 | 90.75 | 93.63 |
| RIGHT Pubis length | 66 | 79.60 | 108.63 | 92.52 | 5.601 | 91.14 | 93.89 |
| LEFT Minimum height of inferior pubic ramus | 85 | 6.23 | 20.61 | 13.87 | 2.801 | 13.27 | 14.47 |
| RIGHT Minimum height of inferior pubic ramus | 91 | 8.05 | 22.62 | 14.39 | 2.909 | 13.79 | 15.00 |
| LEFT Oblique length of inferior pubic ramus | 76 | 18.31 | 32.62 | 26.44 | 3.041 | 25.74 | 27.13 |
| RIGHT Oblique length of inferior pubic ramus | 80 | 17.89 | 33.60 | 26.08 | 3.167 | 25.37 | 26.78 |
| LEFT Tubercolusymphyseal height | 46 | 15.00 | 35.82 | 24.67 | 4.125 | 23.44 | 25.89 |
| RIGHT Tubercolusymphyseal height | 43 | 15.70 | 30.10 | 24.74 | 3.499 | 23.66 | 25.82 |
| LEFT Pubic acetabular length | 63 | 62.91 | 81.87 | 71.26 | 3.883 | 70.29 | 72.24 |
| RIGHT Pubic acetabular length | 67 | 63.00 | 81.44 | 71.45 | 4.051 | 70.46 | 72.44 |
| LEFT Pubic tubercle-acetabular length | 45 | 40.81 | 64.97 | 51.80 | 4.759 | 50.37 | 53.23 |
| RIGHT Pubic tubercle-acetabular length | 44 | 42.20 | 64.68 | 52.30 | 4.749 | 50.85 | 53.74 |
| LEFT Ischial acetabular height | 90 | 77.10 | 125.68 | 103.72 | 9.227 | 101.78 | 105.65 |
| RIGHT Ischial acetabular height | 93 | 79.20 | 125.01 | 105.39 | 9.183 | 103.50 | 107.28 |
| LEFT Pubo-sacroiliac diameter | 60 | 101.40 | 135.00 | 116.88 | 6.887 | 115.10 | 118.65 |
| RIGHT Pubo-sacroiliac diameter | 64 | 101.89 | 130.89 | 117.56 | 6.716 | 115.88 | 119.23 |

**Key:** N Number of values Std.Dev. Standard deviation CI Confidence interval of the mean
Max Maximum

**Table 7.1(v) Descriptive statistics for innominate measurements for total sample (contd.)**

| Variable | N | Min value | Max value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| LEFT Pubic symphysis depth | 66 | 26.60 | 49.35 | 38.72 | 4.825 | 37.18 | 41.32 |
| RIGHT Pubic symphysis depth | 68 | 26.90 | 48.67 | 38.81 | 4.890 | 37.30 | 41.14 |
| LEFT Pubic symphysis superior width | 66 | 8.07 | 21.90 | 13.88 | 2.905 | 12.89 | 14.56 |
| RIGHT Pubic symphysis superior width | 68 | 8.16 | 20.04 | 13.60 | 2.561 | 12.73 | 14.69 |
| LEFT Pubic symphysis inferior width | 66 | 6.37 | 18.30 | 12.47 | 2.716 | 11.45 | 14.09 |
| RIGHT Pubic symphysis inferior width | 67 | 6.54 | 17.70 | 12.71 | 2.421 | 12.29 | 14.48 |
| LEFT Maximum width of pubic symphysis | 69 | 8.89 | 23.90 | 15.43 | 3.048 | 14.36 | 16.51 |
| RIGHT Maximum width of pubic symphysis | 69 | 9.11 | 24.31 | 15.39 | 2.635 | 14.95 | 16.73 |
| LEFT Ischial spine to symphysion | 30 | 98.65 | 122.49 | 110.34 | 5.722 | 106.46 | 112.34 |
| RIGHT Ischial spine to symphysion | 22 | 98.85 | 122.11 | 111.25 | 5.867 | 106.28 | 112.93 |
| LEFT Symphyseal angle | 71 | 121.00 | 158.00 | 140.21 | 6.331 | 138.38 | 143.22 |
| RIGHT Symphyseal angle | 74 | 128.00 | 157.00 | 140.43 | 6.582 | 137.36 | 144.64 |
| LEFT Acetabulosciatic breadth | 97 | 26.98 | 46.67 | 36.78 | 4.075 | 34.01 | 39.02 |
| RIGHT Acetabulosciatic breadth | 97 | 27.42 | 77.80 | 37.32 | 5.910 | 34.36 | 39.35 |
| LEFT Ischium length | 87 | 72.92 | 105.81 | 87.03 | 7.625 | 83.34 | 90.97 |
| RIGHT Ischium length | 93 | 72.27 | 107.50 | 87.94 | 7.215 | 84.22 | 91.15 |
| LEFT Maximum length of obturator foramen | 88 | 33.76 | 64.96 | 49.89 | 4.468 | 48.92 | 52.12 |
| RIGHT Maximum length of obturator foramen | 90 | 41.37 | 63.16 | 50.29 | 3.937 | 49.41 | 52.10 |
| LEFT Maximum width of obturator foramen | 87 | 26.95 | 48.26 | 34.62 | 3.156 | 33.05 | 36.84 |
| RIGHT Maximum width of obturator foramen | 90 | 28.15 | 48.42 | 35.25 | 2.918 | 33.63 | 36.94 |

**Key:**

| | | | |
|---|---|---|---|
| N | Number of values | Std.Dev. | Standard deviation |
| Min | Minimum | CI | Confidence interval of the mean |
| Max | Maximum | | |

**Table 7.1(v) Descriptive statistics for innominate measurements for total sample (contd.)**

| Variable | N | Min value | Max value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| LEFT Auricular surface profile - a | 69 | 34.73 | 64.20 | 49.43 | 6.481 | 46.30 | 52.91 |
| RIGHT Auricular surface profile - a | 71 | 34.60 | 64.82 | 49.83 | 6.782 | 47.25 | 53.92 |
| LEFT Auricular surface profile - b | 70 | 42.55 | 74.61 | 56.46 | 7.310 | 53.35 | 60.02 |
| RIGHT Auricular surface profile - b | 72 | 39.91 | 74.02 | 56.05 | 7.001 | 54.04 | 60.66 |
| LEFT Auricular surface profile - c | 91 | 10.50 | 48.66 | 34.70 | 5.531 | 32.33 | 37.35 |
| RIGHT Auricular surface profile - c | 88 | 15.90 | 45.32 | 34.47 | 4.852 | 30.91 | 37.14 |
| LEFT Auricular surface profile - d | 69 | 30.50 | 70.97 | 50.80 | 9.267 | 47.04 | 55.27 |
| RIGHT Auricular surface profile - d | 67 | 30.30 | 69.46 | 50.54 | 7.925 | 46.40 | 55.29 |
| LEFT Auricular surface profile - e | 69 | 14.68 | 57.20 | 28.75 | 8.034 | 23.09 | 30.78 |
| RIGHT Auricular surface profile - e | 69 | 7.33 | 57.00 | 28.52 | 8.006 | 20.97 | 29.20 |
| LEFT Auricular surface profile - f | 69 | 1.98 | 25.20 | 13.36 | 5.215 | 9.411 | 15.61 |
| RIGHT Auricular surface profile - f | 66 | 2.33 | 24.94 | 13.00 | 4.774 | 12.49 | 16.77 |
| LEFT Sciatic notch width | 26 | 44.80 | 80.64 | 61.14 | 7.986 | 55.92 | 62.84 |
| RIGHT Sciatic notch width | 24 | 41.02 | 69.62 | 57.00 | 8.498 | 56.75 | 64.38 |
| LEFT Sciatic notch height | 23 | 18.24 | 45.08 | 37.00 | 5.529 | 34.90 | 39.37 |
| RIGHT Sciatic notch height | 23 | 31.65 | 45.02 | 37.57 | 3.344 | 35.97 | 39.76 |
| LEFT Sciatic notch position | 22 | 20.50 | 46.41 | 31.08 | 7.011 | 27.97 | 34.80 |
| RIGHT Sciatic notch position | 23 | 21.37 | 45.92 | 31.76 | 5.974 | 31.00 | 37.51 |

**Key:**

| | | | |
|---|---|---|---|
| N | Number of values | Std.Dev. | Standard deviation |
| Min | Minimum | CI | Confidence interval of the mean |
| Max | Maximum | | |

**Table 7.1(vi) Descriptive statistics for innominate measurements for female group**

| Variable | N | Min value | Max value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| LEFT Maximum innominate length (cm) | 55 | 17.60 | 21.50 | 19.56 | 0.927 | 19.31 | 19.81 |
| RIGHT Maximum innominate length (cm) | 57 | 17.60 | 22.00 | 19.55 | 0.998 | 19.29 | 19.82 |
| LEFT Innominate breadth (cm) | 46 | 13.90 | 17.10 | 15.05 | 0.769 | 14.82 | 15.28 |
| RIGHT Innominate breadth (cm) | 47 | 13.30 | 16.50 | 15.05 | 0.846 | 14.80 | 15.30 |
| LEFT Iliac height | 58 | 98.07 | 133.26 | 115.02 | 7.280 | 113.10 | 116.93 |
| RIGHT Iliac height | 58 | 98.62 | 133.28 | 114.69 | 7.490 | 112.72 | 116.66 |
| LEFT Acetabulum diameter | 54 | 41.09 | 51.78 | 45.82 | 2.406 | 45.16 | 46.47 |
| RIGHT Acetabulum diameter | 58 | 39.34 | 52.46 | 45.91 | 2.832 | 45.17 | 46.66 |
| LEFT Pubis length | 33 | 82.20 | 102.54 | 92.88 | 5.179 | 91.04 | 94.71 |
| RIGHT Pubis length | 38 | 81.86 | 106.45 | 92.93 | 5.697 | 91.05 | 94.80 |
| LEFT Minimum height of inferior pubic ramus | 49 | 6.23 | 15.93 | 12.15 | 1.894 | 11.60 | 12.69 |
| RIGHT Minimum height of inferior pubic ramus | 55 | 8.05 | 17.00 | 12.84 | 2.073 | 12.28 | 13.40 |
| LEFT Oblique length of inferior pubic ramus | 42 | 21.76 | 32.62 | 27.94 | 2.597 | 27.13 | 28.75 |
| RIGHT Oblique length of inferior pubic ramus | 46 | 19.83 | 33.60 | 27.32 | 2.852 | 26.48 | 28.17 |
| LEFT Tubercolusymphyseal height | 22 | 15.90 | 35.82 | 26.46 | 4.348 | 24.53 | 28.39 |
| RIGHT Tubercolusymphyseal height | 21 | 19.76 | 30.10 | 26.41 | 2.904 | 25.09 | 27.73 |
| LEFT Pubic acetabular length | 34 | 64.59 | 80.71 | 72.11 | 3.735 | 70.80 | 73.41 |
| RIGHT Pubic acetabular length | 38 | 63.38 | 80.16 | 71.89 | 4.023 | 70.57 | 73.22 |
| LEFT Pubic tubercle-acetabular length | 21 | 40.81 | 56.56 | 50.09 | 4.706 | 47.95 | 52.23 |
| RIGHT Pubic tubercle-acetabular length | 22 | 42.20 | 57.34 | 50.23 | 4.346 | 48.30 | 52.16 |
| LEFT Ischial acetabular height | 55 | 77.10 | 106.91 | 98.13 | 5.732 | 96.58 | 99.68 |
| RIGHT Ischial acetabular height | 56 | 79.20 | 109.01 | 99.44 | 5.478 | 97.98 | 100.91 |
| LEFT Pubo-sacroiliac diameter | 33 | 101.40 | 135.00 | 118.40 | 7.614 | 115.70 | 121.10 |
| RIGHT Pubo-sacroiliac diameter | 37 | 101.89 | 130.89 | 118.38 | 7.462 | 115.90 | 120.87 |

**Key:** N Number of values Std.Dev. Standard deviation CI Confidence interval of the mean
Max Maximum

**Table 7.1(vi) Descriptive statistics for innominate measurements for female group (contd.)**

| Variable | N | Min value | Max value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| LEFT Pubic symphysis depth | 35 | 26.60 | 46.08 | 36.17 | 4.044 | 34.78 | 37.56 |
| RIGHT Pubic symphysis depth | 38 | 26.90 | 44.57 | 36.46 | 4.253 | 35.06 | 37.86 |
| LEFT Pubic symphysis superior width | 35 | 8.07 | 17.42 | 12.20 | 2.233 | 11.43 | 12.97 |
| RIGHT Pubic symphysis superior width | 38 | 8.16 | 18.58 | 12.23 | 1.928 | 11.59 | 12.86 |
| LEFT Pubic symphysis inferior width | 35 | 6.37 | 15.58 | 10.89 | 2.106 | 10.17 | 11.62 |
| RIGHT Pubic symphysis inferior width | 37 | 6.54 | 14.62 | 11.38 | 1.918 | 10.74 | 12.02 |
| LEFT Maximum width of pubic symphysis | 37 | 8.89 | 20.37 | 13.71 | 2.403 | 12.91 | 14.52 |
| RIGHT Maximum width of pubic symphysis | 40 | 9.11 | 20.27 | 14.01 | 2.075 | 13.35 | 14.68 |
| LEFT Ischial spine to symphysion | 16 | 98.65 | 122.49 | 110.09 | 5.930 | 106.93 | 113.25 |
| RIGHT Ischial spine to symphysion | 11 | 98.85 | 122.11 | 111.70 | 6.966 | 107.02 | 116.38 |
| LEFT Symphyseal angle | 40 | 121.00 | 153.00 | 137.18 | 5.918 | 135.28 | 139.07 |
| RIGHT Symphyseal angle | 44 | 128.00 | 153.00 | 136.70 | 4.423 | 135.36 | 138.05 |
| LEFT Acetabulosciatic breadth | 60 | 26.98 | 42.11 | 34.85 | 3.217 | 34.02 | 35.68 |
| RIGHT Acetabulosciatic breadth | 59 | 27.42 | 77.80 | 35.77 | 6.623 | 34.04 | 37.49 |
| LEFT Ischium length | 54 | 72.92 | 95.47 | 82.90 | 5.030 | 81.53 | 84.27 |
| RIGHT Ischium length | 55 | 72.27 | 94.20 | 83.90 | 4.867 | 82.58 | 85.21 |
| LEFT Maximum length of obturator foramen | 53 | 33.76 | 54.85 | 47.69 | 3.681 | 46.67 | 48.70 |
| RIGHT Maximum length of obturator foramen | 57 | 41.37 | 55.67 | 48.56 | 3.303 | 47.68 | 49.44 |
| LEFT Maximum width of obturator foramen | 52 | 26.95 | 39.88 | 34.72 | 3.002 | 33.88 | 35.55 |
| RIGHT Maximum width of obturator foramen | 56 | 28.15 | 39.92 | 35.22 | 2.759 | 34.49 | 35.96 |

**Key:**

| | | | |
|---|---|---|---|
| N | Number of values | Std.Dev. | Standard deviation |
| Min | Minimum | CI | Confidence interval of the mean |
| Max | Maximum | | |

**Table 7.1(vi) Descriptive statistics for innominate measurements for female group (contd.)**

| Variable | N | Min value | Max value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| LEFT Auricular surface profile - a | 39 | 34.73 | 59.80 | 46.78 | 5.439 | 45.02 | 48.55 |
| RIGHT Auricular surface profile - a | 40 | 34.60 | 62.00 | 46.87 | 5.812 | 45.01 | 48.72 |
| LEFT Auricular surface profile - b | 39 | 42.55 | 68.90 | 53.20 | 5.687 | 51.36 | 55.04 |
| RIGHT Auricular surface profile - b | 41 | 39.91 | 65.78 | 52.70 | 5.278 | 51.03 | 54.36 |
| LEFT Auricular surface profile - c | 55 | 10.50 | 44.95 | 33.73 | 5.787 | 32.17 | 35.29 |
| RIGHT Auricular surface profile - c | 54 | 15.90 | 41.04 | 34.26 | 4.350 | 33.08 | 35.45 |
| LEFT Auricular surface profile - d | 39 | 30.50 | 62.00 | 47.32 | 7.709 | 44.82 | 49.82 |
| RIGHT Auricular surface profile - d | 37 | 30.30 | 57.95 | 47.40 | 6.100 | 45.36 | 49.43 |
| LEFT Auricular surface profile - e | 39 | 14.68 | 57.20 | 28.37 | 7.933 | 25.80 | 30.94 |
| RIGHT Auricular surface profile - e | 39 | 12.66 | 52.30 | 28.06 | 7.061 | 25.77 | 30.35 |
| LEFT Auricular surface profile - f | 39 | 1.98 | 25.20 | 12.89 | 5.444 | 11.13 | 14.66 |
| RIGHT Auricular surface profile - f | 37 | 3.85 | 21.33 | 12.61 | 4.451 | 11.12 | 14.09 |
| LEFT Sciatic notch width | 13 | 50.87 | 80.64 | 64.92 | 7.078 | 60.64 | 69.19 |
| RIGHT Sciatic notch width | 9 | 41.02 | 69.62 | 60.42 | 9.831 | 52.86 | 67.97 |
| LEFT Sciatic notch height | 10 | 18.24 | 42.86 | 36.28 | 6.654 | 31.52 | 41.04 |
| RIGHT Sciatic notch height | 9 | 33.26 | 38.30 | 36.22 | 1.623 | 34.98 | 37.47 |
| LEFT Sciatic notch position | 9 | 20.50 | 36.75 | 27.38 | 5.136 | 23.43 | 31.33 |
| RIGHT Sciatic notch position | 9 | 21.37 | 35.90 | 29.10 | 4.720 | 25.47 | 32.73 |

**Key:**

| | | | |
|---|---|---|---|
| N | Number of values | Std.Dev. | Standard deviation |
| Min | Minimum | CI | Confidence interval of the mean |
| Max | Maximum | | |

**Table 7.1(vii) Descriptive statistics for innominate measurements for male group**

| Variable | N | Min value | Max Value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| LEFT Maximum innominate length (cm) | 35 | 18.80 | 24.10 | 21.58 | 1.081 | 21.21 | 21.95 |
| RIGHT Maximum innominate length (cm) | 36 | 19.90 | 23.80 | 21.75 | 0.962 | 21.43 | 22.08 |
| LEFT Innominate breadth (cm) | 35 | 12.90 | 17.50 | 15.57 | 1.021 | 15.21 | 15.92 |
| RIGHT Innominate breadth (cm) | 34 | 13.50 | 17.60 | 15.64 | 1.023 | 15.28 | 16.00 |
| LEFT Iliac height | 38 | 109.69 | 140.33 | 125.94 | 6.913 | 123.67 | 128.21 |
| RIGHT Iliac height | 38 | 109.22 | 137.61 | 125.80 | 6.547 | 123.64 | 127.95 |
| LEFT Acetabulum diameter | 37 | 45.20 | 56.58 | 51.18 | 2.795 | 50.25 | 52.11 |
| RIGHT Acetabulum diameter | 37 | 43.55 | 56.00 | 51.71 | 2.670 | 50.82 | 52.60 |
| LEFT Pubis length | 28 | 78.60 | 109.59 | 91.37 | 6.099 | 89.01 | 93.74 |
| RIGHT Pubis length | 28 | 79.60 | 108.63 | 91.96 | 5.521 | 89.82 | 94.10 |
| LEFT Minimum height of inferior pubic ramus | 36 | 11.88 | 20.61 | 16.22 | 2.024 | 15.53 | 16.90 |
| RIGHT Minimum height of inferior pubic ramus | 36 | 12.51 | 22.62 | 16.76 | 2.368 | 15.96 | 17.56 |
| LEFT Oblique length of inferior pubic ramus | 34 | 18.31 | 28.66 | 24.58 | 2.495 | 23.71 | 25.45 |
| RIGHT Oblique length of inferior pubic ramus | 34 | 17.89 | 30.66 | 24.39 | 2.795 | 23.41 | 25.36 |
| LEFT Tubercolusymphyseal height | 24 | 15.00 | 29.94 | 23.03 | 3.187 | 21.68 | 24.37 |
| RIGHT Tubercolusymphyseal height | 22 | 15.70 | 29.63 | 23.15 | 3.316 | 21.67 | 24.62 |
| LEFT Pubic acetabular length | 29 | 62.91 | 81.87 | 70.28 | 3.883 | 68.80 | 71.75 |
| RIGHT Pubic acetabular length | 29 | 63.00 | 81.44 | 70.86 | 4.083 | 69.31 | 72.42 |
| LEFT Pubic tubercle-acetabular length | 24 | 45.54 | 64.97 | 53.30 | 4.364 | 51.46 | 55.14 |
| RIGHT Pubic tubercle-acetabular length | 22 | 47.00 | 64.68 | 54.36 | 4.283 | 52.46 | 56.27 |
| LEFT Ischial acetabular height | 35 | 100.57 | 125.68 | 112.50 | 6.382 | 110.31 | 114.69 |
| RIGHT Ischial acetabular height | 37 | 99.47 | 125.01 | 114.38 | 5.610 | 112.51 | 116.25 |
| LEFT Pubo-sacroiliac diameter | 27 | 106.90 | 128.95 | 115.01 | 5.452 | 112.85 | 117.17 |
| RIGHT Pubo-sacroiliac diameter | 27 | 105.60 | 127.80 | 116.42 | 5.466 | 114.26 | 118.58 |

**Key:** N Number of values Std.Dev. Standard deviation CI Confidence interval of the mean
Max Maximum

**Table 7.1(vii) Descriptive statistics for innominate measurements for male group (contd.)**

| Variable | N | Min value | Max value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| LEFT Pubic symphysis depth | 31 | 34.28 | 49.35 | 41.59 | 3.975 | 40.13 | 43.05 |
| RIGHT Pubic symphysis depth | 30 | 33.19 | 48.67 | 41.78 | 3.978 | 40.29 | 43.26 |
| LEFT Pubic symphysis superior width | 31 | 12.02 | 21.90 | 15.77 | 2.373 | 14.90 | 16.64 |
| RIGHT Pubic symphysis superior width | 30 | 11.18 | 20.04 | 15.34 | 2.193 | 14.52 | 16.16 |
| LEFT Pubic symphysis inferior width | 31 | 9.93 | 18.30 | 14.26 | 2.182 | 13.46 | 15.06 |
| RIGHT Pubic symphysis inferior width | 30 | 9.29 | 17.70 | 14.35 | 1.933 | 13.63 | 15.07 |
| LEFT Maximum width of pubic symphysis | 32 | 12.81 | 23.90 | 17.42 | 2.467 | 16.53 | 18.31 |
| RIGHT Maximum width of pubic symphysis | 29 | 14.10 | 24.31 | 17.29 | 2.104 | 16.49 | 18.09 |
| LEFT Ischial spine to symphysion | 14 | 100.60 | 120.49 | 110.62 | 5.683 | 107.34 | 113.90 |
| RIGHT Ischial spine to symphysion | 11 | 100.50 | 115.90 | 110.79 | 4.826 | 107.54 | 114.03 |
| LEFT Symphyseal angle | 31 | 138.00 | 158.00 | 144.13 | 4.455 | 142.49 | 145.76 |
| RIGHT Symphyseal angle | 30 | 131.00 | 157.00 | 145.90 | 5.294 | 143.92 | 147.88 |
| LEFT Acetabulosciatic breadth | 37 | 32.50 | 46.67 | 39.92 | 3.316 | 38.81 | 41.02 |
| RIGHT Acetabulosciatic breadth | 38 | 33.75 | 47.22 | 39.73 | 3.469 | 38.59 | 40.87 |
| LEFT Ischium length | 33 | 83.44 | 105.81 | 93.78 | 6.212 | 91.57 | 95.98 |
| RIGHT Ischium length | 38 | 81.23 | 107.50 | 93.79 | 5.947 | 91.84 | 95.75 |
| LEFT Maximum length of obturator foramen | 35 | 46.70 | 64.96 | 53.22 | 3.374 | 52.06 | 54.38 |
| RIGHT Maximum length of obturator foramen | 33 | 47.50 | 63.16 | 53.28 | 3.081 | 52.18 | 54.37 |
| LEFT Maximum width of obturator foramen | 35 | 30.57 | 48.26 | 34.47 | 3.411 | 33.30 | 35.64 |
| RIGHT Maximum width of obturator foramen | 34 | 31.55 | 48.42 | 35.30 | 3.206 | 34.18 | 36.42 |

**Key:**

| | | | |
|---|---|---|---|
| N | Number of values | Std.Dev. | Standard deviation |
| Min | Minimum | CI | Confidence interval of the mean |
| Max | Maximum | | |

**Table 7.1(vii) Descriptive statistics for innominate measurements for male group (contd.)**

| Variable | N | Min value | Max value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| LEFT Auricular surface profile - a | 30 | 39.57 | 64.20 | 52.87 | 6.170 | 50.57 | 55.17 |
| RIGHT Auricular surface profile - a | 31 | 42.33 | 64.82 | 53.66 | 6.042 | 51.45 | 55.88 |
| LEFT Auricular surface profile - b | 31 | 50.00 | 74.61 | 60.57 | 7.116 | 57.96 | 63.18 |
| RIGHT Auricular surface profile - b | 31 | 49.27 | 74.02 | 60.48 | 6.574 | 58.07 | 62.89 |
| LEFT Auricular surface profile - c | 36 | 26.90 | 48.66 | 36.17 | 4.825 | 34.54 | 37.81 |
| RIGHT Auricular surface profile - c | 34 | 20.90 | 45.32 | 34.81 | 5.610 | 32.85 | 36.77 |
| LEFT Auricular surface profile - d | 30 | 32.60 | 70.97 | 55.33 | 9.274 | 51.87 | 58.79 |
| RIGHT Auricular surface profile - d | 30 | 34.40 | 69.46 | 54.42 | 8.281 | 51.33 | 57.51 |
| LEFT Auricular surface profile - e | 30 | 15.82 | 47.30 | 29.25 | 8.273 | 26.16 | 32.34 |
| RIGHT Auricular surface profile - e | 30 | 7.33 | 57.00 | 29.11 | 9.182 | 25.69 | 32.54 |
| LEFT Auricular surface profile - f | 30 | 6.52 | 24.14 | 13.98 | 4.924 | 12.14 | 15.82 |
| RIGHT Auricular surface profile - f | 29 | 2.33 | 24.94 | 13.51 | 5.191 | 11.54 | 15.49 |
| LEFT Sciatic notch width | 13 | 44.80 | 67.14 | 57.37 | 7.202 | 53.01 | 61.72 |
| RIGHT Sciatic notch width | 15 | 41.60 | 66.99 | 54.95 | 7.169 | 50.98 | 58.92 |
| LEFT Sciatic notch height | 13 | 28.62 | 45.08 | 37.56 | 4.698 | 34.72 | 40.39 |
| RIGHT Sciatic notch height | 14 | 31.65 | 45.02 | 38.44 | 3.903 | 36.19 | 40.69 |
| LEFT Sciatic notch position | 13 | 22.72 | 46.41 | 33.63 | 7.149 | 29.31 | 37.95 |
| RIGHT Sciatic notch position | 14 | 25.42 | 45.92 | 33.47 | 6.216 | 29.88 | 37.06 |

**Key:**

| | | | |
|---|---|---|---|
| N | Number of values | Std.Dev. | Standard deviation |
| Min | Minimum | CI | Confidence interval of the mean |
| Max | Maximum | | |

**Table 7.1(viii) Descriptive statistics for reconstructed pelvis measurements for total sample**

| Variable | N | Min value | Max value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| A-P superior diameter of pelvis | 63 | 82.90 | 128.05 | 101.80 | 9.174 | 99.49 | 104.11 |
| A-P inferior diameter of pelvis | 40 | 88.15 | 126.55 | 108.10 | 9.664 | 105.00 | 111.19 |
| Transverse diameter of pelvis | 70 | 107.50 | 149.83 | 127.75 | 9.126 | 125.57 | 129.92 |
| Greatest pelvic diameter | 65 | 97.98 | 141.00 | 122.51 | 8.916 | 120.30 | 124.72 |
| Bispinous breadth | 18 | 76.72 | 118.20 | 94.50 | 12.217 | 88.43 | 100.58 |
| Bi-tuberous diameter | 64 | 47.03 | 124.60 | 74.60 | 15.760 | 70.67 | 78.54 |
| Bi-tuberous width (cm) | 64 | 13.00 | 17.00 | 14.90 | 1.135 | 14.61 | 15.18 |
| Right ischial spine to sacral apex | 15 | 45.10 | 84.85 | 57.08 | 11.070 | 50.95 | 63.21 |
| Left ischial spine to sacral apex | 24 | 44.80 | 75.39 | 60.12 | 9.685 | 56.03 | 64.21 |
| Right ischial tuberosity to sacral apex | 40 | 82.23 | 118.00 | 100.97 | 9.533 | 97.92 | 104.02 |
| Left ischial tuberosity to sacral apex | 38 | 80.23 | 120.84 | 100.52 | 9.855 | 97.28 | 103.76 |
| Subpubic angle | 65 | 48.00 | 101.00 | 79.85 | 13.004 | 76.62 | 83.07 |
| Inlet circumference (cm) | 59 | 30.10 | 40.40 | 35.52 | 2.299 | 34.92 | 36.11 |
| Superior-anterior bi-iliac breadth of pelvis (cm) | 61 | 18.60 | 26.10 | 22.45 | 1.649 | 22.03 | 22.87 |
| Inferior-posterior bi-iliac breadth of pelvis | 53 | 36.74 | 96.52 | 70.54 | 10.944 | 67.52 | 73.55 |
| Bi-acetabular breadth | 69 | 108.40 | 148.00 | 126.34 | 8.683 | 124.25 | 128.42 |

**Key:**

| | | | |
|---|---|---|---|
| N | Number of values | Std.Dev. | Standard deviation |
| Min | Minimum | CI | Confidence interval of the mean |
| Max | Maximum | | |

**Table 7.1(ix) Descriptive statistics for reconstructed pelvis measurements for female group**

| Variable | N | Min value | Max value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| A-P superior diameter of pelvis | 33 | 84.15 | 128.05 | 104.70 | 10.322 | 101.04 | 108.36 |
| A-P inferior diameter of pelvis | 21 | 88.15 | 126.55 | 113.54 | 8.759 | 109.55 | 117.53 |
| Transverse diameter of pelvis | 40 | 113.40 | 149.83 | 131.32 | 8.730 | 128.53 | 134.11 |
| Greatest pelvic diameter | 36 | 97.98 | 141.00 | 125.10 | 9.224 | 121.98 | 128.22 |
| Bispinous breadth | 7 | 82.72 | 118.20 | 102.87 | 13.834 | 90.07 | 115.66 |
| Bi-tuberous diameter | 37 | 61.60 | 124.60 | 83.80 | 12.636 | 79.58 | 88.01 |
| Bi-tuberous width (cm) | 37 | 13.00 | 17.00 | 15.32 | 1.172 | 14.93 | 15.71 |
| Right ischial spine to sacral apex | 6 | 48.75 | 84.85 | 66.38 | 11.824 | 53.97 | 78.79 |
| Left ischial spine to sacral apex | 12 | 48.62 | 75.39 | 67.46 | 7.297 | 62.82 | 72.10 |
| Right ischial tuberosity to sacral apex | 21 | 82.23 | 118.00 | 105.60 | 9.356 | 101.34 | 109.86 |
| Left ischial tuberosity to sacral apex | 20 | 80.23 | 114.70 | 105.08 | 8.605 | 101.06 | 109.11 |
| Subpubic angle | 36 | 70.00 | 101.00 | 88.64 | 8.606 | 85.73 | 91.55 |
| Inlet circumference (cm) | 33 | 30.10 | 40.40 | 36.06 | 2.387 | 35.21 | 36.90 |
| Superior-anterior bi-iliac breadth of pelvis (cm) | 33 | 18.60 | 25.50 | 22.21 | 1.636 | 21.63 | 22.79 |
| Inferior-posterior bi-iliac breadth of pelvis | 27 | 47.54 | 96.52 | 75.77 | 10.110 | 71.77 | 79.77 |
| Bi-acetabular breadth | 38 | 113.30 | 148.00 | 130.71 | 8.176 | 128.02 | 133.40 |

**Key:**

| | | | |
|---|---|---|---|
| N | Number of values | Std.Dev. | Standard deviation |
| Min | Minimum | CI | Confidence interval of the mean |
| Max | Maximum | | |

**Table 7.1(x) Descriptive statistics for reconstructed pelvis measurements for male group**

| Variable | N | Min value | Max value | Mean | Std. Dev. | 95% CI | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| A-P superior diameter of pelvis | 30 | 82.90 | 109.56 | 98.62 | 6.506 | 96.19 | 101.05 |
| A-P inferior diameter of pelvis | 19 | 95.57 | 120.32 | 102.08 | 6.659 | 98.87 | 105.29 |
| Transverse diameter of pelvis | 30 | 107.50 | 137.99 | 122.98 | 7.388 | 120.23 | 125.74 |
| Greatest pelvic diameter | 29 | 108.02 | 134.45 | 119.29 | 7.483 | 116.45 | 122.14 |
| Bispinous breadth | 11 | 76.72 | 101.96 | 89.18 | 7.663 | 84.03 | 94.33 |
| Bi-tuberous diameter | 27 | 47.03 | 84.24 | 62.01 | 9.781 | 58.14 | 65.88 |
| Bi-tuberous width (cm) | 27 | 13.00 | 15.90 | 14.32 | 0.784 | 14.01 | 14.63 |
| Right ischial spine to sacral apex | 9 | 45.10 | 57.98 | 50.88 | 4.361 | 47.53 | 54.24 |
| Left ischial spine to sacral apex | 12 | 44.80 | 59.87 | 52.78 | 5.031 | 49.58 | 55.98 |
| Right ischial tuberosity to sacral apex | 19 | 84.23 | 112.75 | 95.85 | 6.851 | 92.55 | 99.15 |
| Left ischial tuberosity to sacral apex | 18 | 87.39 | 120.84 | 95.44 | 8.766 | 91.08 | 99.80 |
| Subpubic angle | 29 | 48.00 | 87.00 | 68.93 | 8.434 | 65.72 | 72.14 |
| Inlet circumference (cm) | 26 | 30.50 | 39.80 | 34.83 | 2.022 | 34.01 | 35.65 |
| Superior-anterior bi-iliac breadth of pelvis (cm) | 28 | 19.90 | 26.10 | 22.73 | 1.647 | 22.09 | 23.37 |
| Inferior-posterior bi-iliac breadth of pelvis | 26 | 36.74 | 82.39 | 65.11 | 9.090 | 61.44 | 68.78 |
| Bi-acetabular breadth | 31 | 108.40 | 133.00 | 120.98 | 5.878 | 118.82 | 123.13 |

**Key:**

| | | | |
|---|---|---|---|
| N | Number of values | Std.Dev. | Standard deviation |
| Min | Minimum | CI | Confidence interval of the mean |
| Max | Maximum | | |

These values were important, not only for screening for accuracy in a data file, but also for informing about the distribution of the variables and for reporting extent of skewness and kurtosis. In this way, they could later be employed in the exploration of any non-normally distributed variables to give an indication of why data should exhibit distributions other than symmetrical, i.e. with a positive skew distribution, the median would be less than the mean and vice-versa with a negative skew.

Parity status could only be recorded for some of the female individuals from Christ Church, Spitalfields. This data was obtained from consultation of volume two of Cox's 1989 research. Of the 42 females examined from this site, parity status was available for 31 individuals (73.8%) and, of these 23 (74.2%) had borne between one and fifteen children, as detailed in table 7.1(xxvi) below. No documented references to parity status in any of the females from the other three sites exist at the present time.

**Table 7.1(xxvi) Parity status recorded in the Christ Church, Spitalfields sample**

| Parity status | Number of females |
|---|---|
| 1 | 3 |
| 2 | 1 |
| 3 | 6 |
| 4 | 3 |
| 5 | 5 |
| 6 | 0 |
| 7 | 0 |
| 8 | 1 |
| 9 | 1 |
| 10 | 1 |
| 11 | 1 |
| 12 | 0 |
| 13 | 0 |
| 14 | 0 |
| 15 | 1 |
| **Total** | **23** |

Pelvic shape could only be recorded in 75 (72.8%) of the 103 individuals that comprised the sample. Of the 62 females and 41 males examined, a shape was ascertained for 42 (67.7%) and 33 (80.5%) individuals respectively. This information is summarized in Table 7.1(xxvii) below.

**Table 7.1(xxvii) Pelvic shape recorded in the sample**

| Sex | Pelvic shape | | | | Total |
|---|---|---|---|---|---|
| | Gynaecoid | Android | Anthropoid | Platypelloid | |
| Female | 38 | 4 | 0 | 0 | 42 |
| Male | 1 | 31 | 1 | 0 | 33 |
| Total | 39 | 35 | 1 | 0 | 75 |

## 7.2 ASSESSING NORMALITY OF DATA

It is important to assess the normality of data as it dictates which type of statistical tests may subsequently be utilized. Parametric statistics are more powerful (Pallant, 2001), but the data needs to be normally distributed in order to use them. The distribution of data in each of the continuous variables was tested for normality by employing the Kolmogorov-Smirnov test of normality. The Kolmogorov-Smirnov statistic, degrees of freedom and p value were recorded and the distribution described, with a p value of 0.05 or less being recognized as the level for rejection. Results of these analyses are presented first for the total sample and then for the female and male groups. For each of these three aforementioned categories, data is presented for variables in the following order: age at death, measurements for the sacrum, innominate, reconstructed pelvis and femora. Due to the volume of data generated, these tables are also presented in Volume 2, Appendix 5 in Tables 7.2(i) to 7.2(xiii).

Variables that were not normally distributed are summarized for the sacrum, innominate and reconstructed pelvis in Table 7.2(xiv) below.

In the total sample, out of the possible 93 continuous variables examined, eight (8.6%) were found to exhibit a distribution that was not normal. In the case of the constituent groups, 13 (14.0%) female and six (6.5%) male variables were similarly affected.

Five options were available for managing this non-normally distributed data and these are individually discussed below.

**Table 7.2(xiv) Non-normally distributed variables in the sacrum, innominate and reconstructed pelvis**

| Skeletal element | Sample/Group | Variable | Kolmogorov-Smirnov Statistic | Degrees of freedom | p value | Normal distribution |
|---|---|---|---|---|---|---|
| Sacrum | Female | Height of body of first sacral vertebra | .143 | 42 | .031 | ✖ |
| | | Spinal canal maximum A-P width | .250 | 4 | <.001 | ✖ |
| | | Anterior mid-ventral straight height of sacrum | .180 | 30 | .014 | ✖ |
| | Male | Spinal canal maximum A-P width | .220 | 4 | <.001 | ✖ |
| Innominate | Total | RIGHT Ischial acetabular height | .094 | 93 | .040 | ✖ |
| | | RIGHT Pubic symphysis superior width | .111 | 68 | .038 | ✖ |
| | | LEFT Symphyseal angle | .120 | 71 | .012 | ✖ |
| | | RIGHT Symphyseal angle | .121 | 74 | .009 | ✖ |
| | | RIGHT Acetabulosciatic breadth | .118 | 97 | .002 | ✖ |
| | | LEFT Auricular surface profile - b | .118 | 70 | .018 | ✖ |
| | | LEFT Sciatic notch height | .216 | 23 | .007 | ✖ |
| | Female | RIGHT Ischial acetabular height | .121 | 56 | .040 | ✖ |
| | | RIGHT Symphyseal angle | .145 | 44 | .020 | ✖ |
| | | RIGHT Acetabulosciatic breadth | .173 | 59 | <.001 | ✖ |
| | | LEFT Maximum width of obturator foramen | .143 | 52 | .010 | ✖ |
| | | LEFT Auricular surface profile - c | .153 | 55 | .003 | ✖ |
| | | LEFT Auricular surface profile - f | .144 | 39 | .041 | ✖ |
| | | RIGHT Sciatic notch width | .290 | 9 | .028 | ✖ |
| | | LEFT Sciatic notch height | .360 | 10 | .001 | ✖ |
| | Male | LEFT Acetabulum diameter | .169 | 37 | .009 | ✖ |
| | | LEFT Pubis length | .175 | 28 | .027 | ✖ |
| Pelvis | Total | Right ischial tuberosity to sacral apex | .152 | 40 | .020 | ✖ |
| | Female | Greatest pelvic diameter | .177 | 36 | .006 | ✖ |
| | | Right ischial tuberosity to sacral apex | .227 | 21 | .006 | ✖ |
| | Male | A-P inferior diameter of pelvis | .198 | 19 | .049 | ✖ |
| | | Right ischial tuberosity to sacral apex | .206 | 19 | .034 | ✖ |
| | | Inlet circumference (cm) | .179 | 26 | .032 | ✖ |

**a) Leaving data unchanged and applying parametric tests**

Variables that expressed a p (probability) value of 0.045 or above were left unchanged, as this value was deemed mathematically close enough to that of the selected 0.05 (95%) probability level. These variables were subsequently treated as normally distributed and subjected to parametric tests.

**b) Removal of outliers**

Outliers may occur due to a number of factors and these are discussed below. Each of these factors were borne in mind when outliers were examined and the specific points themselves were meticulously investigated to see if they should be excluded on any grounds.

i) *Incorrect transcription of data from recording forms into the excel spreadsheet (before import into the SPSS).*

Individual values were compared to the original written records to verify any mistakes at this stage. No such errors were identified.

ii) *Non-specification of any missing values.*

This factor was deemed irrelevant as SPSS automatically fills missing cells with a symbol.

iii) *Inclusion of data from a population other than that under study*

The sample was representative of an $18^{th}$-$19^{th}$ century, North-west European, middle-class, documented population. Individuals exhibiting prohibitive pathological change were screened for in advance of data collection. However, it may have been possible that some individuals may have expressed some form of pathology, not noted at that time, and they may have subsequently been incorporated into the sample. Burials exhibiting outliers were subsequently checked against documentation, to determine if any such conditions had existed. None were identified.

It was thus concluded that these outliers represented a legitimate part of the sample and that there was no justifiable grounds for removal of any of them.

### c) Transformation (normalization) of the data

Transformation of data is a rather controversial, if not salutary, process, and although it is advocated for managing outliers and failures of normality, linearity and homoscedasticity, it is not a universally recommended procedure (Tabachnick and Fidell, 2001). Proponents argue that statistical inferences become less and less robust as a distribution departs from normality (*ibid.*) and that transformation may improve this situation, by improving the normality and subsequent analysis of data. They also maintain that the impact of outliers may be reduced (*ibid.*). Opponents, however, contend that this practice only serves to increase the difficulty of interpretation (*ibid.*), through the mathematical modification of data using various complex formulas until the distribution takes on a more normal appearance (Pallant, 2001). While it may be straightforward to understand and interpret a particular measurement, the square root or logarithm of this measurement (when transformed) may be far more difficult to explain.

Furthermore, it has also been noted that even after transformation of data, results of analyses may not be particularly different from those obtained by employment of non-parametric methods. To test this theory, both techniques were carried out on three data sets that were investigated for differences in means of measurements between female and male groups in the innominate bone. The independent-samples t-test and Mann-Whitney U test were each undertaken on transformed and unchanged variables respectively. Both techniques generated the same, or very similar, probability values and allowed the same conclusions to be drawn, irrespective of the test employed.

### d) Deletion of a variable

In some cases it may be prudent to remove a variable completely. This may arise due to a totally inadequate number of values. Only one variable in the whole data set was treated in this manner and that was the sacral spinal canal maximum anterior-posterior width. Only eight values were recorded in total for the whole sample (four from the female group, and four from the male). This extremely small sample (and group) size precluded further effective statistical tests.

### e) Leaving data unchanged and applying non-parametric tests

One final option with non-normally distributed data, is to abandon the employment of parametric methods and to use non-parametric ones. These techniques tend, on the whole, to be less sensitive in identifying relationships and differences (Pallant, 2001), but they do eliminate any difficulties that may be encountered with interpreting transformed data.

In consequence, it was felt that non-normally distributed data, with the exception of those variables whose distributions were close enough to normal to be warranted as such, should be analysed by employing non-parametric techniques for the reasons given above.

## 7.3 TESTS OF DIFFERENCES BETWEEN TWO INDEPENDENT SAMPLES

As stated in Chapter 1, sexually dimorphic characteristics exist in the pelvis as a consequence of the female adaptation to accommodate parturition. It is postulated that this morphological modification will have a bearing on the development of degenerative joint disease in the vertebral column. In order to later test this theory, it is imperative to demonstrate that this sample exhibits significant dimorphic differences between the sexes in this aspect. This was undertaken by comparing the means/medians obtained from the female and male continuous data sets, and investigating whether these two groups came from the same population. The data sets that were examined consisted of two types; normally distributed values and variances that were approximately equal, and non-normally distributed data. In the case of the former, an independent-samples t-test was undertaken to compare the means. For the latter, the Mann-Whitney U test was employed to examine the medians.

The significant results of these tests are presented in seven tables. Tables 7.3(i) and 7.3(ii) present the parametric and non-parametric results for the sacral measurements respectively. Tables 7.3(iii) and 7.3(iv) detail the innominate results in the same manner. Reconstructed pelvis results are presented in Tables 7.3(v) and 7.3(vi) for parametric and non-parametric tests respectively. Table 7.3(vii) details results of femoral measurements.

The complete results (including the non-significant correlations) are presented in seven tables in Volume 2, Appendix 6. Tables 7.3(viii) and 7.3(ix) present the parametric and

**Table 7.3(i)** **Independent samples t-test comparing means of female and male for sacral measurements**

| Variable | t-test for equality of means* | | | Difference in means | Eta squared |
|---|---|---|---|---|---|
| | t | df | p value | | |
| Maximum superior sacral width | 2.245 | 95 | .027 | **Yes** | **0.0504 (5.04%)** |
| Maximum transverse diameter of S1 | -7.515 | 73 | <.001 | **Yes** | **0.4362 (43.62%)** |
| Maximum A-P diameter of S1 | -6.179 | 88 | <.001 | **Yes** | **0.3026 (30.26%)** |
| Mid-ventral curved length (cm) | -2.487 | 53 | .016 | **Yes** | **0.1045 (10.45%)** |
| Distance of lateral borders of processus articulares superiores | -2.905 | 89 | .005 | **Yes** | **0.0866 (8.66%)** |
| Combined transverse width of alae | 7.063 | 69 | <.001 | **Yes** | **0.4196 (41.96%)** |
| Maximum depth of curvature of sacrum | -2.774 | 46 | .008 | **Yes** | **0.1433 (14.33%)** |

**Key:**

* $H_0 \quad \bar{x}_d = 0 \quad H_1 \quad \bar{x}_d \neq 0$ (Two-tailed test)

**Table 7.3(ii)** **Mann-Whitney U test comparing medians of female and male for sacral measurements**

| Variable | Mann-Whitney U test** | | Difference in medians |
|---|---|---|---|
| | z | p value | |
| Height of body of 1st sacral vertebra | -3.164 | .002 | **Yes** |

**Key:**

** $H_0 \quad \theta_d = 0 \quad H_1 \quad \theta_d \neq 0$ (Two-tailed test)

**Table 7.3(iii) Independent samples t-test comparing means of female and male for innominate measurements**

| Variable | t-test for equality of means* | | | Difference in means | Eta squared |
|---|---|---|---|---|---|
| | t | df | p value | | |
| LEFT Maximum innominate length (cm) | -9.437 | 88 | <.001 | **Yes** | **0.5030 (50.30%)** |
| RIGHT Maximum innominate length (cm) | -10.492 | 91 | <.001 | **Yes** | **0.5474 (54.74%)** |
| LEFT Innominate breadth (cm) | -2.604 | 79 | .011 | **Yes** | **0.0790 (7.90%)** |
| RIGHT Innominate breadth (cm) | -2.837 | 79 | .006 | **Yes** | **0.0925 (9.25%)** |
| LEFT Iliac height | -7.331 | 94 | <.001 | **Yes** | **0.3638 (36.38%)** |
| RIGHT Iliac height | -7.463 | 94 | <.001 | **Yes** | **0.3721 (37.21%)** |
| RIGHT Acetabulum diameter | -9.951 | 93 | <.001 | **Yes** | **0.5157 (51.57)** |
| RIGHT Pubis length | .690 | 64 | .493 | **Yes** | **0.0074 (0.74%)** |
| LEFT Minimum height of inferior pubic ramus | -9.504 | 83 | <.001 | **Yes** | **0.5211 (52.11%)** |
| RIGHT Minimum height of inferior pubic ramus | -8.321 | 89 | <.001 | **Yes** | **0.4376 (43.76%)** |
| LEFT Oblique length of inferior pubic ramus | 5.701 | 74 | <.001 | **Yes** | **0.3052 (30.52%)** |
| RIGHT Oblique length of inferior pubic ramus | 4.590 | 78 | <.001 | **Yes** | **0.2127 (21.27%)** |
| LEFT Tubercolusymphyseal height | 3.071 | 44 | .004 | **Yes** | **0.1765 (17.65%)** |
| RIGHT Tubercolusymphyseal height | 3.430 | 41 | .001 | **Yes** | **0.2230 )22.30%)** |
| LEFT Pubic tubercle-acetabular length | -2.375 | 43 | .022 | **Yes** | **0.1160 (11.60%)** |
| RIGHT Pubic tubercle-acetabular length | -3.176 | 42 | .003 | **Yes** | **0.1937 (19.37%)** |
| LEFT Ischial acetabular height | -11.093 | 88 | <.001 | **Yes** | **0.5830 (58.30)** |

**Key:**

* $H_0 \ \bar{x}_d = 0 \quad H_1 \ \bar{x}_d \neq 0$ (Two-tailed test)

**Table 7.3(iii)** **Independent samples t-test comparing means of female and male for innominate measurements (contd.)**

| Variable | t-test for equality of means* | | | Difference in means | Eta squared |
|---|---|---|---|---|---|
| | t | df | p value | | |
| LEFT Pubo-sacroiliac diameter | 2.008† | 57.082 | .049 | **Yes** | **0.0660 (6.60%)** |
| LEFT Pubic symphysis depth | -5.477 | 64 | <.001 | **Yes** | **0.3191 (31.91%)** |
| RIGHT Pubic symphysis depth | -5.265 | 66 | <.001 | **Yes** | **0.2958 (29.58%)** |
| LEFT Pubic symphysis superior width | -6.300 | 64 | <.001 | **Yes** | **0.3828 (38.28%)** |
| RIGHT Pubic symphysis superior width | -6.218 | 66 | <.001 | **Yes** | **0.3694 (36.94%)** |
| LEFT Pubic symphysis inferior width | -6.366 | 64 | <.001 | **Yes** | **0.3877 (38.77%)** |
| RIGHT Pubic symphysis inferior width | -6.276 | 65 | <.001 | **Yes** | **0.3773 (37.73%)** |
| LEFT Maximum width of pubic symphysis | -6.303 | 67 | <.001 | **Yes** | **0.3722 (37.22%)** |
| RIGHT Maximum width of pubic symphysis | -6.430 | 67 | <.001 | **Yes** | **0.3816 (38.16%)** |
| LEFT Symphyseal angle | -5.451 | 69 | <.001 | **Yes** | **0.3010 (30.10%)** |
| LEFT Acetabulosciatic breadth | -7.451 | 95 | <.001 | **Yes** | **0.3688 (36.88%)** |
| LEFT Ischium length | -8.944 | 85 | <.001 | **Yes** | **0.4848 (48.48%)** |
| RIGHT Ischium length | -8.798 | 91 | <.001 | **Yes** | **0.4596 (45.96%)** |
| LEFT Maximum length of obturator foramen | -7.127 | 86 | <.001 | **Yes** | **0.3713 (37.13%)** |
| RIGHT Maximum length of obturator foramen | -6.689 | 88 | <.001 | **Yes** | **0.3371 (33.71%)** |

**Key:**

† Equal variances not assumed

* $H_0 \quad \bar{x}_d = 0 \quad H_1 \quad \bar{x}_d \neq 0$ (Two-tailed test)

**Table 7.3(iii)** **Independent samples t-test comparing means of female and male for innominate measurements (contd.)**

| Variable | t-test for equality of means* | | | Difference in means | Eta squared |
|---|---|---|---|---|---|
| | t | df | p value | | |
| LEFT Auricular surface profile - a | -4.347 | 67 | <.001 | Yes | 0.2200 (22.00%) |
| RIGHT Auricular surface profile - a | -4.804 | 69 | <.001 | Yes | 0.2506 (25.06%) |
| LEFT Auricular surface profile - b | -4.820 | 68 | <.001 | Yes | 0.2547 (25.47%) |
| RIGHT Auricular surface profile - b | -5.571 | 70 | <.001 | Yes | 0.3072 (30.72%) |
| LEFT Auricular surface profile - d | -3.914 | 67 | <.001 | Yes | 0.1861 (18.61%) |
| RIGHT Auricular surface profile - d | -3.995 | 65 | <.001 | Yes | 0.1971 (19.71%) |
| LEFT Sciatic notch width | 2.696 | 24 | .013 | Yes | 0.2325 (23.25%) |
| LEFT Sciatic notch position | -2.247 | 20 | .036 | Yes | 0.2016 (20.16%) |

**Key:**

* $H_0 \ \bar{x}_d = 0 \quad H_1 \ \bar{x}_d \neq 0$ (Two-tailed test)

**Table 7.3(iv)** **Mann-Whitney U test comparing medians of female and male for innominate measurements**

| Variable | Mann-Whitney U test** | | Difference in medians |
|---|---|---|---|
| | z | p value | |
| LEFT Acetabulum diameter | -6.727 | <.001 | Yes |
| RIGHT Ischial acetabular height | -7.810 | <.001 | Yes |
| RIGHT Symphyseal angle | -6.147 | <.001 | Yes |
| RIGHT Acetabulosciatic breadth | -5.136 | <.001 | Yes |

**Key:**

** $H_0 \ \theta_d = 0 \quad H_1 \ \theta_d \neq 0$ (Two-tailed test)

**Table 7.3(v)** **Independent samples t-test comparing means of female and male for reconstructed pelvis measurements**

| Variable | t-test for equality of means* | | | Difference in means | Eta squared |
|---|---|---|---|---|---|
| | t | df | p value | | |
| A-P superior diameter of pelvis | 2.823† | 54.580 | .007 | **Yes** | **0.1274 (12.74%)** |
| A-P inferior diameter of pelvis | 4.620 | 38 | <.001 | **Yes** | **0.3597 (35.97%)** |
| Transverse diameter of pelvis | 4.218 | 68 | <.001 | **Yes** | **0.2074 (20.74%)** |
| Bispinous breadth | 2.719 | 16 | .015 | **Yes** | **0.3160 (31.60%)** |
| Bi-tuberous diameter | 7.470 | 62 | <.001 | **Yes** | **0.4737 (47.37%)** |
| Bi-tuberous width (cm) | 4.092 | 61.614 | <.001 | **Yes** | **0.2137 (21.37%)** |
| Right ischial spine to sacral apex | 3.634 | 13 | .003 | **Yes** | **0.5039 (50.39%)** |
| Left ischial spine to sacral apex | 5.737 | 22 | <.001 | **Yes** | **0.5994 (59.94%)** |
| Left ischial tuberosity to sacral apex | 3.418 | 36 | .002 | **Yes** | **0.2450 (24.50%)** |
| Subpubic angle | 9.259 | 63 | <.001 | **Yes** | **0.5764 (57.64%)** |
| Inferior-posterior bi-iliac breadth of pelvis | 4.032 | 51 | <.001 | **Yes** | **0.2417 (24.17%)** |
| Bi-acetabular breadth | 5.555 | 67 | <.001 | **Yes** | **0.3153 (31.53%)** |

**Key:**

† Equal variances not assumed * $H_0 \ \bar{x}_d = 0 \quad H_1 \ \bar{x}_d \neq 0$ (Two-tailed test)

**Table 7.3(vi)** **Mann-Whitney U test comparing medians of female and male for reconstructed pelvis measurements**

| Variable | Mann-Whitney U test** | | Difference in medians |
|---|---|---|---|
| | z | p value | |
| Greatest pelvic diameter | -3.147 | .002 | **Yes** |
| Right ischial tuberosity to sacral apex | -3.047 | .002 | **Yes** |
| Inlet circumference (cm) | -2.184 | .029 | **Yes** |

**Key:**

** $H_0 \ \theta_d = 0 \quad H_1 \ \theta_d \neq 0$ (Two-tailed test)

**Table 7.3(vii)** **Independent samples t-test for comparing means of female and male femoral measurements**

| Variable | t-test for equality of means* | | | Difference in means | Eta squared |
|---|---|---|---|---|---|
| | t | df | p value | | |
| LEFT femur | -5.103 | 74 | <.001 | **Yes** | **0.2603 (26.03%)** |
| RIGHT femur | -5.019 | 94 | <.001 | **Yes** | **0.2113 (21.13%)** |

**Key:**

* $H_0 \ \bar{x}_d = 0 \quad H_1 \ \bar{x}_d \neq 0$ (Two-tailed test)

non-parametric results for the sacral measurements respectively. Tables 7.3(x) and 7.3(xi) detail the innominate results in the same manner. Reconstructed pelvis results are presented in Tables 7.3(xii) and 7.3(xiii) for parametric and non-parametric tests respectively. Table 7.3(xiv) details results of femoral measurements.

Effect size statistics were also employed to provide an indication of the magnitude of difference between the female and male groups. This was accomplished by calculating the eta squared value. If this value is then multiplied by 100, the resulting percentage provides an indication of how much variance in the variable under study is explained by sex. This procedure can only be performed with parametric tests and is included in all tables displaying results for the independent samples t-test.

In summary, this data shows that eight sacral, 23 innominate (20 paired, three from left side only) and 15 reconstructed pelvis measurements were found to exhibit significant differences in the means/medians of the female and male groups in this data set.

### 7.3.1 The sacrum

Given that there are sexually dimorphic differences between the two sexes, it is not surprising therefore to find that certain measurements demonstrate this variability with respect to size. Within the literature there is specific reference to disparities in size and shape of the sacrum and innominate. With respect to the former, the sacral width (also reflected in the combined width of alae) is larger in females (Byers, 2002; Fawcett, 1938; Krogman and Iscan, 1986; Schwartz, 1995). As a consequence of this, the width of the first sacral vertebra also varies and thus tends to be smaller in females (Fawcett, 1938). In males, the length of the sacrum is usually greater (Krogman and Iscan , 1986) and the maximum depth of curvature (a relative measure of the degree of intrusion into the pelvic cavity) more pronounced (Schwartz, 1995). These particular measurements are all represented in this data set, with significant differences being evident between the means/medians of the values collected (see Tables 7.1(iii) and 7.1(iv) in section 7.1 for means of these measurements and Tables 7.3(i) and 7.3(ii) here for details of statistical comparison of means/medians). Three additional sacral measurements were also identified: the anteroposterior diameter and height of the first sacral vertebra, and the distance between the lateral borders of the processus articulares superiores. In contrast to work published on the characteristics of the width of the first sacral vertebrae (Flander, 1978), there is none specifically referring to sex differences in the anteroposterior length or

indeed the height of this entity. Consequently it is not possible to ascertain whether the differences found in this data set reflect the general trend. The distance between the lateral borders of the processus articulares superiores was also a new measurement devised by the author and so it is not unsurprising to discover that there is no published literature available to compare the statistical results with. Future research utilizing this measurement may help to redress this.

Effect size statistics also need to be considered to give some idea of the magnitude between the female and male groups. The eta squared value provides a numerical scale for this purpose, but can be only calculated where parametric tests have been undertaken. Results shown in Table 7.3(i) for the sacral measurements discussed above reveal surprising facts. The maximum superior sacral width exhibits only 5.04% difference in the means ($p=0.05$) between the sexes, closely followed by that of the distance between the lateral borders of the processus articulares superiores (8.66%, $p=0.01$), the mid-ventral curved length (10.45%, $p=0.05$) and maximum depth of curvature (14.33%, $p=0.01$). The greatest magnitudes of difference were found with the maximum anteroposterior diameter of the first sacral vertebra (30.26%), combined transverse width of alae (41.96%) and the maximum transverse diameter of the first sacral vertebra (43.62%), where $p=0.01$. This suggests, that for this particular data set, these latter three measurements are revealing the greater sexually dimorphic differences in size.

### 7.3.2 The Innominate

The innominate has a wealth of landmarks that are employed for sexual differentiation and many of these rely on relative disparities in size between component lengths/areas. Twenty-three measurements were found to have significant differences between the sexes. Of these, 20 were from both left and right elements. The three that only involved one side were from the left aspect. These included the left sciatic notch width ($p=0.013$), left sciatic notch position ($p=0.036$) and the pubo-sacroiliac diameter ($p=0.049$). This latter measurement was deemed mathematically close enough to the selected 0.05 (95%) probability level for rejecting the hypothesis that there is a difference in the means between the two sexes, so it was ultimately excluded.

With the left pubo-sacroiliac diameter thus discounted, six of the remaining twenty-two measurements referred to previously in Tables 7.3(iii) and 7.3(iv) are included among

those documented as displaying sexual dimorphic characteristics in the literature. The iliac blade is larger, higher and more laterally flared in the male (Byers, 2002; Krogman and Iscan, 1986; Schwartz, 1995; Steele and Bramblett, 1988) and this in part reflects the overall height of the ilium. The greater sciatic notch is obtuse in females and contracted in males (Buikstra and Ubelaker, 1994; Krogman and Iscan, 1986; Schwartz, 1995; Steele and Bramblett, 1988; White and Folkens, 1991). Females tend to exhibit a smaller acetabular diameter (Schwartz, 1995; White and Folkens, 1991) and their ischiopubic rami are also more gracile, tapering towards the pubic symphysis (Schwartz, 1995). The obturator foramen has also been identified as an area displaying morphological differences between the sexes. This entity is small, triangular and fairly wide in females. In males it tends to be larger, oval and exhibiting a larger vertical axis (Byers, 2002; Krogman and Iscan, 1986; Schwartz, 1995). Some measurements are employed in the calculation of specific indices, with scores indicating a particular sex. Such measurements include the aforementioned width of the sciatic notch and diameter of the acetabulum, as well as the lengths of the pubis and ischium (Kelley, 1979a; Schulter-Ellis *et al.*, 1983; Washburn, 1948). These measurements are also substituted into discriminant function formulae for the purpose of sex determination (Taylor and DiBennardo, 1984). Of the six areas described above, effect size statistics have revealed variable magnitudes of difference between the means of the sexes. The greatest was that of the minimum height of inferior pubic ramus (left side 52.11%, right side 43.76%), closely followed by the acetabulum diameter (right side 51.57 %, left side non-parametrically assessed, so no eta squared value calculable). The ischium length displayed 48.48% variance between females and males on the left aspect and 45.96% on the right. Iliac height exhibited 36.38% on the left side and 37.21% on the right. Similar magnitudes of difference were found for the maximum length of the obturator foramen (left side 37.13%, right side 33.71%). All of the above magnitudes of differences in means were significant at $p=0.01$. The smallest magnitudes were revealed for the oblique length of inferior pubic ramus, at 30.52% for the left side and 21.27% for the right ($p=0.01$), and for the left sciatic notch width at 23.25% ($p=0.05$). From the size perspective, these values lend support for these areas being among those most sexually dimorphic within this sample.

In addition to the aforementioned regions of the innominate, fifteen (fourteen paired and one single-side) measurements produced statistically different means between the sexes. The former paired values included the maximum innominate length; innominate breadth; ischial-acetabular height; pubic tubercle-acetabular length; tuberculosymphyseal height; pubic symphysis depth, superior width, inferior width and maximum width; symphyseal

angle, acetabulosciatic breadth; and auricular surface profiles 'a', 'b' and 'd', as detailed in Tables 7.3(iii) and 7.3(iv). The left sciatic notch position represented the single-side dimension. Of these, the ischium length, ischial acetabular height and auricular surface components were all obtained by a refinement to standardized means of measurement as previously detailed in section 6.2.2 of chapter 6. As such, these resulting values cannot be *directly* compared to similar dimensions in the literature, despite the fact that they are related to a certain extent. Nevertheless, it would not be unreasonable to suggest that if the latter were considered sexually dimorphic, then the former would most likely also be. The ischium length produced magnitudes of difference between females and males of 48.48% for the left aspect and 45.96% for the right. Ischial acetabular heights were also significantly different, expressing 58.30% variance on the left side. The right aspect was non-parametrically tested and so no eta squared value could be used. The auricular surface measurement (see Figure 6.6 in Chapter 6) differences ranged between 19.71% and 30.72%, with the 'b' component displaying the greatest overall dissimilarities (left side 25.47%, right side 30.72%). The 'a' component was the next sexually dimorphic with values of 22.00% and 25.06% for the left and right aspects respectively. The dimension with the least significant difference was that of the 'd' component (left side 18.61%, right side 19.71%). Each of these five aforementioned measurements was found to be statistically significant ($p=0.01$). Ali and MacLaughlin's (1991) work measured the latter component on the auricular surface (see section 6.2.2v) and found that there was a statistically significant difference between the means of their female and male groups. Results for the t-test produced a t-value of 4.12 ($p= <0.001$).

For those measurements more directly comparable, the innominate length and breadth are considered sexually dimorphic, as the male possesses a taller and narrower structure (Byers, 2002). The left and right maximum innominate lengths produced significant statistical differences of 50.30% and 54.74% respectively. However, in this study, the innominate breadth exhibited less dimorphism, with a magnitude of 7.90% difference in the left side and 9.25% difference in the right. However, each of these measurements was statistically significant at ($p=0.01$), with the exception of the left innominate breadth ($p=0.011$). This value, however, is close enough to 0.01 to warrant being considered at that level also. Although the innominate breadth presents a relative gauge of the size of the pelvis running in an anteromedial-posterosuperior oblique plane, the contribution of this element to overall pelvic capacity is tempered by the contrasting degrees of flaring of the ilium and this may account for the smaller percentages found with this measurement.

The pubis length, or pubic ramus, has long been considered as a differentiating feature between females and males, with this feature being longer in the former (Schwartz, 1995; White and Folkens, 1991). In this data set, however, this measurement was not found to significantly differ between the sexes. For the right pubis length, which was assessed by parametric methods, the eta squared value reflects only a non-significant 0.74% shared variance overall (p=0.493). The left pubis was evaluated by non-parametric means and although there was still no significant difference, no eta squared value could be calculated. Despite this finding, two other measurements, namely the pubic tubercle acetabular length and tuberculosymphyseal height, could be considered as corollaries given their anatomical position. Certainly the pubic tubercle tends to be situated at a further distance from the pubic symphysis in females (Schwartz, 1995). The pubic tubercle acetabular length describes the distance from the pubic tubercle to the nearest point on the acetabulum and as this is a ratio of the overall pubic length, this measurement could be similar in both sexes, if the tuberculosymphyseal height was contributing to the greater overall length of the pubic ramus. In this data set, however, there is an appreciable and significant difference between the left and right tuberculosymphyseal heights (17.65% and 22.30% respectively, p=0.01) as well as the pubic tubercle acetabular lengths (11.60% on the left aspect, p=0.05, and 19.37% on the right, p=0.01). This is therefore suggesting that each of these measurements, in their own right, is sexually dimorphic within this sample.

The various measurements conducted on the pubic symphysis (depth, superior width, inferior width and maximum width) all produced statistically significant differences in the means of the female and male groups at the 0.01 probability level. The magnitude of variance between the means ranged from 29.58% for the right pubic symphysis depth to 38.77% for the left pubic symphysis inferior width. The acetabulosciatic breadth and sciatic notch position are two measurements that have not been evaluated elsewhere with respect to sexual variation. In this data set, they each revealed significant differences between the sexes. Only the left acetabulosciatic breadth was assessed parametrically and so only an eta squared value could be calculated for this side. It produced a magnitude of 36.88% variance (p=0.01). With regard to the sciatic notch position, only the left aspect was found to exhibit statistically different means with a 20.16% magnitude of variance (p=0.05). The right side showed a 13.31% difference, but this was not statistically significant (p=0.087).

The symphyseal angle, although not considered as a separate entity for sexual differentiation alone on the innominate bone, does contribute to the overall subpubic angle,

which was measured on the reconstructed pelvis. In this data set, it was found to exhibit statistically significant differences, with a magnitude of variation of 30.10% (p=0.01) on the left aspect. The right symphyseal angle was assessed by employment of non-parametric tests and so no eta squared value was calculable. This information was re-examined in light of the results obtained from analysis of the subpubic angle.

Of the variables previously discussed, it is worth noting that three (pubosacroiliac diameter, sciatic notch width and sciatic notch position), only displayed a significant difference in size between the sexes on the left aspect (see Table 7.3(x)), although for the left sciatic notch position, the p value is far closer to 0.05 than for the others. It is interesting to speculate as to a cause for this and given the propensity for one particular side to be affected with respect to these measurements, it may be that some form of dominance in the lower limb is being reflected in these values for this particular sample. With respect to modern populations, between 85-92% of individuals exhibit right side dominance in the hand (Annett and Kilshaw, 1983; Coren and Porac, 1972; McManus, 1991; Plato *et al.*, 1980). Studies in the literature on living subjects have confirmed a corresponding trait in the lower limb, which is usually referred to as 'footedness' or 'leggedness' (Gabbard *et al.*, 1991; Hart and Gabbard, 1998). As such, it may then be possible that such preferential use of the lower limb may result in the development of observable size differences between each side's soft and hard tissues. It is therefore possible that extra stresses may manifest, not only in the skeletal elements of the dominant side, but also across the associated joints and girdles and result in an increase in size/weight/volume of these associated elements. The important question here then, is whether the extra preferential stress on one side will increase the absolute amount of sexual dimorphism on that side and if so, on what side would the greater difference be expected? Given the well documented dominance of right handedness, then if this trait and 'leggedness' are concordant, it would be expected that the right measurements would be exhibiting a greater degree of dimorphism in the majority of individuals. Conversely, if upper and lower limb preferences oppose, then the left side would be favoured. In the sample used for this study, the three measurements exhibiting a side preference, all herald from the left – possibly suggesting opposing dominance in upper and lower limbs. However, it does not explain why only three (out of a possible 31-paired measurements), should be the only variables exhibiting such a significant difference between the sexes.

### 7.3.3 The reconstructed pelvis

Fifteen of the sixteen measurements taken from the reconstructed pelvis were found to have significantly different means/medians for the female and male groups (see Tables 7.3(v) and 7.3(vi). The only exception was the superior bi-iliac breadth of the pelvis, where 2.57% variance was noted, but was not statistically significant at the 0.05 probability level (p=0.217). Of the remaining dimensions, 13 (86.7%) were statistically significant at the 0.01 probability level. The only two that were significant at the 0.05 level were the bispinous breadth and the inlet circumference.

Classically, the female pelvis is described as being more capacious than the male counterpart and this is reflected, in one aspect, in the broader dimensions of the pelvic aperture (Byers, 2002; Schwartz, 1995; Steele and Bramblett, 1988; White and Folkens, 1991). It is not surprising therefore to find that the dimensions reported as expressing significant sexual dimorphism essentially reflect overall capacity in the pelvis, and that the means for these measurements are consistently greater in the females than the males (see Tables 7.1(ix) and 7.1(x)). What is interesting to explore is the magnitude of these differences. Within the current data set, the left and right ischial spines to sacral apex produced two of the highest orders of variation, at 59.94% and 50.39% respectively. The slightly lower value obtained in the latter case probably arises as a consequence of an overall smaller number of measurements taken for that dimension (13 as opposed to 22). Although this measurement does not constitute one of the standard boundaries defined for the pelvic outlet (see section 2.1), it is nevertheless comparable, as the ischial spine is positioned only a short distance posterolateral to the ischial tuberosity, and the sacral apex is similarly located only slightly posterosuperiorly to the coccyx. It would thus seem reasonable to expect that measurements for the ischial tuberosity to the sacral apex should demonstrate similar levels of sexual dimorphism. A magnitude of difference between the sexes was only calculable for the parametrically assessed left ischial tuberosity to sacral apex and produced a value of 24.50%. The subpubic angle also displayed a large significant difference in the means for the female and male groups, with 57.64% of the variance being explained by sex alone. This is not unsurprising as this area, which comprises the anterior aspect of the pelvic outlet, is greater in the female (Byers, 2002; Schwartz, 1995; Steele and Bramblett, 1988; White and Folkens, 1991).

The three next dimorphic dimensions, in decreasing order of magnitude, comprise the bi-tuberous diameter (47.37%), the anteroposterior inferior diameter of the pelvis (35.97%) and the bi-acetabular breadth (31.53%). All of these reflect the relative capaciousness of

the pelvic outlet. The bi-tuberous width, which arguably could be considered comparable to the bi-tuberous diameter (see sections 6.2.3f and 6.2.3g), however, only demonstrated a 21.37% difference in means between the sexes. The least dimorphic measurements within the data set included the inferior posterior bi-iliac breadth (24.17%), the transverse diameter (20.74%) and the anteroposterior superior diameter (12.74%) of the pelvis. The first of these three measurements was one formulated by the author and so no literature is extant on the sexually dimorphic value of this dimension. The latter two measurements, however, are regularly cited diameters of the pelvis and are employed in descriptions of overall pelvic shape. Each of these is larger in the female (means for the female and male groups presented in Tables 7.1(ix) and 7.1(x) respectively defend this assertion) and so it is expected that they will demonstrate a not unsubstantial difference in size between the sexes. It is surprising therefore that the magnitudes of these differences are among the smallest recorded for this data set. This discovery suggests that these particular measurements, although expressing statistically significant differences between females and males at the 0.01 probability level (as might be expected), are not as sexually dimorphic as other markers of pelvic capaciousness in this particular sample when considering the *magnitude* of the difference.

## 7.4 THE CHI-SQUARED TEST OF ASSOCIATION BETWEEN SEX AND PELVIC SHAPE

The chi-squared ( $\chi^2$ ) test was employed to investigate the relationship between sex and pelvic shape (i.e. categorical/nominal data). This test allows a comparison to be carried out between observed frequencies and those expected if the null hypothesis of no association holds. Preliminary analysis showed that the expected counts for two cells (numbers of females and males with an anthropoid configuration) were less than five (Table 7.4(i)). The chi-squared test needs to have all expected frequencies at values of five or greater, and so this category (anthropoid pelvic shape) was omitted from the analysis. Results of subsequent analysis, detailing calculation of $\chi^2$ value is presented in Table 7.4(ii).

The calculated value for $\chi^2$ is 55.56 and this is greater than the tabulated $\chi^2$ values of 3.84 (for 5%), 6.63 (for 1%) and 10.8 (for 0.01%) at one degree of freedom. This means that the null hypothesis can be rejected and the alternative one, stating that there is a

significant association between sex and pelvic shape, can be accepted. In reality this means that the gynaecoid pelvic shape and android configuration are significantly related to the female and male sex respectively. However, in order to examine the strength of this association, Cramer's V statistic was calculated. Results showed that V = 0.75 and this suggests that there is significant evidence of association. Yule's Q, another measure of association only applicable to 2x2 tables, was also calculated. A value of 0.99 was generated, and once again shows an extremely strong association.

These results correlate with reported frequencies of pelvic types in the literature. As early as 1933, Caldwell and Moloy observed that 50% of females demonstrated a gynaecoid configuration, with only 33% of white, and 16% of black, women being android. Over four decades later, Steer (1975) documented that 78.3% of women attending the Sloane Hospital for women in New York exhibited a pelvic gynaecoid shape, with the remaining 21.7% of patients being spread between the android, anthropoid and platypelloid forms.

**Table 7.4(i) Preliminary chi-squared contingency table**

| | | | Pelvic shape | | | Total |
|---|---|---|---|---|---|---|
| | | | Gynaecoid | Android | Anthropoid | |
| Sex | Female | Observed count | 38 | 4 | 0 | 42 |
| | | Expected Count | 21.8 | 19.6 | 0.6* | 42.0 |
| | | % within sex | 90.5% | 9.5% | .0% | 100% |
| | | % within pelvic shape | 97.4% | 11.4% | .0% | 56.0% |
| | | % of Total | 50.7% | 5.3% | .0% | 56.0% |
| | Male | Observed count | 1 | 31 | 1 | 33 |
| | | Expected Count | 17.2 | 15.4 | 0.4* | 33.0 |
| | | % within sex | 3.0% | 93.9% | 3.0% | 100% |
| | | % within pelvic shape | 2.6% | 88.6% | 100% | 44.0% |
| | | % of Total | 1.3% | 41.3% | 1.3% | 44.0% |
| Total | | Count | 39 | 35 | 1 | 75 |
| | | Expected Count | 39.0 | 35.0 | 1.0 | 75.0 |
| | | % within sex | 52.0% | 46.7% | 1.3% | 100% |
| | | % within pelvic shape | 100% | 100% | 100% | 100% |
| | | % of Total | 52.0% | 46.7% | 1.3% | 100% |

**Key:**

* Cells with expected counts less than five

**Table 7.4(ii) Chi-squared contingency table**

| | | | Pelvic shape | | Total |
|---|---|---|---|---|---|
| | | | Gynaecoid | Android | |
| Sex | Female | Observed count | 38 | 4 | 42 |
| | | Expected count | 22.14 | 19.86 | |
| | | O-E | 15.86 | -15.86 | |
| | | $(O-E)^2$ | 251.54 | 251.54 | |
| | | $(O-E)^2 / E$ | 11.36 | 12.67 | |
| | Male | Observed count | 1 | 31 | 32 |
| | | Expected Count | 16.86 | 15.14 | |
| | | O-E | -15.86 | 15.86 | |
| | | $(O-E)^2$ | 251.54 | 251.54 | |
| | | $(O-E)^2 / E$ | 14.92 | 16.61 | |
| | | Total | 39 | 35 | 74 |

**Key:**

O Observed count
E Expected count

Total for $(O-E)^2 / E$ (calculated $\chi^2$) = 55.56

## 7.5 TESTS OF CORRELATION BETWEEN AGE AND MEASUREMENTS AND CORRELATION BETWEEN INDIVIDUAL MEASUREMENTS

### 7.5.1 Correlation between age and individual measurements

The amount of correlation between the continuous variables of age and measurements in the sacrum, innominate and reconstructed pelvis were examined by employing Spearman's Rank Order Correlation. This was undertaken because if a relationship exists between age and size, then each of these in turn may also relate to the site, severity and distribution of degenerative disease observed in the spine.

The examination of correlation between individual measurements utilized both Spearman's Rank Order Correlation (for non-normally distributed variables) and Pearson's product moment correlation coefficient.

The measure of the strength of the relationship between the two variables is described in various ways, depending on authors, but it is generally accepted that values of 0.4 or –0.4 represent moderate correlations, while those of 0.5 or above (-0.5 or below) are deemed stronger. However, a more realistic assessment of the relationship can be determined by calculating the square of the correlation. This value ($r^2$) is termed the coefficient of determination and provides a means of demonstrating how much variance each of the two variables in question share, and consequently quantifying the value. If this value is then multiplied by 100, the percentage of variance is produced. For a correlation value of 0.4 therefore, the coefficient of determination is 0.16 (16%) and this means that 16% of the variance is shared. This shows that for a value, which is usually described as representing a moderate correlation, only a small proportion of variation in one variable is related to the other. This knowledge was utilized when examining results of the tests of correlation undertaken.

The measurements in the sacrum, innominate and reconstructed pelvis that produced statistically significant results at the 0.05 or 0.01 level are listed in Table 7.5.1(i) on the following pages. All of those in the sacrum (five) and innominate (29) produced positive correlations with age. In the reconstructed pelvis, three of the four measurements revealed negative correlations. These will be discussed further.

The complete results for all analyses undertaken are presented in Tables 7.5.1(ii) (sacrum), 7.5.1(iii) (innominate), 7.5.1(iv) (reconstructed pelvis) and 7.5.1(v) (femora). These are all presented in Volume 2, Appendix 7.

**Table 7.5.1(i)** **Measurements in the sacrum, innominate and reconstructed pelvis showing significant correlation with age**

| Skeletal area | Measurement | Sample | Correlation coefficient | Coefficient of determination (%) |
|---|---|---|---|---|
| Sacrum | Maximum superior sacral width | Female | .281* | 7.90% |
| | Maximum inferior sacral width | Total | .222* | 4.93% |
| | | Female | .310* | 9.61% |
| | Maximum anteroposterior diameter of S1 | Total | .309** | 9.55% |
| | | Female | .435** | 18.92% |
| | Distance of lateral borders of processes articulares superiores | Total | .216* | 4.67% |
| | | Female | .325* | 10.56% |
| | Maximum depth of curvature of sacrum | Female | .366* | 13.40% |
| Innominate | Right maximum innominate length | Female | .267* | 7.13% |
| | Right innominate breadth | Total | .247* | 6.10% |
| | | Female | .378** | 14.29% |
| | Left iliac height | Total | .343** | 11.76% |
| | | Female | .363** | 13.18% |
| | Right iliac height | Female | .389** | 15.13% |
| | Left acetabulum diameter | Total | .255* | 6.50% |
| | | Female | .428** | 18.32% |
| | Right acetabulum diameter | Total | .261* | 6.81% |
| | | Female | .396** | 15.68% |

* Correlation is significant at the 0.05 level (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed)

**Table 7.5.1(i) Measurements in the sacrum, innominate and reconstructed pelvis showing significant correlation with age (contd.)**

| Skeletal area | Measurement | Sample | Correlation coefficient | Coefficient of determination (%) |
|---|---|---|---|---|
| Innominate | Left pubis length | Total | .346** | 11.97% |
| | | Female | .344* | 11.83% |
| | Right pubis length | Total | .261* | 6.81% |
| | | Female | .363* | 13.18% |
| | Right minimum height of inferior pubic ramus | Female | .316* | 9.99% |
| | Left pubic acetabular length | Total | .351** | 12.32% |
| | | Female | .423* | 17.89% |
| | Right pubic acetabular length | Total | .244* | 5.95% |
| | | Female | .334* | 11.16 |
| | Left ischial acetabular height | Female | .289* | 8.35% |
| | Left ischial acetabular height | Female | .267* | 7.13% |
| | Left pubic symphysis depth | Male | .426* | 18.15% |
| | Right pubic symphysis depth | Total | .302* | 9.12% |
| | | Male | .463** | 21.44% |
| | Left ischial spine to symphysion | Total | .362* | 13.10% |
| | Right ischial spine to symphysion | Male | .683* | 46.65% |
| | Right symphyseal angle | Total | .233* | 5.43% |

* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

**Table 7.5.1(i) Measurements in the sacrum, innominate and reconstructed pelvis showing significant correlation with age (contd.)**

| Skeletal area | Measurement | Sample | Correlation coefficient | Coefficient of determination (%) |
|---|---|---|---|---|
| Innominate | Left acetabulosciatic breadth | Total | .455** | 20.70% |
| | | Female | .638** | 40.70% |
| | | Male | .419** | 17.56% |
| | Right acetabulosciatic breadth | Total | .478** | 22.85% |
| | | Female | .657** | 43.16% |
| | | Male | .398* | 15.84% |
| | Left maximum length of obturator foramen | Total | .243* | 5.90% |
| | | Female | .343* | 11.76% |
| | Left auricular surface profile - a | Total | .237* | 5.62% |
| | Right auricular surface profile - a | Total | .288* | 8.29% |
| | Left auricular surface profile - b | Total | .296* | 8.76% |
| | | Female | .465** | 21.62% |
| | Right auricular surface profile - b | Total | .302* | 9.12% |
| | | Female | .346* | 11.97% |
| | Right auricular surface profile - c | Total | .221* | 4.88% |
| | | Female | .275* | 7.56% |
| | Left auricular surface profile – d | Female | .346* | 11.97% |
| | Right auricular surface profile - d | Total | .373** | 13.91% |
| | | Female | .500** | 25.00% |
| | Left sciatic notch width | Female | .718** | 51.55% |
| Pelvis | Bituberous diameter | Male | -.497** | 24.70% |
| | Bituberous width | Female | .412* | 16.97% |
| | Subpubic angle | Male | -.628** | 39.44% |
| | Inferior posterior bi-iliac breadth of pelvis | Male | -.468* | 21.90% |

* Correlation is significant at the 0.05 level (2-tailed)

** Correlation is significant at the 0.01 level (2-tailed)

A significant correlation (irrespective of direction) between the age of the individual and a specific measurement can be interpreted in one of two ways. In the first instance, this may arise subsequent to compounding of continuous shifts in pelvic morphological structure during life. Such continual expansion (if positively correlated) or contraction (if negatively correlated) of the pelvis may be attributable to changing distributions and strengths of biomechanical loads with time. These will affect not only the microscopic remodelling processes of the living bone tissue, but also the macroscopic configurations of the sacro-iliac joint and pubic symphysis. In the second scenario, the significant correlation with age could be considered as an evolutionary adaptation, whereby a particular measurement, or set of measurements, is/are genetically pre-programmed to be either larger or smaller – whichever confers the greatest benefit. Differentiating between which of these two processes is responsible is a difficult task, although it could be argued that in the former situation, measurements most likely to exhibit significant positive or negative correlations with age, would be those most closely associated with and reflecting relative conformation of the sacro-iliac joint and pubic symphysis. In the latter situation, no specific measurement bias should be identified.

### *a) The sacrum*

In the sacrum, three of the significant measurements identified at the 0.05 probability level (maximum superior sacral width, maximum inferior sacral width and maximum depth of curvature of sacrum) are all indicators of the overall capaciousness of the pelvis. Significant, but small positive correlations were found for females, but not for males, although the maximum inferior sacral width did prove significant within the whole sample. As these particular measurements are not directly contributing to the joints within the pelvis, it can be postulated that they are naturally larger in those individuals of a greater age. This, in turn, suggests an evolutionary effect, whereby females exhibiting a genetic predilection for larger dimensions are naturally selected for. This makes biological sense as parturition is facilitated by a more obstetrically efficient (i.e. more capacious) pelvis. When the magnitudes of the correlations are explored, it can be seen that the maximum depth of curvature of the sacrum is the largest (13.40%), compared to the maximum superior and inferior sacral widths (7.90% and 9.61% respectively). This may be explained by the fact that the latter two measurements essentially contribute to the pelvic inlet, whereas the former one plays a major role in dictating the volume of the pelvic cavity itself. This is an important issue obstetrically, as during the process of parturition, the fetal

head has to not only pass into the pelvic cavity (via the inlet), but also rotate *within it* to facilitate birth.

The other two significant measurements comprised the maximum anteroposterior diameter of the first sacral vertebra and the distance of lateral borders of processes articulares superiores. Each of these was significant in both the total sample and female group – p=0.01 in the former, p=0.05 in the latter. These dimensions describe part of the lumbosacral area of the vertebral column, the angulation of which is directly proportional to increasing upright posture (section 3.3). Fetal head size in the human has necessitated an increase in the birth canal size and in order to accommodate this, sacral repositioning and a concomitant increase in the lumbosacral angulation has developed (Lovejoy *et al.*, 1973). The consequent exaggeration of the lordotic nature of the lumbar curvature produces an increase in biomechanical loading across this articular area. Such loads can be compensated for by dissipating them across an increased articular surface area. This is demonstrated, both at the cartilaginous (anteroposterior diameter of the first sacral vertebra) and synovial (distance of lateral borders of processes articulares superiores) intervertebral joints. Due to reproductive function, it would be expected that these biomechanical compensations would be more pronounced in the female, as compared to say the male or a combined group of individuals. Correlation coefficients for the female group are indeed larger than for the total sample, with magnitudes of effect being almost twice as much. In contrast, the male group was not statistically significant for either the anteroposterior diameter of the first sacral vertebra (p=0.517) or the distance of lateral borders of processes articulares superiors (p=0.636). These results thus support the theory of adaptive change within the lumbosacral region.

***b) The innominate***

The measurements that proved to be statistically correlated with age (at a probability level of at least 0.05) can essentially be considered within two groups. In the first are those that are considered as pelvic markers of bipedal adaptation. The second include those that reflect the overall capaciousness of the pelvis (when reconstructed). In the first group, the right maximum innominate length was found to be positively correlated with age in females only (p=0.045), although the magnitude of the correlation was small ($r_s$= .267). Measurements on the left aspect were not significant for either of the sexes, or the total sample. Generally speaking, the innominate length has shortened in the ilial region in response to bipedal demands. As such, it is surprising to discover that this length should

be positively correlated with age – in evolutionary terms, it should demonstrate a negative relationship. However, the correlation is small and only just significant at the 0.05 probability level with a coefficient of determination of 0.0713. In other words, only 7.13% of the maximum length is explained by age.

The right and left iliac heights were significantly positively correlated with age (p=0.01) in both females and the total sample (latter for left iliac height only). It is widely accepted that the ilia have shortened and widened to accommodate greater attachment areas for musculature concerned with development of hind limb power in habitual bipeds (Aiello and Dean, 1990; Campbell, 1998). Consequently, significant correlation coefficients of between .343 and .363 were recorded for these dimensions (p=0.01). As ilial length increased, the pelvic inlet was maintained by the concomitant widening of the sciatic notch, and so it is no surprise to find that this particular measurement also shows a significant positive correlation with age in females ($r_s$= .718, p=0.006). However, this relationship was only evident on the left side. The sacral position within the pelvis is influenced by the ilial angulation and as a consequence assumes a more horizontal position. This configuration increases weight transmission acting across the sacro-iliac joint and thus necessitates an enlargement in its surface area to dissipate these loads. As such, it would thus make evolutionary sense to select for larger dimensions in this region of articulation. Of the six measurements obtained from the auricular surface (see section 6.2.2v), four describe the greater proportions of the superior ('d') and inferior ('a', 'b' and 'e') limbs. Three of these ('a', 'b' and 'd') were found to be significantly correlated with age in either the total sample or female group. The maximum length ('a') of the left and right sides produced significant correlations of .237 and .288 respectively (p=0.05) in the total sample alone. The arcuate length ('b') revealed significant correlations in both the total sample and female groups, with the females exhibiting larger correlation coefficients (.465 for the left aspect (p=0.01) and .346 for the right (p=0.05), compared to .296 (p=0.05) and .302 (p=0.05) respectively). The maximum width ('d') produced significant correlations with age in the female group ($r_s$= .346, p=0.05 for the left aspect, $r_s$= .500, p=0.01 for the right aspect). In addition, this measurement was also significant ($r_s$= .373, p=0.01) for the right element of the total sample. The dimension designated by the letter 'c', which described a shorter proportion of the superior limb, was the final auricular measurement yielding a significant correlation for the total sample ($r_s$= .221, p=0.05) and female group ($r_s$= .275, p=0.05), but only on the right aspect. The remaining two measurements ('e' and 'f') did not produce statistically significant correlations. This may be explained by the fact that these dimensions do not describe the longest contact lengths across the area of the sacro-iliac joint (see Figure 6.6). Therefore these will not be

involved in direct weight transmission either across the whole of their length (as with 'e') or if they are, are very short in proportion (as with 'f'). This suggestion is further supported by the fact that of the four measurements reported as expressing significant correlations with age, the shortest one ('c'), does in fact show the smallest significant correlation of those reported. As adaptation of the pelvis to bipedal posture is more pronounced in the female as a result of reproductive function, it naturally follows that surface area of the auricular articulation will need to increase further to accommodate and dissipate the increased biomechanical loads acting across this region. It is therefore not surprising that it is within this sex group that the most significant correlations are found.

The acetabulum has also undergone change in order to facilitate a closer approximation between the sacro-iliac joint and the hip. This has resulted in an enlargement of this area (coupled to that of the femoral head). Significant positive correlations were found in the acetabular diameter in both the total sample ($r_s$= .255 and .261 for the left and right sides respectively, p=0.05) and the female group ($r_s$= .428 and .396 for the left and right sides respectively, p=0.01). These values reflect the fact that the female pelvis, more than the male, has to undergo greater adaptive change to not only preserve the best possible bipedal posture, but also to maintain the most obstetrically efficient pelvis.

Measures of overall pelvic capaciousness were identified by seven parameters: the innominate breadth, pubis length, pubic-acetabular length, pubic symphysis depth, ischial spine to symphysion, maximum length of the obturator foramen and symphyseal angle. All correlations were positive in nature and with the exception of the pubic symphysis depth, ischial spine to symphysion and symphyseal angle, were significant in both the total sample and female groups. In these cases, reported female correlation coefficients were greater than those for the total sample (where the overall effect is diluted). Correlation coefficients within the female group were small to moderate, with that of the right innominate breadth ($r_s$= .378, p=0.01) being the most significant. Reported correlation coefficients for the left and right pubis lengths, pubic acetabular lengths and left maximum length of the obturator foramen were all significant at the 0.05 probability level and ranged from .334 to .423. These results suggest that a greater (and more obstetrically efficient) pelvic capacity is being selected for in females - a process that makes evolutionary sense.

In the ischium, the body and tuberosities have reduced in length and width and migrated further apart – a configuration which has resulted from altered hamstring muscle function. In the most bipedally efficient organism, these dimensions would remain small and

contracted and correlations with age would be expected to show negative values. Two ischial dimensions recorded significant correlations. These included the ischial acetabular height and acetabulosciatic breadth. The former produced positive correlations in the female group only (p=0.05), whereas the latter expressed positive correlations for the total sample plus female and male groups (p=0.01). The right value for males was quoted with p=0.013, but this is mathematically close enough to the 0.01 level to be considered as such. This is surprising, as it is suggesting that older individuals are more likely to exhibit larger ischial dimensions, a trait that seems to contradict evolutionary development. In the female group, this could be argued against on the grounds of obstetric efficiency, where reproductive demands have necessarily tempered the efficiency of bipedalism. However, within the male group, this argument cannot be sustained and so either suggests that ischial dimensions are increasing with age as a result of continual shifts in pelvic morphological structure during life, or simply reflects the fact that male pelvic structure within this sample may be of a larger magnitude overall, but still bipedally efficient. This latter statement is further supported by the positive correlations found in the male group in the pubic symphysis depth.

Of all of the reported measurements above, those exhibiting the greatest degree of positive correlation with age (p=0.01) were the left and right acetabulosciatic breadths (in the total sample plus female and male groups) and left sciatic notch width in the female group.

### *c) The reconstructed pelvis*

Within the reconstructed pelvis, there are a number of measurements that provide an indication of capaciousness of this structure. It is very surprising then, that only four dimensions have expressed statistically significant correlations with age at the 0.05 probability level or above and these are by no means the most obvious. They include the bituberous width and diameter, the subpubic angle and the inferior posterior bi-iliac breadth of the pelvis. The last three of these were only significant in the male group and expressed moderate negative correlations with age for the bituberous diameter ($r_s$ =-.497, p=0.01), subpubic angle ($r_s$ =-.628, p=0.01) and inferior posterior bi-iliac breadth of the pelvis ($r_s$ =-.468, p=0.05). These negative correlations suggest that smaller values for these measurements are being selected for in the male. This process makes evolutionary sense from the bipedal aspect, where the most efficient pelvic configurations are those that remain as small and compact as possible. Only the bituberous width was positively and moderately significant in the female group ($r_s$ =.412, p=0.05). Once again, as with the

ischial results discussed above, this is a surprising result as bipedally efficient pelves retain small and contracted dimensions within this area. In the female, however, this positive correlation may simply reflect the selective preference for obstetric capaciousness over bipedal efficiency. It is quite possible, however, that these results may possibly be an artefact of the weaknesses associated with dry bone reconstruction of the pelvis, as expressed earlier in section 6.2.3.

### 7.5.2 Correlation between individual measurements

Individual measurements taken of the sacrum, innominate and reconstructed pelvis were then correlated against one another. Pearson's product moment correlation coefficient was employed for variables that were both normally distributed. Spearman's Rank Order Correlation test was used in cases where at least one of the variables did not exhibit a normal distribution.

The significance of the r value is strongly affected by the size of the sample/group, so that where numbers are less than 30, there may actually be moderate correlations, which because of the small size, do not reach statistical significance at the $p < 0.05$ level. Conversely, where there are larger samples (of 100 or above), smaller correlations may become more statistically significant. In nearly all of the cases examined here, sizes have been less than 100, and so the latter situation is less of a concern. Although some sizes have been less than 30, the majority have tended to fall between 50 and 90.

It was therefore considered prudent to set the Pearson's (r) or Spearman's ($r_s$) correlation at 0.75 or above. The coefficient of determination was an important consideration in this aspect. As detailed above, the square of the Pearson correlation gives an indication of the amount of variance shared, that is to say what proportion of one variable is related to the other. Again, as noted above, correlation values of 0.4, which are traditionally taken as representing moderate degrees of relationship, in fact only exhibit a 16% shared variance. Given that many of the measurements taken in the sacrum, innominate and reconstructed pelvis are essentially ratios of other measurements in the same skeletal element, it is not unreasonable therefore to suggest that many such measurements will show correlations of 0.4 or above. This hypothesis was tested by selecting a total of eight measurement combinations which the author felt reflected such ratio relationships - three in the sacrum, three in the innominate (left values only) and two in the reconstructed pelvis. All of these

measurements were normally distributed and so Pearson's product moment correlation coefficient test was undertaken on all of them. Results of these analyses are presented in Table 7.5.2(i).

Following on from this initial test, each individual measurement was compared with all others and correlations of 0.700 and above were selected for. Where a significant result has been found for a left or right measurement in the innominate, the corresponding measurement on the opposite side has also been included for comparative reasons. Results of these analyses are presented in Table 7.5.2(ii) in Volume 2, Appendix 8. These results were borne in mind when later exploration of the relationships between specific measurements (single and paired) and the presence of degenerative disease in the vertebral column were undertaken. Evaluation of the effect of size of the pelvis and it constituent parts in the site, severity and distribution of spinal joint disease needed to be conducted in an efficient manner. By highlighting those measurements that were significantly related to one another at the 0.05 probability level or less, it was hoped that any pairings could effectively be compared and contrasted with respect to the different degenerative traits examined in section 7.8.

### 7.5.2(i) Test of association between selected measurements in the sacrum, innominate and reconstructed pelvis by sample/group (Pearson's product moment correlation coefficient)

| Skeletal area | Variable 1 | Variable 2 | Sample/group | Pearson's product moment correlation coefficient | | | Coefficient of determination |
|---|---|---|---|---|---|---|---|
| | | | | r | n | p value | |
| Sacrum | Maximum superior sacral width | Combined transverse width of alae | Total | .751** | 71 | <.001 | 0.5640 (56.40%) |
| | | | Female | .836** | 42 | <.001 | 0.6989 (69.89%) |
| | | | Male | .567** | 29 | .001 | 0.3215 (32.15%) |
| | Maximum transverse diameter of S1 | Combined transverse width of alae | Total | -.695** | 71 | <.001 | 0.4830 (48.30%) |
| | | | Female | -.472** | 42 | .002 | 0.2228 (22.28%) |
| | | | Male | -.528** | 29 | .003 | 0.2788 (27.88%) |
| | Distance of medial borders of processus articulares superiores | Distance of lateral borders of processus articulares superiores | Total | .571** | 88 | <.001 | 0.3260 (32.60%) |
| | | | Female | .519** | 50 | <.001 | 0.2694 (26.94%) |
| | | | Male | .631** | 38 | <.001 | 0.3982 (39.82%) |
| Innominate | Left maximum innominate length | Left iliac height | Total | .904** | 87 | <.001 | 0.8172 (81.72%) |
| | | | Female | .856** | 53 | <.001 | 0.7327 (73.27%) |
| | | | Male | .867** | 34 | <.001 | 0.7517 (75.17%) |
| | | Left ischial acetabular height | Total | .912** | 87 | <.001 | 0.8317 (83.17%) |
| | | | Female | .781** | 53 | <.001 | 0.6100 (61.00%) |
| | | | Male | .859** | 34 | <.001 | 0.7379 (73.79%) |
| | | Left ischium length | Total | .866** | 84 | <.001 | 0.7500 (75.00%) |
| | | | Female | .714** | 52 | <.001 | 0.5098 (50.98%) |
| | | | Male | .764** | 32 | <.001 | 0.5837 (58.37%) |
| Pelvis | Bispinous breadth | Left ischial spine To sacral apex | Total | .939** | 14 | <.001 | 0.8817 (88.17%) |
| | | | Female | .958** | 6 | .003 | 0.9178 (91.78%) |
| | | | Male | .744** | 8 | .034 | 0.5535 (55.35%) |
| | Transverse diameter Of pelvis | Superior bi-iliac Breadth of pelvis | Total | .537** | 59 | <.001 | 0.2884 (28.84%) |
| | | | Female | .697** | 32 | <.001 | 0.4858 (48.58%) |
| | | | Male | .727** | 27 | <.001 | 0.5285 (52.85%) |

**Key:**

** Correlation is significant at the 0.01 level (2-tailed)

## 7.6 EXAMINATION OF ABSOLUTE DIFFERENCES IN PAIRED MEASUREMENTS IN THE INNOMINATE AND RECONSTRUCTED PELVIS

Absolute differences between measurements taken on the right and left innominate bones were calculated and presented as 31 new variables. Two measurements in the reconstructed pelvis (ischial spine to sacral apex and ischial tuberosity to sacral apex) could also be calculated in a similar manner. The distribution of data in these 33 new variables was then tested for normality by employing the Kolmogorov-Smirnov test of normality (and for the same reason as that given in section 7.2). The Kolmogorov-Smirnov statistic, degrees of freedom and p value were recorded and the distribution described for the female and male groups, with a p value of 0.05 0r less being recognized as the level for rejection. Results of these analyses are presented in Table 7.6(i) for the innominate measurements and Table 7.6(ii) for the reconstructed pelvis measurements in Volume 2, Appendix 9.

Variables that were not normally distributed are summarized for the innominate and reconstructed pelvis in table 7.6(iii) below.

The means and medians (from normally and non-normally distributed variables respectively), of the female and male data sets generated in this way, were compared to each other to investigate whether these two groups came from the same population. In the case of the former, an independent-samples t-test was undertaken to compare the means. For the latter, the Mann-Whitney U test was employed to examine the medians. Results of these tests are presented for the innominate measurements in Tables 7.6(iv) (parametric) and 7.6(v) (non-parametric), and for the reconstructed pelvic measurements in Table 7.6(vi) in Volume 2, Appendix 9.

Effect size statistics were also employed to provide an indication of the magnitude of difference between the female and male groups. This was accomplished by calculating the eta squared value. If this value is then multiplied by 100, the resulting percentage provides an indication of how much variance in the variable under study is explained by sex. None of the variables examined in this way expressed significant differences in either the means or medians between the female and male groups, implying that asymmetry, when present, affects females and males to the same extent. This is interesting, as it would seem reasonable to suggest that in the more capacious female pelvis (where biomechanical.

**Table 7.6(iii) Non-normally distributed variables in the innominate and reconstructed pelvis**

| Variable (absolute difference between left and right values) | Group | Kolmogorov-Smirnov Statistic | Degrees of freedom | p value | Normal distribution |
|---|---|---|---|---|---|
| Maximum innominate length | Female | .286 | 53 | <0.001 | ✖ |
| | Male | .248 | 32 | <0.001 | ✖ |
| Innominate breadth | Female | .213 | 40 | <0.001 | ✖ |
| | Male | .231 | 34 | <0.001 | ✖ |
| Iliac height | Female | .124 | 55 | .035 | ✖ |
| Pubis length | Male | .191 | 25 | .020 | ✖ |
| Minimum height of inferior pubic ramus | Female | .257 | 47 | <0.001 | ✖ |
| | Male | .161 | 33 | .029 | ✖ |
| Oblique length of inferior pubic ramus | Female | .243 | 41 | <0.001 | ✖ |
| | Male | .174 | 31 | .017 | ✖ |
| Tubercolusymphyseal height | Male | .237 | 21 | .003 | ✖ |
| Pubic tubercle- acetabular length | Female | .405 | 18 | <0.001 | ✖ |
| Pubic symphysis depth | Male | .179 | 32 | .010 | ✖ |
| | Female | .183 | 27 | .020 | ✖ |
| Pubic symphysis superior width | Male | .167 | 32 | .023 | ✖ |
| Maximum width of pubic symphysis | Male | .165 | 34 | .020 | ✖ |
| | Female | .360 | 27 | <0.001 | ✖ |
| Symphyseal angle | Female | .155 | 39 | .020 | ✖ |
| Acetabulosciatic breadth | Female | .387 | 59 | <0.001 | ✖ |
| Ischium length | Male | .180 | 32 | .010 | ✖ |
| Maximum length of obturator foramen | Female | .309 | 51 | <0.001 | ✖ |
| | Male | .224 | 31 | <0.001 | ✖ |
| Maximum width of obturator foramen | Female | .128 | 49 | .043 | ✖ |
| Auricular surface profile – b | Female | .169 | 30 | .029 | ✖ |
| | Male | .197 | 30 | .004 | ✖ |
| Auricular surface profile – c | Female | .146 | 52 | .007 | ✖ |
| Auricular surface profile – e | Male | .173 | 29 | .026 | ✖ |
| Sciatic notch height | Female | .440 | 5 | .002 | ✖ |
| Ischial tuberosity to sacral apex | Female | .287 | 18 | <0.001 | ✖ |

forces experienced within the structure are greater), any asymmetrical tendencies would be amplified to a greater extent. However, this is not the case, possibly intimating that some form of corrective process operates to prevent such biomechanical destabilization from occurring.

Although the human body appears to consist of two equal parts, divided by the median sagittal plane, this configuration is by no means perfectly symmetrical. Degrees of asymmetry are seen to exist in otherwise commensurate structures and this imbalance poses interesting questions. For example, do these possibly reflect preferential use in the lower limb? Perhaps a more relevant question (in as far as this research is concerned) is at what magnitude of difference between paired skeletal structures does the normal physiological functioning of that unit become compromised, if at all? Furthermore, is the asymmetrical nature of the skeletal structure compounded by factors such as biomechanical loading and longevity, or will relatively minor imbalances be corrected for? In order to test these hypotheses, the amount of correlation between age and the absolute differences between the right and left measurements was examined using Spearman's Rank Order Correlation. Only four measurements yielded significant results at the 0.05 probability level or above and these are summarized in Table 7.6(vii) below. All results for these analyses on the innominate and reconstructed pelvis measurements are presented in Tables 7.6(viii) and 7.6(i) respectively, in Volume 2, Appendix 9.

**Table 7.6(vii) Absolute differences in paired measurements in the innominate and reconstructed pelvis showing significant correlation with age**

| Skeletal area | Measurement | Sample | Correlation coefficient | Coefficient of determination (%) |
|---|---|---|---|---|
| Innominate | Iliac height | Male | .341* | 11.63% |
| | Ischium length | Total | -.292** | 8.53% |
| | | Female | -.318* | 10.11% |
| | Auricular surface profile - a | Male | .386* | 14.90% |
| Pelvis | Ischial spine to sacral apex | Total | .543* | 29.48% |

**Key:**

* Correlation is significant at the 0.05 level (2-tailed)
** Correlation is significant at the 0.01 level (2-tailed)

As Table 7.6(viii) clearly demonstrates, statistically significant positive and negative correlations were found. In the case of the iliac height, auricular surface profile 'a' and the ischial spine to sacral apex, correlation coefficients were moderately positive (p=0.05), indicating that an increase in the relative measure of asymmetry was associated with increasing age. These findings were applicable to the male group for the first two measurements and for the total sample for the third. If one assumes that nature abhors any degree of disproportionation and will attempt to redress the balance, then correlations, by definition, should be negative in nature. This is certainly not the case with these three measurements. It could be argued that the iliac height and ischial spine to sacral apex do not have any direct bearing on weight transfer in the pelvis and so any incongruities will impact less upon the efficiency of, say, bipedal locomotion, thereby reducing the need for any non-advantage conferring 'corrections'. That said, the ischial spine to sacral apex does reflect, if somewhat approximately, the relative size of pelvic outlet. Any asymmetry on the part of this dimension could technically compromise obstetric efficiency in the female and so it would be expected that correlations with age would be negative once again, but they are clearly not. In this data set, the correlation coefficient for the female group was .638 (p=0.173). The only measurement that did prove negatively correlated was that of ischium length in both the total sample and the female group. As detailed previously in section 7.5.1b, the ischial region of the innominate has effectively widened and shortened in response to the demands of a bipedal posture. Here it would seem that smaller discrepancies in left and right measurements were being selected for, which seems to make biological and evolutionary sense. However, it cannot be explained as to why other important dimensions of the innominate (such as the pubic length, pubic acetabular length, pubic tubercle acetabular length and pubo-sacroiliac diameter) are not producing statistically significant negative correlations with age, when discrepancies in their size could potentially destabilize the overall integrity of the pelvis as a weight bearing and an obstetric structure. Perhaps the magnitude of difference in the left and right measurements is too small (range 0.13-6.06 mm) overall to warrant any real biological destabilization in this particular data set. If this is the case, then it would be interesting to see at what magnitude differences have effects.

## 7.7 TESTS OF ASSOCIATION BETWEEN PELVIC SHAPE AND DEGENERATIVE CHANGE IN THE VERTEBRAL COLUMN

Three different pelvic shapes were identified within the sample (see table 7.1(xxvii) in section 7.1). The chi-squared ($\chi^2$) test was employed to investigate the relationship between this variable and vertebral degenerative disease. This test allows a comparison to be carried out between observed frequencies and those expected if the null hypothesis of no association holds. Previous analysis undertaken in section 7.4 showed that the expected counts for two cells (numbers of females and males with an anthropoid configuration) were less than five (Table 7.4(i)). The chi-squared test needs to have all expected frequencies at values of five or greater (Glantz, 1987; Pallant, 2001; Swinscow, 1983), and so this particular category (anthropoid pelvic shape) was omitted from the analysis.

Results of subsequent analyses are presented in section 7.7a of Appendix CD2 on the accompanying CD-ROM. The arrangement of data files contained in Appendix CD2 is specified in Figure 7.7 below and instructions for accessing this media are presented in Volume 2, Appendix 10.

**Appendix CD2**

| | |
|---|---|
| Section 7.7a | Chi-squared tests between pelvic shape and degenerative disease in the vertebral column |
| Section 7.7b | Chi-squared tests between pelvic shape and recoded degenerative disease in the vertebral column |

**Figure 7.7 Structure of folders in Appendix CD2 on the accompanying CD-ROM**

Of the 1296 individual chi-squared tests undertaken, 1289 (99.5%) had to be disregarded due to the fact that they either a) violated the assumption that at least 80% of the cells therein had frequencies of five or more, or b) that they only presented one category for degenerative change grading and therefore acted as a constant and allowed no statistic to be generated. Of the remaining seven (0.5%) results that were acceptable, none of them produced statistically significant results.

Utilization of this test therefore did not show any significant evidence of an association between pelvic shape and the magnitude of degenerative disease. Given the overwhelming number of tests that had to be disregarded, it is possible to omit cells with low expected cell counts or even to combine categories in order to deal with the problem and possibly secure more promising results. Excluding any of the grading categories for the three types of degenerative disease examined for was not considered an option, as such data clearly represents a legitimate part of the sample and there are no justifiable grounds for such removal. An alternative approach would involve combining categories. Although this step could no longer examine for any relationship between pelvic shape and the *magnitude* of the degenerative change observed, it could explore the association with the presence/absence of disease alone.

Results of the analyses subsequently computed for combined categories are presented in section 7.7b of Appendix CD2. Of the 1296 individual chi-squared tests undertaken here, 988 (76.2%) had to be disregarded as before, as they either a) violated the assumption that at least 80% of the cells therein had frequencies of five or more, or b) that they only presented one category for degenerative change grading and therefore acted as a constant and allowed no statistic to be generated. Of the remaining 308 (23.8%) results that were acceptable, 297 (22.9%) of these produced non-statistically significant results. Only 11 (0.9%) results were statistically significant and they are summarized in Table 7.7(i). Technically speaking, one could argue that the result generated for the extent of osteophytes on the superior body surface of C3 is not statistically significant at the 0.05 level, but the p value was deemed close enough to warrant its inclusion in this instance.

It had been hoped that combining categories would have produced more favourable results. However, this has not proved to be the case. At the 95% confidence limit, one would expect 5% of the results to be statistically significant by chance alone. That means that in this particular case (where 1296 tests were computed), at least 65 should have met this requirement - a far greater number than the 11 that actually did. As a consequence, these particular results cannot be deemed to have any statistical merit and must be disregarded. This outcome is obviously disappointing and the low cell counts responsible for the unsuccessful chi-squared tests have arisen as an unavoidable consequence of insufficient data collection. As previously noted in section 6.1, the latter transpired due to post mortem erosion of, and/or soft tissue adherement to, areas under examination for evidence of degenerative change.

**Table 7.7(i)** **Results of significant tests of correlation between pelvic shape and the presence/absence of degenerative disease (Chi-squared test)**

| Vertebral area | Vertebral level | Degenerative change | Chi-squared test | | Degenerative change | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Sample tested | | Gynaecoid shape | | Android shape | |
| | | | | | Present (%) | Absent (%) | Present (%) | Absent (%) | Present (%) | Absent (%) |
| Superior body surface | C3 | Osteophytes extent | $\chi^2$ | 3.813 | 79.1 | 20.9 | 10.8 | 89.2 | 33.3 | 66.7 |
| | | | p | 0.051 | | | | | | |
| | L3 | Osteophytes severity | $\chi^2$ | 4.662 | 58.9 | 41.1 | 28.2 | 71.8 | 55.9 | 44.1 |
| | | | p | 0.031 | | | | | | |
| | | Osteophytes extent | $\chi^2$ | 4.662 | 58.9 | 41.1 | 28.2 | 71.8 | 55.9 | 44.1 |
| | | | p | 0.031 | | | | | | |
| Inferior body surface | C3 | Osteophytes severity | $\chi^2$ | 5.831 | 45.5 | 54.5 | 30.6 | 69.4 | 63.3 | 36.7 |
| | | | p | 0.016 | | | | | | |
| | | Osteophytes extent | $\chi^2$ | 5.741 | 47.1 | 52.9 | 32.4 | 67.6 | 64.5 | 35.5 |
| | | | p | 0.017 | | | | | | |
| | T12 | Osteophytes severity | $\chi^2$ | 4.729 | 35.7 | 64.3 | 22.2 | 77.8 | 50.0 | 50.0 |
| | | | p | 0.030 | | | | | | |
| | | Osteophytes extent | $\chi^2$ | 4.729 | 35.7 | 64.3 | 22.2 | 77.8 | 50.0 | 50.0 |
| | | | p | 0.030 | | | | | | |
| Right superior articular facet | S1 | Eburnation severity | $\chi^2$ | 7.776 | 75.3 | 24.7 | 39.5 | 60.5 | 8.6 | 91.4 |
| | | | p | 0.005 | | | | | | |
| | | Eburnation extent | $\chi^2$ | 7.776 | 75.3 | 24.7 | 39.5 | 60.5 | 8.6 | 91.4 |
| | | | p | 0.005 | | | | | | |
| Right inferior articular facet | T5 | Porosity severity | $\chi^2$ | 5.237 | 18.3 | 81.7 | 29.7 | 70.3 | 5.9 | 94.1 |
| | | | p | 0.022 | | | | | | |
| | | Porosity extent | $\chi^2$ | 5.237 | 18.3 | 81.7 | 29.7 | 70.3 | 5.9 | 94.1 |
| | | | p | 0.022 | | | | | | |

## 7.8 TESTS OF CORRELATION BETWEEN MEASUREMENTS IN THE SACRUM, INNOMINATE AND RECONSTRUCTED PELVIS AND DEGENERATIVE CHANGE IN THE VERTEBRAL COLUMN

### 7.8.1 Introduction

The amount of correlation between the individual measurements taken in the reconstructed pelvis, and its constituent elements, and degenerative disease in the vertebral column were examined by employing Spearman's Rank Order Correlation. Due to constraints with the present study, each of the pelvic measurements was only considered in isolation and not in combination. Further work involving the use of partial correlation will also be necessary in the future, to control for the possible effects of another confounding variable. However, it was felt that the current approach adopted could potentially highlight those individual measurements (if any) that were more likely to contribute to the development of degenerative change in the vertebral column. Any such measurements being thus identified could then be employed in further multivariate analysis as well, for example in the utilization of discriminant function analysis, to explore the predictive ability of a combination of measurements on the severity and extent of the three degenerative disease indicators (osteophytes, porosity, eburnation) in a particular vertebral area. The latter of these is the subject of a preliminary exploration in section 7.8.3.

Results for all of the Spearman's Rank Order Correlation tests conducted are presented in the 'Spearman's rank order correlation tests' folder in Appendix CD3 on the accompanying CD-ROM. The significant correlations that were found are tabulated in the 'Significant Spearman's rank order correlation tests' folder, also in Appendix CD3. In order to fully evaluate the significant results of these tests, an appropriate mechanism to effectively (visually) display the relationship was created. This 'signpost' configuration has been described in section 6.2.9 and a contrived example presented in Figure 6.15. The significant p values generated from the statistical analyses were employed to construct these 'signposts' and thus dictated the length of the horizontal axis/axes. Thus, the horizontal axis/axes could be seen as representing the amount of correlation between the measurement concerned and the severity and extent of the degenerative disease indicator (osteophytes, porosity and eburnation) at that particular vertebral level. Therefore longer axes would suggest a greater degree of (positive) correlation. Put another way, at any particular vertebral level, the length of the horizontal axes represents the amount of

correlation (positive) between the pelvic measurement concerned and the severity and extent of osteophytes, porosity and eburnation.

These 'signpost' configurations are all contained in the 'Signpost data files' folder of Appendix CD3.

Due to the volume of data generated for these analyses, details pertaining to its content and presentation on the accompanying CD-ROM are given in the next section.

### 7.8.2 Data storage in Appendix CD3 on the accompanying CD-ROM

The arrangement of data files contained in Appendix CD3 is specified in Figure 7.8(i) and instructions for accessing this media are presented in Volume 2, Appendix 10.

**Appendix CD3**

- Spearman's rank order correlation tests
- Significant Spearman's rank order correlation tests
- Signpost data files
  - *Sacral measurements*
  - *Innominate measurements*
  - *Reconstructed pelvis measurements*
- Programmes needed to run signposts

**Figure 7.8(i) Structure of folders in Appendix CD3 on the accompanying CD-ROM**

The data is essentially arranged in four main sections as detailed below.

### *a) Spearman's rank order correlation tests*

This folder contains 26 subfolders, which present the output from the Spearman's rank order correlation tests that were undertaken. The subfolders represent each of the levels examined in the vertebral column from the occipital condyles (superior aspect) through to the first sacral vertebra (inferior aspect). Within each of these subfolders, there are six HTM (hypertext markup language) files, each representing a group of measurements taken - one each for the sacral and reconstructed pelvis measurements and a further four for the innominate measurements. The latter had to be divided in this way due to restrictions on numbers of variables that could be processed by SPSS at any one time. These HTM files contain the total SPSS generated outputs for the Spearman's rank order correlation tests that were undertaken.

### *b) Significant results of Spearman's rank order correlation tests*

This folder contains 26 subfolders, one for each of the levels examined in the vertebral column from the occipital condyles (superior aspect) through to the first sacral vertebra (inferior aspect). Within each subfolder is a word document that tabulates the significant correlations generated from the Spearman's rank order correlation tests. These results present the correlation coefficient (r), number (n) and probability value (p) of the significant correlations between specific measurements and the six degenerative indicators observed (osteophytes - severity, osteophytes - extent, porosity - severity, porosity - extent, eburnation - severity and eburnation - extent).

### *c) Signpost data files*

This folder contains three subfolders, one for each of the pelvic skeletal areas that measurements were taken from, namely the sacrum, innominate and reconstructed pelvis. Within each of these subfolders, a further subfolder exists for each individual measurement observed in that particular skeletal area. Fifteen measurements are thus represented in the sacral subfolder. In the innominate subfolder there are 93 measurements, 62 of which comprise the original measurements taken plus the additional 31 generated as absolute differences between left and right skeletal elements (see section 7.6). Eighteen measurements are included in the reconstructed pelvis subfolder, 16 of which were original measurements and two of which were absolute differences subsequently calculated for the paired measurements (see section 7.6).

For each of the measurements listed, there are a further 12 subfolders representing each of the vertebral areas examined for evidence of degenerative change. These comprise the superior body surface, inferior body surface, left superior articular fact, right superior articular fact, left inferior articular fact, right inferior articular fact, left superior costal facet, right superior costal facet, left inferior costal facet, right inferior costal facet, left transverse process facet and right transverse process facet (see section 6.2.4). These vertebral area subfolders each contain two files. One is an excel spreadsheet (.xls) which essentially presents the significant correlation coefficients for the vertebral level and degenerative indicator concerned. This spreadsheet was subsequently converted (as detailed in the next section) to a data file (.DAT), which was required to run the 'signposts'. The spreadsheets can be opened directly, but the data files must be accessed by using a specific programme that is detailed further in the next section.

*d) Programmes needed to run signposts*

This folder contains eight files, which are required to run and view the 'signposts'. These files are briefly described below.

i) Converter.xls

This file converted the data from the excel spreadsheet (.xls) format into the data file (.DAT) format.

ii) sp.exe

This executable file is needed to read the data files (.DAT) and display its data as a 'signpost' configuration.

iii) sp.ini

This file configures how the sp.exe executable file finally displays the 'signpost'.

iv) opengl32.dll

This is an additional file required to run the sp.exe file.

v) glu32.dll

This is an additional file required to run the sp.exe file.

vi) glut32.dll

This is an additional file required to run the sp.exe file.

vii) glmf32.dll

This is an additional file required to run the sp.exe file.

viii) cgwin1.dll

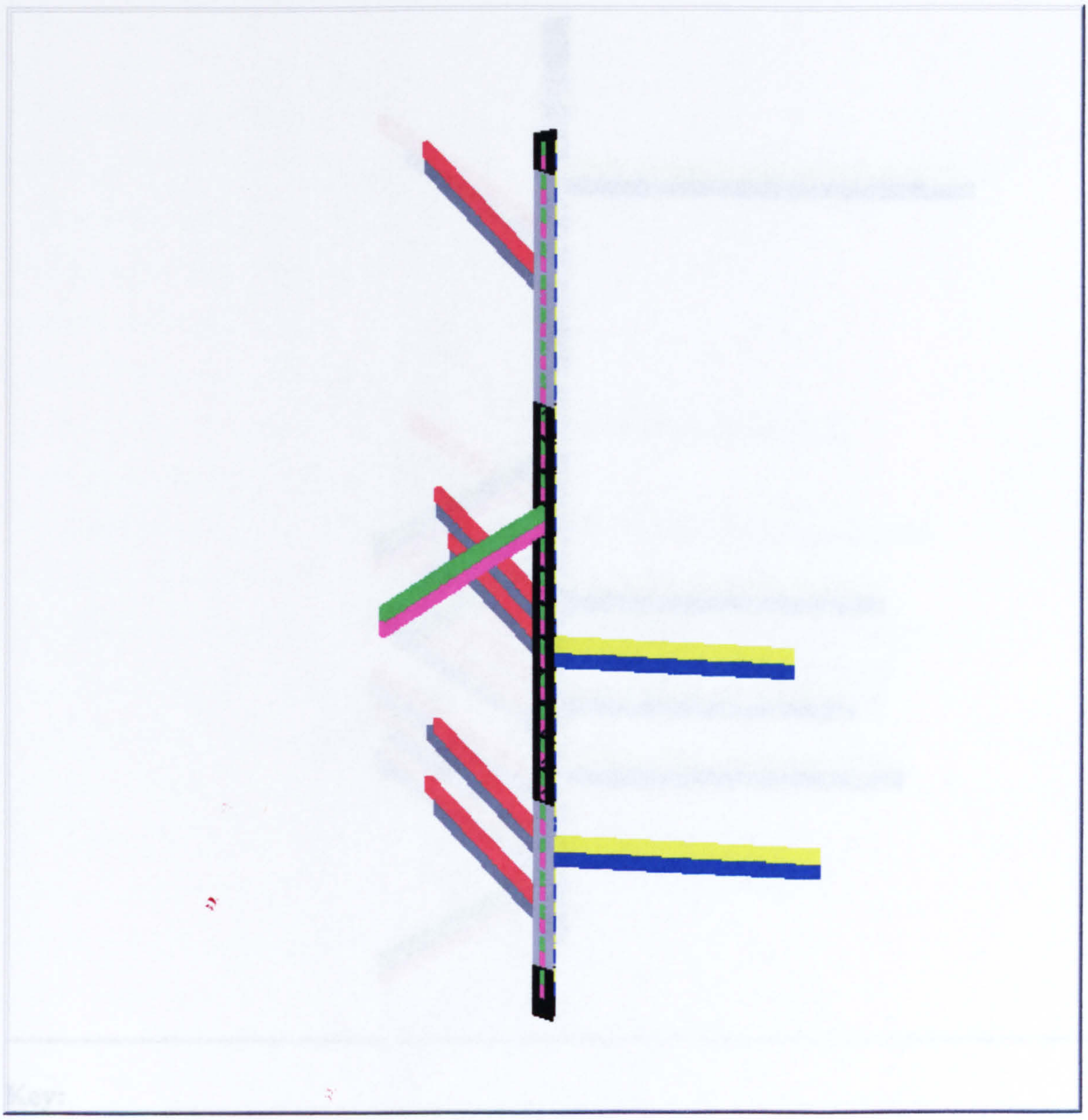
This is an additional file required to run the sp.exe file.

### 7.8.3 Data interpretation in Appendix CD3

Once the 'signposts' had been created, it became clear that configurations were varied. In some instances, there was little or no data available across the vertebral levels for the six degenerative disease indicators concerned for a particular measurement. Figure 7.8(ii) gives an example of this, and shows correlation between the left ischium length and degenerative disease indicators by vertebral level in the left inferior articular facet. In other cases, moderate amounts of data comprised the horizontal axes, but was either spread diffusely across vertebral levels or concentrated in certain regions. Figures 7.8(iii) and 7.8(iv) give examples of this. The former shows correlation between the left pubis length and degenerative disease indicators by vertebral level in the inferior body. The latter shows correlation between the right pubis length and degenerative disease indicators by vertebral level in the left superior articular facet. In only a very small number of cases, data was in existence across almost all of the vertebral levels. Figure 7.8(v) gives an example of this and shows correlation between the right acetabulosciatic breadth and degenerative disease indicators by vertebral level in the superior body.

It thus became imperative to identify the minimum number of data points required, on any particular horizontal axis, to qualify a 'signpost' for interpretation. There were a total of 26 levels comprising the vertical axis of each 'signpost'. With the exception of the superior-most one, these represent each vertebral level from the first cervical through to the first sacral. Given that the human vertebral column consists of four curvatures, then if the total spine is evenly, rather than *anatomically*, divided into these areas, then at least six vertebral levels could be considered to comprise those curvatures. This part of the research is seeking to evaluate if there is any relationship between pelvic size and the site, severity and distribution of degenerative disease. If such a relationship should exist, then it is

**Figure 7.8(ii) Signpost configuration showing correlation between left ischium length and degenerative disease indicator by vertebral level in the left inferior articular facet**



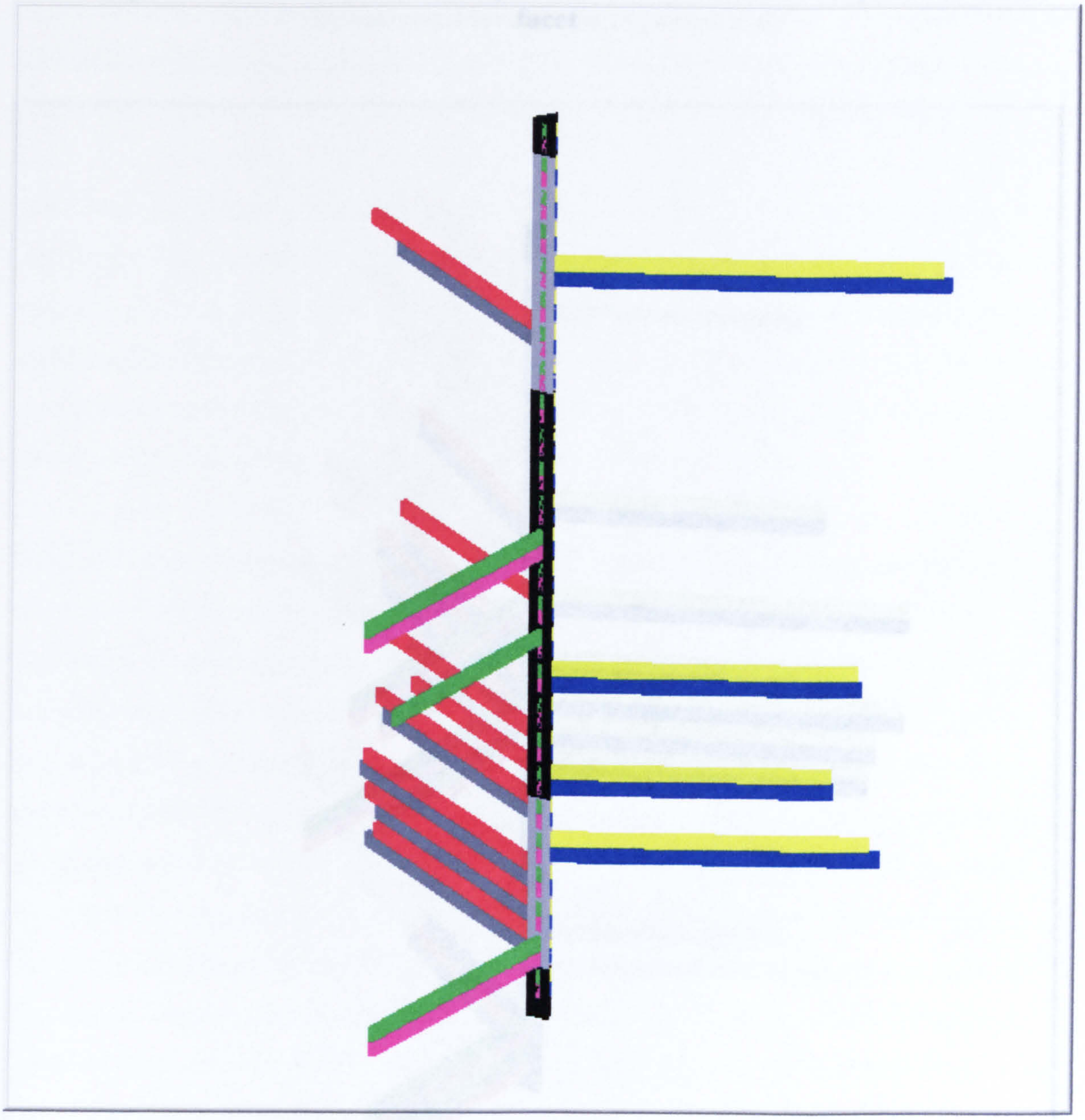
**Key:**

Osteophytes (Severity, Extent)

Porosity (Severity, Extent)

Eburnation (Severity, Extent)

**Figure 7.8(iii) Signpost configuration showing correlation between left pubis length and degenerative disease indicator by vertebral level in the inferior body**



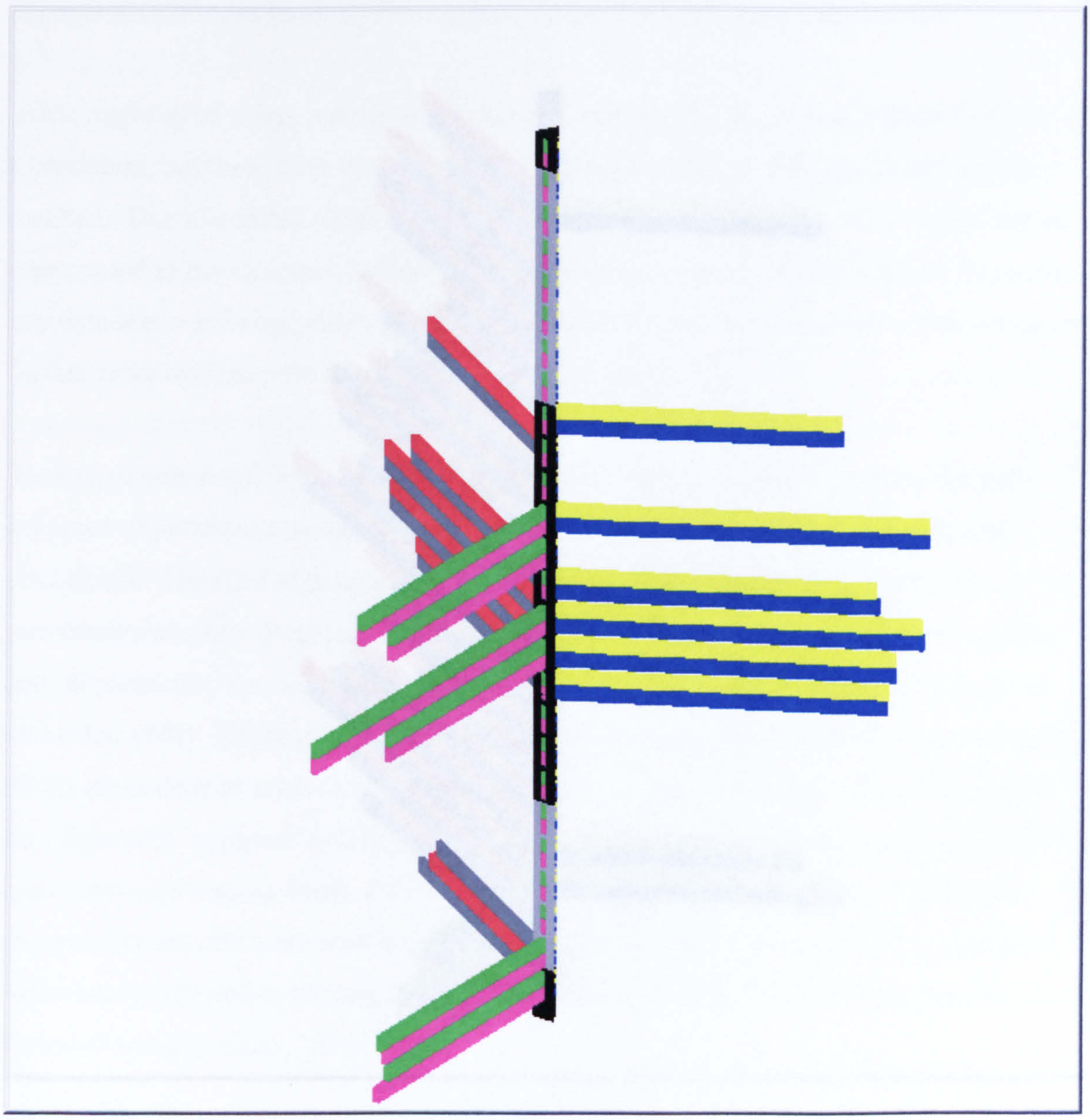
**Key:**

Osteophytes (Severity, Extent)

Porosity (Severity, Extent)

Eburnation (Severity, Extent)

**Figure 7.8(iv) Signpost configuration showing correlation between right pubis length and degenerative disease indicator by vertebral level in the left superior articular facet**



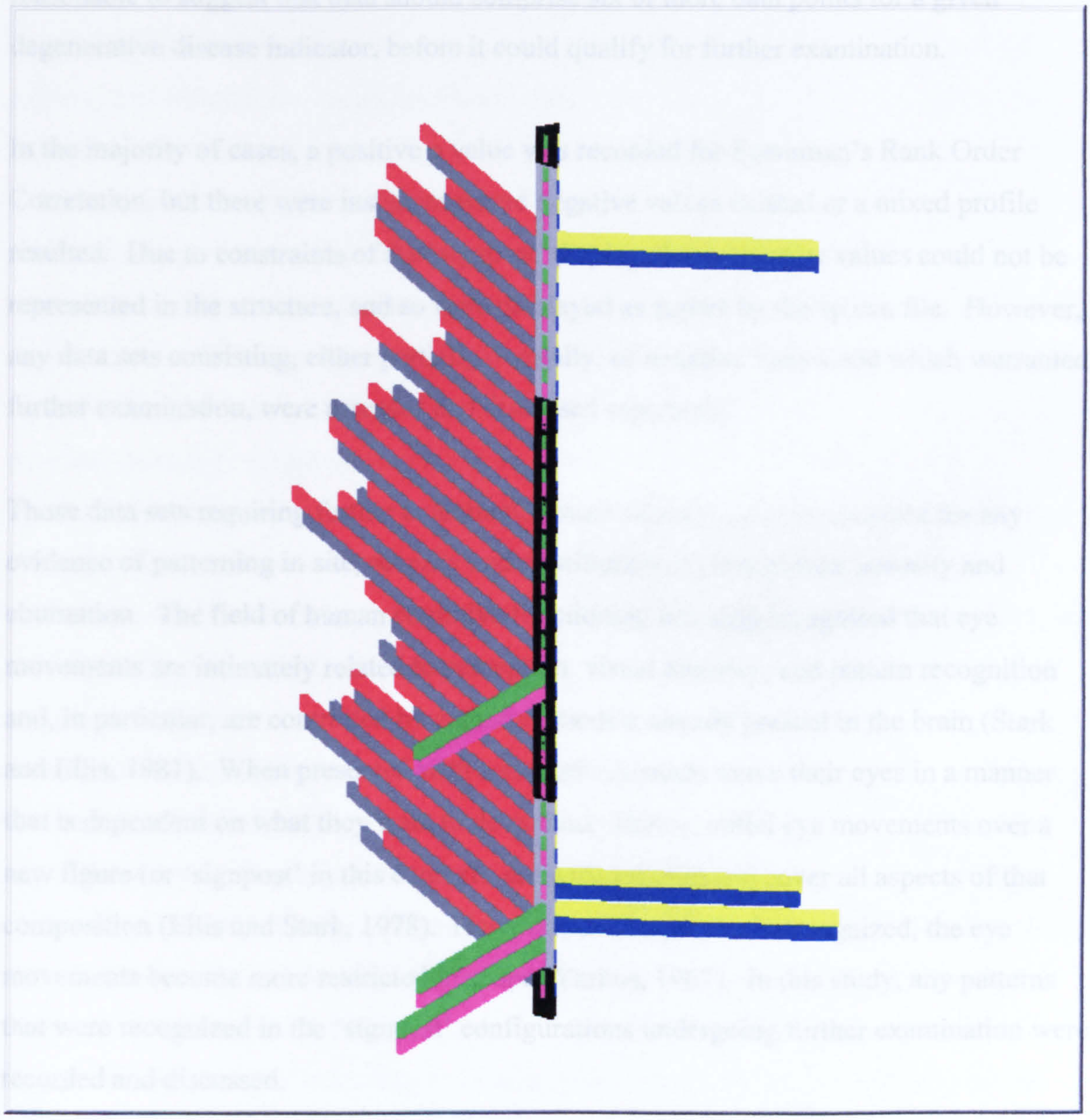
**Key:**

Osteophytes (Severity, Extent)

Porosity (Severity, Extent)

Eburnation (Severity, Extent)

**Figure 7.8(v) Signpost configuration showing correlation between right acetabulosciatic breadth and degenerative disease indicator by vertebral level in the superior body**



**Key:**

Osteophytes (Severity, Extent)

Porosity (Severity, Extent)

Eburnation (Severity, Extent)

hypothesized that the areas of greatest curvature in the vertebral column should preferentially exhibit such manifestations or an increased level of intensity in their presentation. In order to realize this, one curvature (or six vertebral levels), at least, should be represented in the 'signpost' configurations. In light of this, it was therefore considered reasonable to suggest that data should comprise six or more data points for a given degenerative disease indicator, before it could qualify for further examination.

In the majority of cases, a positive p value was recorded for Spearman's Rank Order Correlation, but there were instances where negative values existed or a mixed profile resulted. Due to constraints of the 'signpost' display, these negative values could not be represented in the structure, and so were displayed as zeroes by the sp.exe file. However, any data sets consisting, either partially or totally, of negative values and which warranted further examination, were assessed and discussed separately.

Those data sets requiring further examination were initially visually assessed for any evidence of patterning in site, severity and distribution of osteophytes, porosity and eburnation. The field of human cognitive functioning has long recognised that eye movements are intimately related to perception, visual memory, and pattern recognition and, in particular, are controlled by cognitive models already present in the brain (Stark and Ellis, 1981). When presented with a scenario, humans move their eyes in a manner that is dependent on what they want to do or find. Hence, initial eye movements over a new figure (or 'signpost' in this context), are wide ranging and cover all aspects of that composition (Ellis and Stark, 1978). However, once a pattern is recognized, the eye movements become more restricted in scope (Yarbus, 1967). In this study, any patterns that were recognized in the 'signpost' configurations undergoing further examination were recorded and discussed.

Where patterns were more apparent, or the data comprising the 'signpost' arms was more plentiful, further statistical analyses were undertaken to determine if there was any significant difference between the degenerative change noted at specific vertebral levels and the particular pelvic measurement concerned. It has already been noted that the human vertebral column consists of four curvatures and that the points of maximum (C5, T8 and L4) and minimum (T1, T12 and L5/S1) stress within this structure are suggested as agents responsible for the variation of pathological change observed in the spine (Bridges, 1992; Nathan, 1962). This current study hypothesizes that a more capacious pelvis will predispose to a greater level of degenerative disease developing in the vertebral column

and that the areas of maximum curvature will show a greater predilection for such development. If this were the case, then one would expect to find a significant difference between the values comprising the maximum and minimum vertebral levels of the 'signpost' configuration.

In order to facilitate this, it was necessary to first designate the levels of the vertebral column that would form the areas of maximum and minimum stress. These had to form discrete boundaries and not overlap. As a consequence, four specific areas were identified and comprised C4-C6, C7-T2, T7-T9 and T11-L1. The first and third of these represented the areas of maximum stress centred around the fifth cervical and eighth thoracic vertebrae respectively. The second and fourth represent the areas of minimum stress centred around the first and twelfth thoracic vertebrae respectively. Due to the close approximation of the reported maximum and minimum areas of stress in the lower lumbar and sacral regions, it was not possible to divide these regions into discrete sections for analysis. The aforementioned four specific areas (C4-C6, C7-T2, T7-T9 and T11-L1) could then be respectively recoded as four new groups (1, 2, 3 and 4) and these groupings then statistically tested to examine for any significant differences between them. The first step with this analysis involved assessment of the normality of the p values comprising the horizontal axes of the 'signpost'. In the case of normally distributed values, an independent-samples t-test was undertaken to compare the means between the groups (e.g. between Group 1 and 2, Group1 and 4, Group 3 and 2, or Group 3 and 4). For non-normally distributed values, the Mann-Whitney U test was employed to examine the medians between these groups. In order for this analysis to be undertaken, values had to be in existence for all three levels of the groups under scrutiny. Although, in practice, it would not normally be advisable to use such small group sizes for analysis, the author thought that it would be interesting to run the tests nevertheless and explore any results generated.

Examination of the 'signpost' data did, however, demonstrate that although a minimum of six data points on any horizontal axis had qualified a 'signpost' for additional assessment, a reduced and greater spread of these values essentially precluded any visual or statistical interpretation. As a consequence, 'signposts' displaying results in this particular manner were not discussed further, although the measurements they represented were noted and revisited again in section 7.8.4.

In total, 1512 'signposts' were constructed, of which 180 represented each of the sacral measurements; 1116, the innominate; and 216, the reconstructed pelvis. From this total, 112 (7.4%) qualified for further examination. At the 95% confidence limit, one would expect 5% of the results to be statistically significant by chance alone and for these tests the results do fall (albeit very marginally) outside of that threshold. On that basis, one can therefore argue that these particular results, although somewhat disappointingly low, do have statistical merit, although any interpretation should be tempered with caution. Another aspect to bear in mind with this data is the risk of developing type-1 errors. It is an accepted fact that statistical tests are employed to essentially test hypotheses, but with these types of analysis there is always that possibility that a wrong conclusion may be reached. In this case, type 1 errors (a false positive) may arise. Although this may be controlled for to a certain degree by selecting an appropriate confidence limit (at *either* 1% or 5%), if more stringent levels are adopted (i.e. 1% *rather* than 5%) then the chance of generating the opposite error (type 2 or a false negative) is increased (Pallant, 2001; Rowntree, 1981). Clearly this inverse relationship poses a dilemma. In practical terms this means that if one is very strict with the choice of significance level, then it is reasonable to be fairly confident of the reality of any differences detected, although promising possibilities may be missed. Conversely, if the significance level is relaxed, those promising leads will be caught, but this will also highlight differences that are merely due to sampling variation (Rowntree, 1981). Ultimately this boils down to a subtle, but nonetheless, very important distinction. The results either positively demonstrate that pelvic size does *not* affect the site, severity and distribution of vertebral degenerative change, or fail to demonstrate that it *does* have an effect? In this particular study, based on archaeological material, the author considered the latter to be the error to avoid and felt that the promising possibilities alluded to earlier would be more important to potentially detect than to miss completely, even at the expense of generating false indicators of correlation. Hence the significance level is less stringent (at 5% or less). Naturally, it is not possible to prove if a type 1 or type 2 error has been made, although further research within the field (which would be a further recommendation to this thesis) may reduce that uncertainty.

The 'signpost' configurations that warranted further examination are considered by pelvic area in the following sections. However, bearing in mind the provisos already mentioned, it must be stressed that any interpretations have been tentatively made and must be tempered with caution.

### *a) The sacrum*

For each of the 15 measurements obtained from this skeletal element, 12 individual 'signposts' were created (one for each of the vertebral areas graded for degenerative change). Hence, 180 'signposts' were configured in total for the sacrum. Of these, 13 qualified for further examination and represented six of the measurements and 30 degenerative disease indicators as detailed in Table 7.8(i).

*Results based on visual appearance*

Of the 30 degenerative disease indicators represented in the 13 'signposts' examined, 19 were deemed amenable to visual interpretation only (nine involving general area observations and 10 with regards to patterns). Two were amenable to both visual and statistical interpretation. The remaining nine were excluded due to the preclusive nature of data values comprising the horizontal axes (see table 7.8(i)).

All values comprising the 'signposts' were positive, thus implying a positive correlation between the sacral measurement concerned and the degree of degenerative change observed in the vertebral column. Therefore, as the measurements concerned increased in size, so did the severity and extent of the change observed in particular regions of the vertebral column.

In order to discuss any patterns detected, be they general or specific, the measurements concerned were divided into three general categories: medial-lateral measurements (incorporating the maximum superior sacral width, maximum inferior sacral width, maximum transverse diameter of S1, distance of lateral borders of processus articulares superiores); anteroposterior (A-P) measurements (comprising maximum A-P diameter of S1); and an oblique measurement orientated in the posterosuperior-anteroinferior plane (maximum depth of curvature of sacrum).

For the medial-lateral measurements, the correlation between these and the severity and extent of osteophyte development in the body of the vertebra (superior and inferior surfaces) was mainly noted in the lower half of the thoracic region, with areas of maximum affect appearing around T7 and T11. With respect to the articular facets, only the right inferior one could be visually assessed and this exhibited a general spread of correlation

**Table 7.8(i) Significant 'signpost' configurations for sacral measurements**

| Sacral measurement | Vertebral area | Degenerative disease indicator | Interpretation |
|---|---|---|---|
| Maximum superior sacral width | Superior body | Osteophytes (severity) | ●P |
| | | Osteophytes (extent) | ●P |
| | | Porosity (severity) | ●P |
| | | Porosity (extent) | ●P |
| | Inferior body | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| | | Porosity (severity) | ▲ |
| | | Porosity (extent) | ▲ |
| | Left superior articular facet | Porosity (severity) | ▲ |
| | | Porosity (extent) | ▲ |
| | Right inferior articular facet | Osteophytes (severity) | ●P |
| | | Osteophytes (extent) | ●P |
| | | Porosity (extent) | ●P |
| Maximum inferior sacral width | Superior body | Osteophytes (extent) | ▲ |
| | Left inferior costal facet | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| Maximum transverse diameter of S1 | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| Maximum A-P diameter of S1 | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ●P |
| | | Osteophytes (extent) | ●P |
| Distance of lateral borders of processus articulares superiores | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ●G |
| Maximum depth of curvature of sacrum | Superior body | Osteophytes (severity) | ■ |
| | | Osteophytes (extent) | ▲ |
| | Inferior body | Osteophytes (severity) | ■ |
| | | Osteophytes (extent) | ●P |

**Key:**

▲ Visual and statistical interpretation precluded

●G Visual interpretation possible. Observations made with regards to *general* areas affected, but no statistical analysis undertaken

●P Visual interpretation possible. Observations made with regards to actual *patterning* in presentation, but no statistical analysis undertaken

■ Visual and statistical interpretation undertaken

between the maximum superior sacral width and the severity and extent of osteophytes from the mid to lower cervical region through to the lumbar area, with T1 and T8 being the levels of least and greatest affectation respectively. Only the left inferior costal facet could be examined for the amount of correlation between the maximum inferior sacral width and severity and extent of osteophyte presentation and this involved only the lower two-thirds of the thoracic spine.

For the maximum A-P diameter of S1, the correlation between this measurement and the severity and extent of osteophyte development was noted to mainly occur in the lower half of the thoracic spine through to the sacral area on the superior body, and from the mid thoracic through to lumbar spine on the inferior surface.

With the maximum depth of curvature, both superior and inferior body surfaces exhibited the same diverse spread of correlation between this measurement and the severity and extent of osteophyte development, extending from the mid to lower regions of the cervical spine through to the lower lumbar. The levels of maximum and minimum correlation were noted at T10 and T6 respectively on the superior body surface. On the inferior body surface, T2 and T8 were areas exhibiting the greatest correlation with osteophyte development (severity and extent) and T5/6 and the mid/lower lumbar regions were those with the smallest. These areas of maximum and minimum affectation exhibited enough data to warrant further statistical examination and this is discussed in the next section.

Porotic change was only assessed with signposts constructed for one measurement - the maximum superior sacral width - but could only be assessed for any patterning with respect to the superior body surface. This showed that the lower half of the thoracic region was most affected, with L1 exhibiting the greatest correlation between this measurement and the severity and extent of osteophyte development.

*Results based on statistical analysis*

Of the 30 degenerative disease indicators concerned, only two exhibited full data sets for at least one of each of the groups representing the maximum and minimum areas of stress in the vertebral column and are presented in Table 7.8(ii)

**Table 7.8(ii) Areas of maximum and minimum stress (as defined by group) exhibiting sufficient data for statistical analysis with sacral measurements**

| Sacral measurement | Vertebral area | Degenerative disease indicator | Group | | | |
|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 |
| Maximum depth of curvature of sacrum | Superior body | Osteophytes (severity) | | | • | • |
| | Inferior body | Osteophytes (severity) | | • | • | • |

**Key:**

- Groups suitable for statistical analysis

Group 1 Area of maximum stress in vertebral column (C4-C6)
Group 2 Area of minimum stress in vertebral column (C7-T2)
Group 3 Area of maximum stress in vertebral column (T7-T9)
Group 4 Area of minimum stress in vertebral column (T11-L1)

The values presented for these two data sets were tested for normality by employing the Kolmogorov-Smirnov test of normality. The Kolmogorov-Smirnov statistic, degrees of freedom and p value were recorded and the distribution described, with a p value of 0.05 or less being recognized as the level for rejection. Results of these analyses are presented in Table 7.8(iii). As both data sets were normally distributed, the independent-samples t-test was undertaken to compare the means in the groups under consideration.

With respect to the correlation between the maximum depth of curvature of the sacrum and the severity of osteophytes observed on the superior body surface, a difference between expression in the areas of maximum and minimum curvature in T7-T9 and T11-L1 respectively was examined for. In the case of the inferior body surface, a difference in the correlation between this measurement and the severity of osteophyte development was examined for between the areas of maximum and minimum curvature in T7-T9 and C7-T2 respectively. Results of these tests are presented in table 7.8(iv) and show that the correlation between the measurements concerned and the severity/extent of the degenerative disease indicator is not statistically significant in the areas of maximum and minimum stress under examination.

*Summary of results for sacrum*

Of the 30 'signpost' configurations examined, osteophytes development was the most frequently occurring manifestation observed. Twenty-three (76.7%) of the configurations

**Table 7.8(iii)** **Kolmogorov-Smirnov test of normality for degenerative disease indicators in the sacrum**

| Sacral measurement | Vertebral area | Degenerative disease indicator | Kolmogorov-Smirnov Statistic | Degrees of freedom | p value | Normal distribution |
|---|---|---|---|---|---|---|
| Maximum depth of curvature of sacrum | Superior body | Osteophytes (severity) | .106 | 16 | .200 | ✓ |
| | Inferior body | Osteophytes (severity) | .169 | 18 | .186 | ✓ |

**Table 7.8(iv)** **Independent samples t-test comparing means of groups for degenerative change associated with sacral measurements**

| Sacral measurement | Vertebral area | Degenerative disease indicator | Groups tested | t-test for equality of means* | | | Difference in means |
|---|---|---|---|---|---|---|---|
| | | | | t | df | p value | |
| Maximum depth of curvature of sacrum | Superior body | Osteophytes (severity) | 3 and 4 | .486 | 4 | .653 | **No** |
| | Inferior body | Osteophytes (severity) | 2 and 4 | -.636 | 4 | .559 | **No** |
| | | Osteophytes (severity) | 3 and 4 | -.381 | 4 | .722 | **No** |

**Key:**

* $H_0 \ \bar{x}_d = 0 \quad H_1 \ \bar{x}_d \neq 0$ (Two-tailed test)
Group 2 Area of minimum stress in vertebral column (C7-T2)
Group 3 Area of maximum stress in vertebral column (T7-T9)
Group 4 Area of minimum stress in vertebral column (T11-L1)

exhibited osteophytic change. Of these, 12 (40%) represented the extent of the osteophytic development and 11 (36.7%), the severity of the change. Porotic changes were noted in a total of seven (23.3%) 'signposts', with four (13.3%) and three (10%) representing the extent and severity of the manifestation respectively.

With regard to the presence of any patterning observed in the presentation of the degenerative disease indicators, it can be suggested that the lower half of the thoracic spine tended to generally exhibit the greatest correlation between the measurements concerned and the severity and extent of osteophytic and porotic change. Reports in the literature attest to this area of the spine exhibiting greater affectation with pathological change (see Section 5.1.2). The current findings show that the correlation between the six sacral measurements concerned (see Table 7.8(i)) and the degenerative disease indicator observed are indeed most notable in this region and thus suggest that pelvic size, as represented by the aforementioned sacral measurements, is contributing to this manifestation.

If the different categories of measurements are considered, then those in the medial-lateral plane tended to show a greater correlation with osteophyte development (severity and extent) on the superior body surface in the lower half of the thoracic spine. The anteroposterior measurement also exhibited a similar relationship in this area, but also extended inferiorly into the lumbar and sacral regions.
With respect to the inferior body surface, the medial-lateral measurements showed greater correlation with osteophytic development (severity and extent) in the mid to lower thoracic regions, whereas the anteroposterior measurement showed this correlation extending from the mid thoracic area through to the lumbar region.

The maximum depth of curvature showed the greatest correlation with osteophyte development (severity and extent) from the mid cervical to lower lumbar region on the superior body. On the inferior surface, this extended from the lower aspect of the cervical region through to the lower lumbar.

The data for porotic change and also the changes observed on the articular and costal facets was very limited and so no comparison could be made between measurement types for these areas or comment made on any possible patterning with regard to side predisposition or level of affectation for the paired facets.

Statistical analyses conducted showed that there was no statistically significant difference between the correlations observed between the maximum depth of curvature of the sacrum and the site and severity of osteophytosis observed at the points of maximum and minimum curvature on either the superior or inferior body surface.

***b) The innominate***

From the 1116 'signpost' configurations created for this skeletal element, 93 qualified for further examination and represented 39 of the measurements and 179 degenerative disease indicators as detailed in Table 7.8(v)

*Results based on visual appearance*

Of the 179 degenerative disease indicators represented in the 93 'signposts' examined, 108 were deemed amenable to visual interpretation only (89 involving general area observations and 19 with regards to patterns). Seventeen were amenable to both visual and statistical interpretation. The remaining 54 were excluded due to the preclusive nature of data values comprising the horizontal axes (see table 7.8(v)).

All values comprising the 'signposts' were positive, thus implying a positive correlation between the innominate measurement concerned and the degree of degenerative change observed in the vertebral column. Therefore, as the measurements concerned increased in size, so did the severity and extent of the change observed in particular regions of the vertebral column.

For the left and right maximum innominate lengths, the correlation between these and the severity and extent of osteophyte development on the superior body of the vertebra was mainly noted in the lower third of the thoracic region through to the lower lumbar, with an area of maximum affect appearing around L1 with the left measurement. With respect to affect, the inferior body surface, the correlation between the left and right measurements were noted extending from the lower half of the thoracic through to the mid lower lumbar region.

For the left and right maximum innominate breadths, the correlation between these and the severity and extent of osteophyte development on the superior body of the vertebra was

## Table 7.8(v) Significant 'signpost' configurations for innominate measurements

| Innominate measurement | Vertebral area | Degenerative disease indicator | Interpretation |
|---|---|---|---|
| Left maximum innominate length | Superior body | Osteophytes (severity) | ●P |
| | | Osteophytes (extent) | ●P |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Right superior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| | Left inferior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| Right maximum innominate length | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Right superior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| Left innominate breadth | Superior body | Osteophytes (severity) | ●P |
| | | Osteophytes (extent) | ■ |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Left superior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| | Right superior articular facet | Osteophytes (severity) | ▲ |
| Right innominate breadth | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Left inferior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| Left iliac height | Superior body | Osteophytes (severity) | ●P |
| | | Osteophytes (extent) | ●P |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Right superior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| Right iliac height | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |

**Key:**

▲ Visual and statistical interpretation precluded

●G Visual interpretation possible. Observations made with regards to *general* areas affected, but no statistical analysis undertaken

●P Visual interpretation possible. Observations made with regards to actual *patterning* in presentation, but no statistical analysis undertaken

■ Visual and statistical interpretation undertaken

## Table 7.8(v) Significant 'signpost' configurations for innominate measurements (contd.)

| Innominate measurement | Vertebral area | Degenerative disease indicator | Interpretation |
|---|---|---|---|
| Left acetabulum diameter | Superior body | Osteophytes (severity) | ●P |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ●P |
| | | Osteophytes (extent) | ■ |
| Right acetabulum diameter | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ■ |
| | | Osteophytes (extent) | ■ |
| Left pubis length | Superior body | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| | Inferior body | Osteophytes (severity) | ●G |
| | Left superior articular facet | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Right superior costal facet | Porosity (extent) | ●G |
| Right pubis length | Superior body | Osteophytes (severity) | ■ |
| | | Osteophytes (extent) | ■ |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Left superior articular facet | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | | Porosity (severity) | ●G |
| | | Porosity (extent) | ●G |
| | Right superior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| | Left inferior articular facet | Osteophytes (severity) | ●P |
| | | Osteophytes (extent) | ●P |
| | | Eburnation (severity) | ●G |
| | | Eburnation (extent) | ●G |
| | Right inferior articular facet | Porosity (severity) | ▲ |
| | | Porosity (extent) | ▲ |
| Left minimum height of inferior pubic ramus | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| Right minimum height of inferior pubic ramus | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |

**Key:**

▲ Visual and statistical interpretation precluded

●G Visual interpretation possible. Observations made with regards to *general* areas affected, but no statistical analysis undertaken

●P Visual interpretation possible. Observations made with regards to actual *patterning* in presentation, but no statistical analysis undertaken

■ Visual and statistical interpretation undertaken

## Table 7.8(v) Significant 'signpost' configurations for innominate measurements (contd.)

| Innominate measurement | Vertebral area | Degenerative disease indicator | Interpretation |
|---|---|---|---|
| Left pubic acetabular length | Superior body | Osteophytes (severity) | ▲ |
| | Inferior body | Osteophytes (extent) | ▲ |
| Right pubic acetabular length | Superior body | Osteophytes (extent) | ▲ |
| | Inferior body | Osteophytes (severity) | ▲ |
| Left ischial acetabular height | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| Right ischial acetabular height | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| Right pubo-sacroiliac diameter | Superior body | Osteophytes (severity) | ■ |
| | | Osteophytes (extent) | ●P |
| | | Porosity (severity) | ●G |
| | | Porosity (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ▲ |
| | Right superior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| | Left inferior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| | Right inferior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| Left pubic symphysis depth | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ▲ |
| Right pubic symphysis depth | Superior body | Osteophytes (severity) | ■ |
| | | Osteophytes (extent) | ■ |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| Left pubic symphysis inferior width | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| Right pubic symphysis inferior width | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| Left maximum width of pubic symphysis | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |

**Key:**

▲ Visual and statistical interpretation precluded

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●P Visual interpretation possible. Observations made with regards to actual *patterning* in presentation, but no statistical analysis undertaken

■ Visual and statistical interpretation undertaken

## Table 7.8(v) Significant 'signpost' configurations for innominate measurements (contd.)

| Innominate measurement | Vertebral area | Degenerative disease indicator | Interpretation |
|---|---|---|---|
| Left ischial spine to symphysion | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | | Porosity (severity) | ▲ |
| | | Porosity (extent) | ▲ |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | | Porosity (severity) | ●G |
| | | Porosity (extent) | ●G |
| | Left superior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| | Right superior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| | Left inferior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| | Right inferior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| Right ischial spine to symphysion | Superior body | Osteophytes (severity) | ●P |
| | | Osteophytes (extent) | ●P |
| | Inferior body | Osteophytes (severity) | ●P |
| | | Osteophytes (extent) | ●P |
| | Left inferior articular facet | Porosity (severity) | ●G |
| | | Porosity (extent) | ●G |
| | Right inferior articular facet | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| Absolute difference in ischial spine to symphysion | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ▲ |
| Right symphyseal angle | Superior body | Osteophytes (severity) | ●P |
| | | Osteophytes (extent) | ●P |
| Left acetabulosciatic breadth | Superior body | Osteophytes (severity) | ■ |
| | | Osteophytes (extent) | ■ |
| | Inferior body | Osteophytes (severity) | ■ |
| | | Osteophytes (extent) | ■ |
| | Right superior articular facet | Osteophytes (extent) | ▲ |
| Right acetabulosciatic breadth | Superior body | Osteophytes (severity) | ■ |
| | | Osteophytes (extent) | ■ |
| | Inferior body | Osteophytes (severity) | ■ |
| | | Osteophytes (extent) | ■ |

**Key:**

▲ Visual and statistical interpretation precluded

●G Visual interpretation possible. Observations made with regards to *general* areas affected, but no statistical analysis undertaken

●P Visual interpretation possible. Observations made with regards to actual *patterning* in presentation, but no statistical analysis undertaken

■ Visual and statistical interpretation undertaken

## Table 7.8(v) Significant 'signpost' configurations for innominate measurements (contd.)

| Innominate measurement | Vertebral area | Degenerative disease indicator | Interpretation |
|---|---|---|---|
| Right acetabulosciatic breadth (contd.) | Right superior articular facet | Osteophytes (extent) | ▲ |
| | Right inferior articular facet | Osteophytes (severity) | ▲ |
| Left ischium length | Superior body | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| | Left inferior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| Right ischium length | Superior body | Osteophytes (severity) | ●G |
| Left maximum length of obturator foramen | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| Right auricular surface profile - a | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●P |
| | Inferior body | Osteophytes (severity) | ●G |
| Left auricular surface profile - b | Superior body | Osteophytes (severity) | ●P |
| | | Osteophytes (extent) | ●P |
| | Inferior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Left inferior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |
| Right auricular surface profile - b | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ●G |
| Right auricular surface profile - c | Superior body | Osteophytes (severity) | ●G |
| | Inferior body | Osteophytes (severity) | ▲ |
| Right auricular surface profile - d | Superior body | Osteophytes (severity) | ●G |
| | | Osteophytes (extent) | ●G |
| | Inferior body | Osteophytes (severity) | ●G |
| Right auricular surface profile - f | Left inferior articular facet | Porosity (severity) | ●G |
| | | Porosity (extent) | ●G |
| Right sciatic notch position | Left inferior articular facet | Osteophytes (severity) | ▲ |
| | | Osteophytes (extent) | ▲ |

**Key:**

▲ Visual and statistical interpretation precluded

●G Visual interpretation possible. Observations made with regards to *general* areas affected, but no statistical analysis undertaken

●P Visual interpretation possible. Observations made with regards to actual *patterning* in presentation, but no statistical analysis undertaken

mainly noted in the mid thoracic region through to the sacral, with an area of maximum effect appearing around L1 with the left measurement. With respect to the inferior body surface, the correlation between the left and right measurements tended to be concentrated around the lower half of the thoracic region.

For the iliac height, both the left and right measurements exhibited a correlation with the severity and extent of osteophytes, on the superior body surface, extending from the lower half of the thoracic region through to the lumbar area. The left measurement showed enhanced correlations around the levels of T10/L2 and T8/L2 for the severity and extent of the pathology respectively. Reduced correlations were noted with both the severity and extent of osteophytosis around the level of L1. On the inferior body surface, the correlation between the left and right iliac heights and the severity and extent of osteophyte development were concentrated in the lower thoracic to mid lumbar regions.

In the case of the left and right acetabulum diameter, the correlation between these measurements and the severity of osteophytosis on the superior body surface, was mainly noted in the lower half of the cervical region and extending from the lower thirds of the thoracic to the lower lumbar spine. These correlations between measurements and degenerative change were greatest in the areas of T10 and L3 and least around the level of L1. The correlation between the extent of osteophyte development and the two measurements on the superior body surface was seen to be concentrated from the lower half of the thoracic region through to L5/S1. On the inferior body surface, both the severity and extent of osteophytosis was found to be correlated with these measurements in the lower half of the thoracic region and upper half of the lumbar. The left measurement showed enhanced correlations around the level of T9 and the right measurement exhibited a reduced correlation around the level of L1.

The left and right pubis lengths exhibited a correlation between the severity and extent of osteophyte development on the inferior body surface in the lower half of the thoracic region and extending across the lumbar one. With respect to the superior body surface, only the right measurement could be visually assessed and this suggested that correlations between this measurement and the severity and extent of osteophytosis was concentrated from the mid thoracic to mid/lower lumbar regions. For the severity of the pathological manifestation, the greatest correlation was observed around at the level of T12 and the least, at T9. In the case of the extent of the osteophytosis, the greatest correlation was observed around at the level of T6 and the least, at L1. The correlation between these

measurements and the severity and extent of osteophyte development was also visually assessed on the left superior and inferior articular facets. Both areas showed a concentration of affect in the mid thoracic region.

In the case of the left minimum height of the inferior pubic ramus, the correlation between this measurement and the severity and extent of osteophyte development on the superior body surface was mainly noted in the lower third of the thoracic region. For the right side measurement, the area of noted affect mainly extended from the lower third of the thoracic region through to the lower lumbar area. Both left and right measurements exhibited correlations with the severity and extent of osteophytosis on the inferior body surface in the lower and upper halves of the thoracic and lumbar regions inclusively.

On the inferior body surface, the correlation between the left and right ischial acetabular heights and the severity and extent of osteophyte development were concentrated in the lower thoracic to mid lumbar regions. On the superior body surface the correlations between both measurements and the degree of degenerative change were noted in the lower cervical and lower third through to lumbar regions of the spine

Only the right pubo-sacroiliac diameter could be visually assessed with respect to the superior body surface. The correlations between this measurement and the severity and extent of osteophyte development in this vertebral area were generally spread across vertebral levels, although there was a concentration of data in the mid thoracic region.

On the superior body surface, the correlations between the left and right pubic symphysis inferior widths and the severity and extent of osteophytosis were noted to mainly occur in the lower quarter of the thoracic region through to the lower lumbar one.

For the left ischial spine to symphysion, the correlation between this measurement and the severity and extent of osteophyte development was noted to mainly occur in the lower third of the thoracic spine through to the lower lumbar area on the superior body surface, and in the lumbar region itself on the inferior surface. For the right ischial spine to symphysion, the correlation between this measurement and the severity and extent of osteophyte development was noted to be diffusely spread from T1 to S1 on the superior body surface, with areas of maximum and minimum affectation centred around T3/L1 and T9 respectively. On the inferior body surface, the correlations were located in the upper half of the thoracic spine and mid lumbar area, with an area of maximum affectation centred

around T2. With respect to the articular facets, only the right inferior one could be visually assessed and this exhibited a general spread of correlation between the right ischial spine to symphysion and the severity of osteophytosis between T4 and T10.

Data comprising the left symphyseal angle was too limited to warrant further examination, but the right symphyseal angle could be visually assessed with respect to the superior body surface. The correlations between this measurement and the severity and extent of osteophytosis in this vertebral area were mainly concentrated in the lower quarter of the thoracic region through to the lower lumbar.

In a similar fashion, only the right ischium length could be visually assessed with respect to the superior body surface. The correlations between this measurement and the severity of osteophyte development were noted to extend from the lower third of the thoracic region through to the lower lumbar.

The maximum length of the obturator foramen was another measurement where the 'signpost' configuration could only be visually assessed on the left aspect and with respect to the superior body surface (the right aspect 'signposts' did not warrant further examination). Correlations between this measurement and the severity and extent of osteophytosis were concentrated in the lower third of the thoracic region.

Due to the limitation of data presented in the 'signpost' configurations for the auricular surface, only four (a, b, c and d) of the six measurements observed warranted further examination and only one of these (b) could be considered on both sides. For the left and right auricular surface profile 'b' measurements, correlations with the severity and extent of osteophyte development were noted to mainly occur in the lower half of the thoracic spine and upper lumbar area on the superior body, and in the lower half of the thoracic spine on the inferior surface. Both measurements showed enhanced correlations around the level of L4.

On the superior body surface, the correlation between the right auricular surface profile 'a' measurement and the severity and extent of osteophyte development was concentrated in the lower third of the thoracic to lower lumbar regions. On the inferior body surface, the correlation between this measurement and the severity of osteophytosis alone was noted to occur in the lower half of the thoracic spine.

Correlation between the severity of osteophytosis and the right auricular surface profile 'c' measurement on the superior body surface was concentrated between T12 and L5.

On the superior body surface, the correlation between the right auricular surface profile 'd' measurement and the severity and extent of osteophyte development was noted in the lower half of the cervical region and also extending from the lower quarter of the thoracic to mid lumbar areas. On the inferior body surface, the correlation between this measurement and the severity of osteophytosis alone was noted to occur in the mid cervical region and the lower half of the thoracic spine.

Of all the visual patterns detected, those observed with the acetabulosciatic breadth and osteophyte development were the most promising due to the extent of data presented in the 'signpost' configurations. The 'signpost' configuration showing the correlation between the left acetabulosciatic breadth and the degenerative disease indicators in the superior and inferior bodies is presented in figures 7.8(vi) and 7.8(vii) respectively. Those presenting the correlation between the right acetabulosciatic breadth and the degenerative disease indicators in the superior and inferior bodies are presented in figures 7.8(viii) and 7.8(ix) respectively.

Generally speaking, for the left and right acetabulosciatic breadths, the correlation with the severity and extent of osteophyte development was noted to extend from the upper/mid cervical vertebral levels through to the lower lumbar and sacral regions on the superior body surface, and from the upper cervical through to mid/lower lumbar regions on the inferior surface. If the 'signpost' configurations are studied more closely, then a pattern in the presentation of the correlations can be observed. In the case of the correlations between the left acetabulosciatic breadth and the severity and extent of osteophytosis on the superior body surface, maximum values can be observed around the levels of C5-7, T10 and L4 and minimal values, around T1 and L1. On the inferior body surface, maximum and minimum correlations are centred on C3, T9, L3 and T1, L1 respectively. With the right acetabulosciatic breadth, maximum and minimum correlations with the severity and extent of osteophytosis are seen on the superior body surface around the levels of C7, T10, L4 and T1, T12/L1, S1 respectively. On the inferior body surface, a minimum correlation appears to occur around the level of L1.

Of the absolute difference calculated between the paired measurements in the innominate, only one (the ischial spine to symphysion) warranted further examination and this was with respect to the superior body surface. The correlation between this measurement and the severity and extent of osteophytosis was noted to be concentrated between T4 and T10.

Porotic change was only assessed with signposts constructed for four measurements (the left and right pubis lengths, the right pubo-sacroiliac diameter and the right ischial spine to symphysion) and four vertebral areas (superior body, left superior and inferior articular facets and right superior costal facet). In the case of the right pubis length, the correlation with the severity and extent of porosity on the left superior articular facet was found to be concentrated in the mid thoracic region. With the left pubis length, the correlation with the extent of porotic change on the right superior costal facet was mainly sited in the upper two-thirds of the thoracic spine. On the superior body surface, the correlation between the severity and extent of this pathological manifestation was concentrated from the mid thoracic through upper sacral areas. Finally, in the case of the right ischial spine to symphysion, the correlation with the severity and extent of porosity on the left inferior articular facet was found to be concentrated in the upper two-thirds of the thoracic spine.

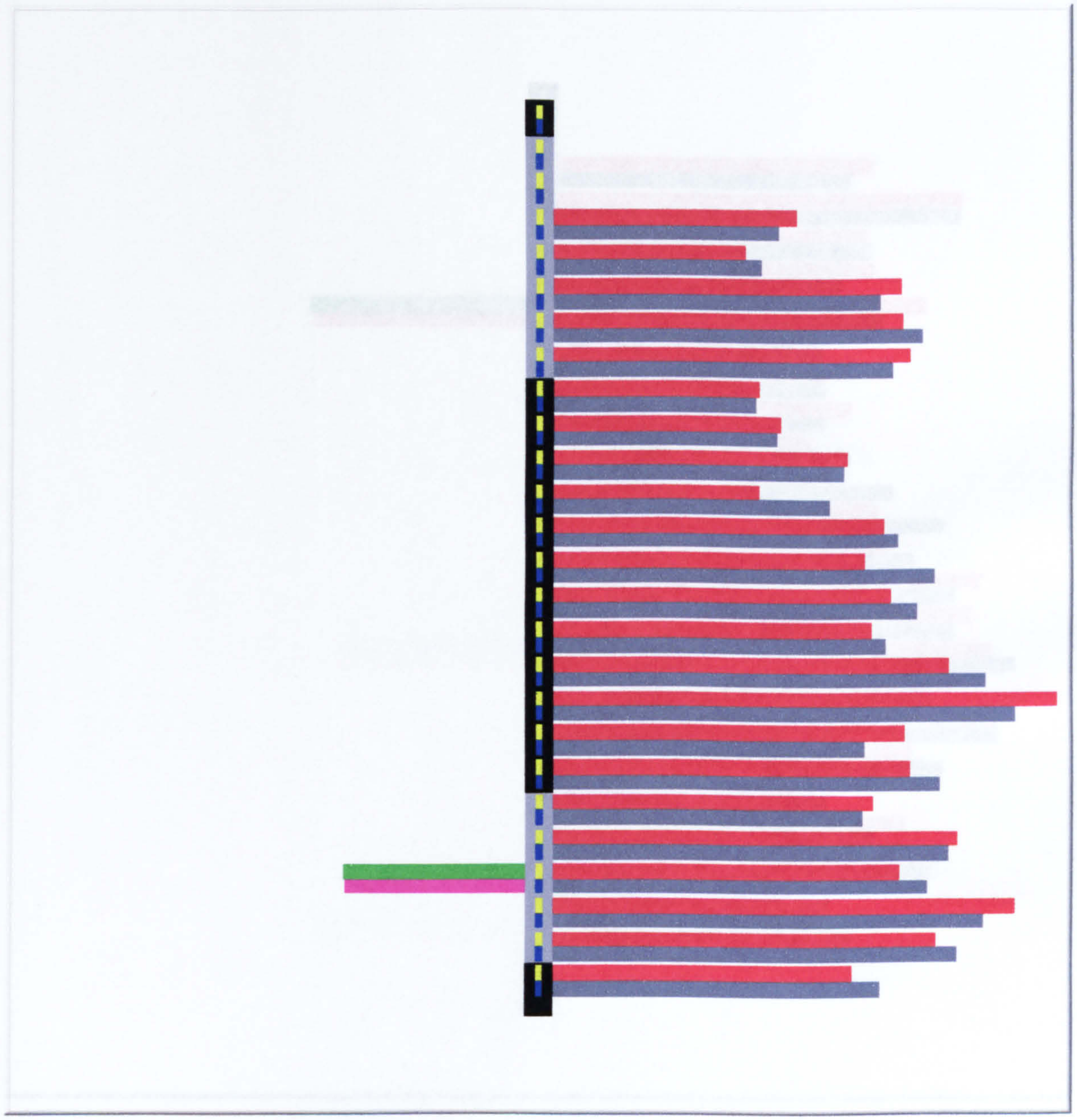
Eburnation was only assessed with signposts constructed for one measurement - the right pubis length - but could only be assessed for any patterning with respect to the left inferior articular facet. This showed that the correlation with the severity and extent of this manifestation was concentrated in the upper two-thirds of the thoracic region.

*Results based on statistical analysis*

Of the 190 degenerative disease indicators concerned, 17 exhibited full data sets for at least one of each of the groups representing the maximum and minimum areas of stress in the vertebral column. These are presented in Table 7.8(vi).

The values presented for these 17 data sets were tested for normality by employing the Kolmogorov-Smirnov test of normality. The Kolmogorov-Smirnov statistic, degrees of freedom and p value were recorded and the distribution described, with a p value of 0.05 or less being recognized as the level for rejection. Results of these analyses are presented in Table 7.8(vii). Fourteen data sets were normally distributed and the independent-samples t-test was undertaken to compare the means in these groups. The other three, non-normally distributed data sets, were examined using Mann Whitney U to compare the medians. Results of these tests are presented in Table 7.8(viii) and Table 7.8(ix) respectively.

**Figure 7.8(vi) Signpost configuration showing correlation between left acetabulosciatic breadth and degenerative disease indicator by vertebral level in the superior body**



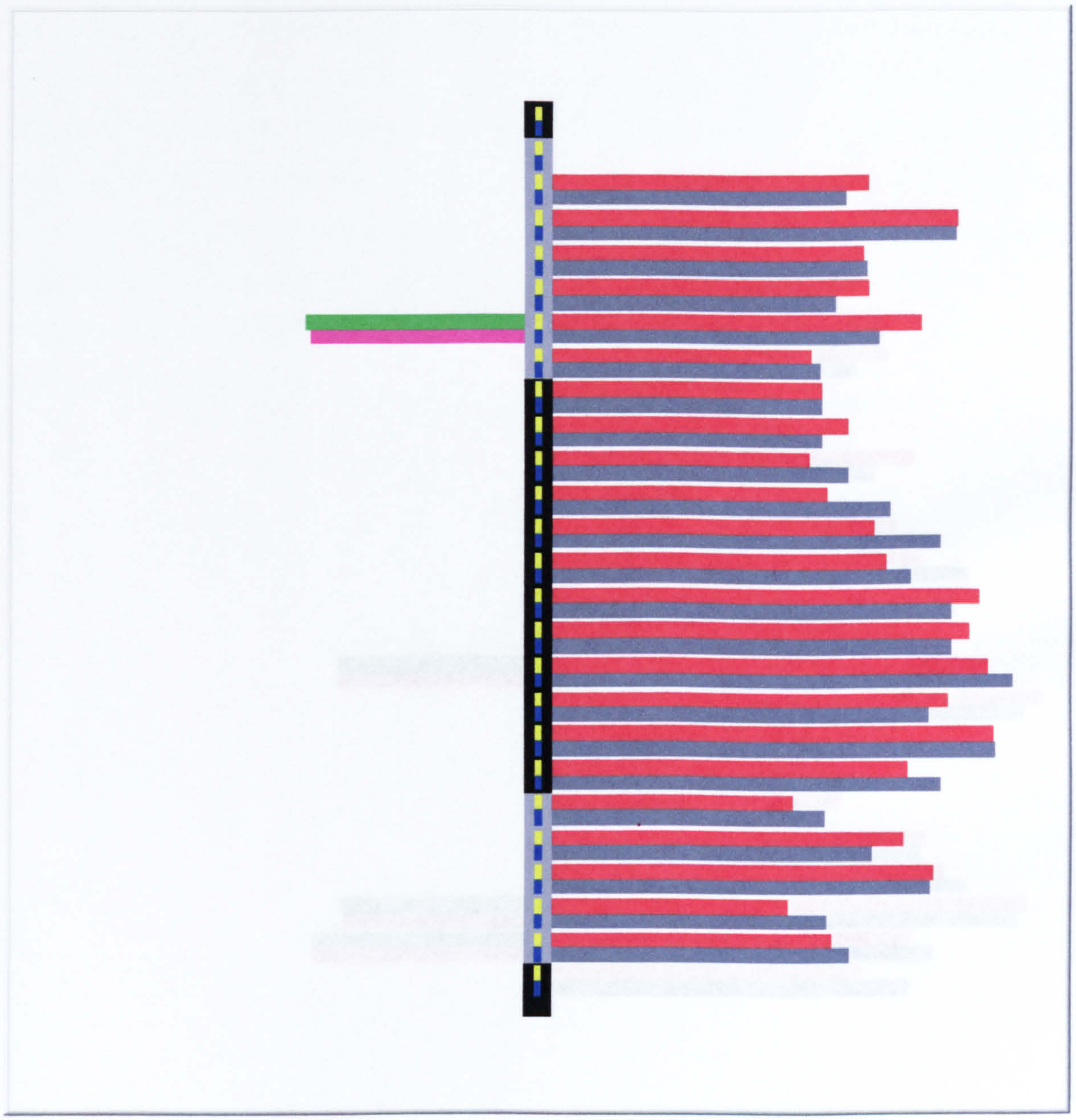
**Key:**

Osteophytes (Severity, Extent)

Porosity (Severity, Extent)

Eburnation (Severity, Extent)

**Figure 7.8(vii) Signpost configuration showing correlation between left acetabulosciatic breadth and degenerative disease indicator by vertebral level in the inferior body**



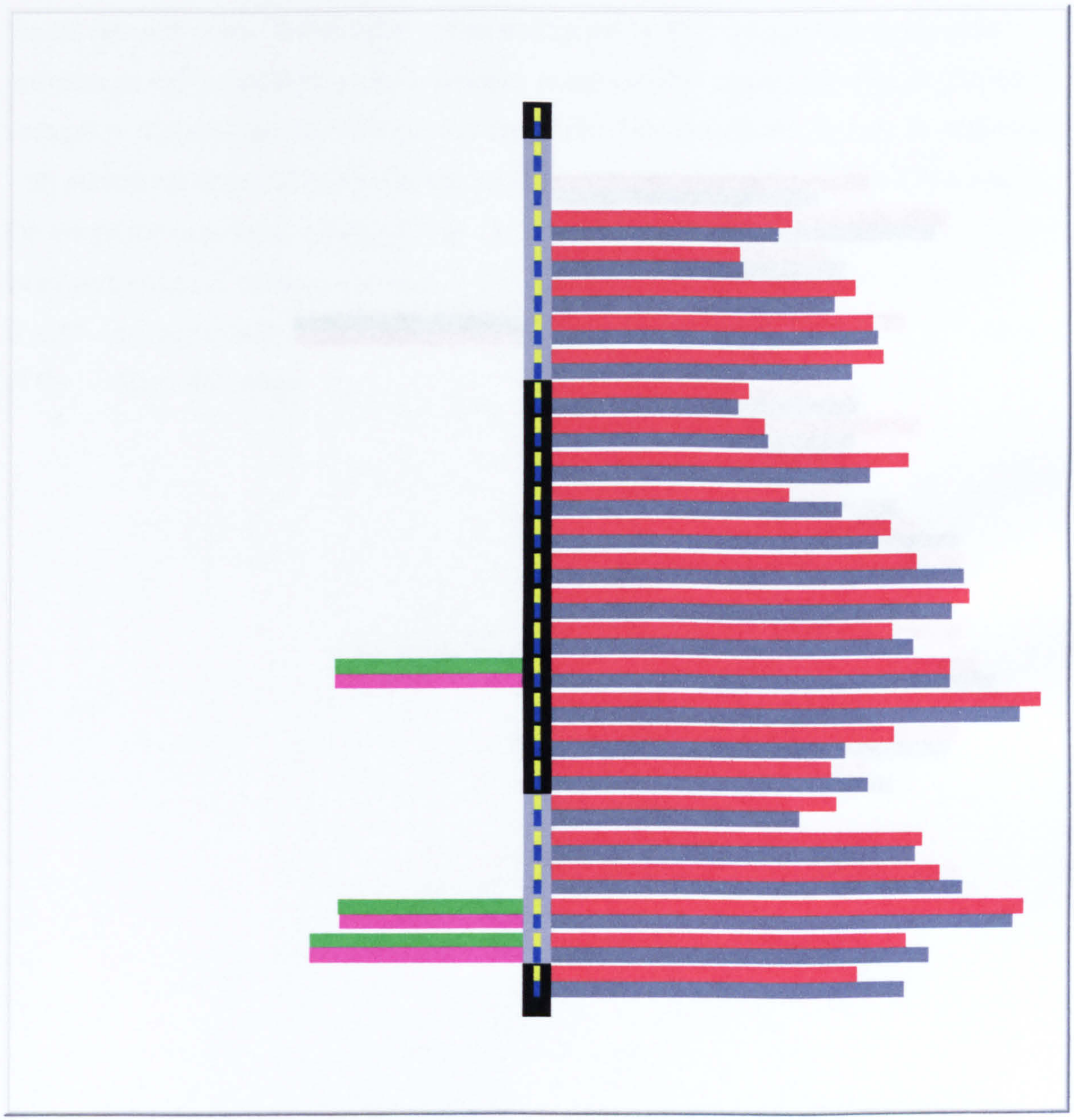
**Key:**

Osteophytes (Severity, Extent)

Porosity (Severity, Extent)

Eburnation (Severity, Extent)

**Figure 7.8(viii) Signpost configuration showing correlation between right acetabulosciatic breadth and degenerative disease indicator by vertebral level in the superior body**



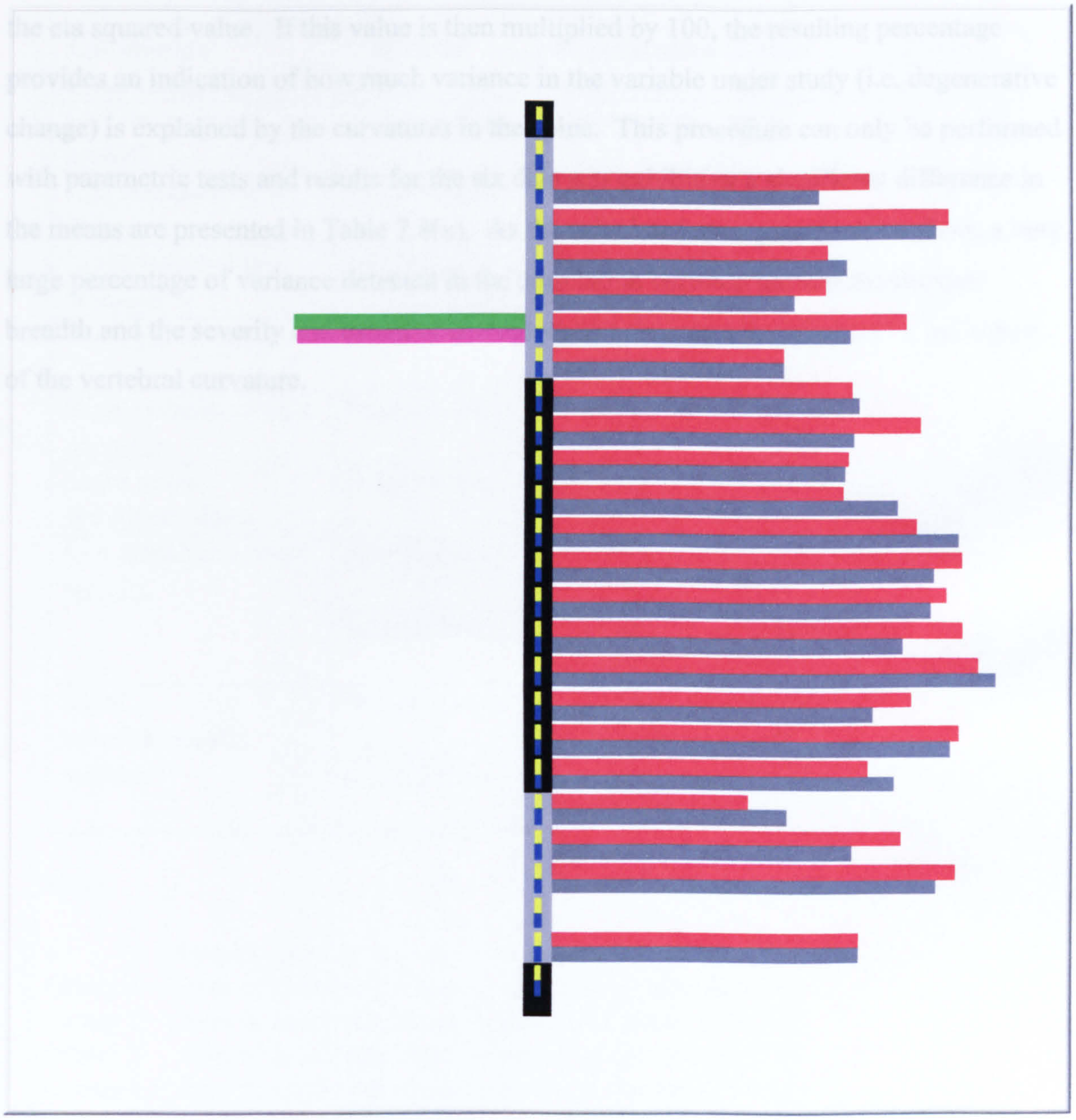
**Key:**

Osteophytes (Severity, Extent)

Porosity (Severity, Extent)

Eburnation (Severity, Extent)

**Figure 7.8(ix) Signpost configuration showing correlation between right acetabulosciatic breadth and degenerative disease indicator by vertebral level in the inferior body**



**Key:**

Osteophytes (Severity, Extent)

Porosity (Severity, Extent)

Eburnation (Severity, Extent)

Where significant differences were detected, effect size statistics were also employed to provide an indication of the magnitude of the difference between the correlations observed in the different areas of the vertebral column (i.e. the correlation between the innominate measurements and degenerative change indicators). This was accomplished by calculating the eta squared value. If this value is then multiplied by 100, the resulting percentage provides an indication of how much variance in the variable under study (i.e. degenerative change) is explained by the curvatures in the spine. This procedure can only be performed with parametric tests and results for the six data sets exhibiting a significant difference in the means are presented in Table 7.8(x). As the calculated eta squared values show, a very large percentage of variance detected in the correlation between the acetabulosciatic breadth and the severity and extent of osteophyte development is explained by the nature of the vertebral curvature.

**Table 7.8(vi) Areas of maximum and minimum stress (as defined by group) exhibiting sufficient data for statistical analysis with innominate measurements**

| Innominate measurement | Vertebral area | Degenerative disease indicator | Group | | | |
|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 |
| Left innominate breadth | Superior body | Osteophytes (extent) | | | • | • |
| Left acetabulum diameter | Inferior body | Osteophytes (extent) | | | • | • |
| Right acetabulum diameter | Inferior body | Osteophytes (severity) | | | • | • |
| | | Osteophytes (extent) | | | • | • |
| Right pubis length | Superior body | Osteophytes (severity) | | | • | • |
| | | Osteophytes (extent) | | | • | • |
| Right pubo-sacroiliac diameter | Superior body | Osteophytes (severity) | | | • | • |
| Right pubic symphysis depth | Superior body | Osteophytes (severity) | • | | | • |
| | | Osteophytes (extent) | • | | | • |
| Left acetabulosciatic breadth | Superior body | Osteophytes (severity) | • | • | • | • |
| | | Osteophytes (extent) | • | • | • | • |
| | Inferior body | Osteophytes (severity) | • | • | • | • |
| | | Osteophytes (extent) | • | • | • | • |
| Right acetabulosciatic breadth | Superior body | Osteophytes (severity) | • | • | • | • |
| | | Osteophytes (extent) | • | • | • | • |
| | Inferior body | Osteophytes (severity) | • | • | • | • |
| | | Osteophytes (extent) | • | • | • | • |

**Key:**

• Groups suitable for statistical analysis
Group 1 Area of maximum stress in vertebral column (C4-C6)
Group 2 Area of minimum stress in vertebral column (C7-T2)
Group 3 Area of maximum stress in vertebral column (T7-T9)
Group 4 Area of minimum stress in vertebral column (T11-L1)

**Table 7.8(vii) Kolmogorov-Smirnov test of normality for degenerative disease indicators in the innominate**

| Innominate measurement | Vertebral area | Degenerative disease indicator | Kolmogorov-Smirnov Statistic | Degrees of freedom | p value | Normal distribution |
|---|---|---|---|---|---|---|
| Left innominate breadth | Superior body | Osteophytes (extent) | .255 | 12 | .030 | ✖ |
| Left acetabulum diameter | Inferior body | Osteophytes (extent) | .285 | 11 | .013 | ✖ |
| Right acetabulum diameter | Inferior body | Osteophytes (severity) | .162 | 13 | .200 | ✓ |
| | | Osteophytes (extent) | .146 | 11 | .200 | ✓ |
| Right pubis length | Superior body | Osteophytes (severity) | .110 | 11 | .200 | ✓ |
| | | Osteophytes (extent) | .125 | 13 | .200 | ✓ |
| Right pubo-sacroiliac diameter | Superior body | Osteophytes (severity) | .186 | 12 | .200 | ✓ |
| Right pubic symphysis depth | Superior body | Osteophytes (severity) | .149 | 14 | .200 | ✓ |
| | | Osteophytes (extent) | .247 | 13 | .029 | ✖ |
| Left acetabulosciatic breadth | Superior body | Osteophytes (severity) | .136 | 23 | .200 | ✓ |
| | | Osteophytes (extent) | .110 | 23 | .200 | ✓ |
| | Inferior body | Osteophytes (severity) | .103 | 23 | .200 | ✓ |
| | | Osteophytes (extent) | .155 | 23 | .157 | ✓ |
| Right acetabulosciatic breadth | Superior body | Osteophytes (severity) | .082 | 23 | .200 | ✓ |
| | | Osteophytes (extent) | .075 | 23 | .200 | ✓ |
| | Inferior body | Osteophytes (severity) | .131 | 22 | .200 | ✓ |
| | | Osteophytes (extent) | .135 | 22 | .200 | ✓ |

**Table 7.8(viii) Independent samples t-test comparing means of groups for degenerative change associated with innominate measurements**

| Innominate measurement | Vertebral area | Degenerative disease indicator | Groups tested | t-test for equality of means* | | | Difference in means |
|---|---|---|---|---|---|---|---|
| | | | | t | df | p value | |
| Right acetabulum diameter | Inferior body | Osteophytes (severity) | 3 and 4 | .006 | 4 | .995 | **No** |
| | | Osteophytes (extent) | 3 and 4 | -.982 | 4 | .382 | **No** |
| Right pubis length | Superior body | Osteophytes (severity) | 3 and 4 | -2.397 | 4 | .075 | **No** |
| | | Osteophytes (extent) | 3 and 4 | .770 | 4 | .484 | **No** |
| Right pubo-sacroiliac diameter | Superior body | Osteophytes (severity) | 3 and 4 | 1.320 | 4 | .257 | **No** |
| Right pubic symphysis depth | Superior body | Osteophytes (severity) | 1 and 4 | -2.219 | 4 | .091 | **No** |
| Left acetabulosciatic breadth | Superior body | Osteophytes (severity) | 1 and 2 | .489 | 4 | .650 | **No** |
| | | | 1 and 4 | -.860† | 2.189 | .473 | **No** |
| | | | 3 and 2 | -1.660 | 4 | .172 | **No** |
| | | | 3 and 4 | .261 | 4 | .807 | **No** |
| | | Osteophytes (extent) | 1 and 2 | .732 | 4 | .504 | **No** |
| | | | 1 and 4 | -.612 | 4 | .573 | **No** |
| | | | 3 and 2 | -2.352 | 4 | .078 | **No** |
| | | | 3 and 4 | 1.051 | 4 | .353 | **No** |

**Key:**

* $H_0 \ \bar{x}_d = 0 \quad H_1 \ \bar{x}_d \neq 0$ (Two-tailed test)

† Equal variances not assumed

Group 1 Area of maximum stress in vertebral column (C4-C6)

Group 2 Area of minimum stress in vertebral column (C7-T2)

Group 3 Area of maximum stress in vertebral column (T7-T9)

Group 4 Area of minimum stress in vertebral column (T11-L1)

**Table 7.8(viii) Independent samples t-test comparing means of groups for degenerative change associated with innominate measurements (contd.)**

| Innominate measurement | Vertebral area | Degenerative disease indicator | Groups tested | t-test for equality of means* | | | Difference in means |
|---|---|---|---|---|---|---|---|
| | | | | t | df | p value | |
| Left acetabulosciatic breadth (contd.) | Inferior body | Osteophytes (severity) | 1 and 2 | 2.651 | 4 | .057 | No |
| | | | 1 and 4 | -.216 | 4 | .840 | No |
| | | | 3 and 2 | -12.591 | 4 | <.001 | Yes |
| | | | 3 and 4 | 1.408 | 4 | .232 | No |
| | | Osteophytes (extent) | 1 and 2 | 3.064† | 2.015 | .091 | No |
| | | | 1 and 4 | -1.146 | 4 | .316 | No |
| | | | 3 and 2 | -7.437† | 2.006 | .017 | Yes |
| | | | 3 and 4 | .936 | 4 | .402 | No |
| Right acetabulosciatic breadth | Superior body | Osteophytes (severity) | 1 and 2 | .401 | 4 | .709 | No |
| | | | 1 and 4 | -.681 | 4 | .533 | No |
| | | | 3 and 2 | -2.882 | 4 | .045 | Yes |
| | | | 3 and 4 | -2.742 | 4 | .052 | No |
| | | Osteophytes (extent) | 1 and 2 | .626 | 4 | .565 | No |
| | | | 1 and 4 | -.407 | 4 | .705 | No |
| | | | 3 and 2 | -4.204 | 4 | .014 | Yes |
| | | | 3 and 4 | -4.215 | 4 | .014 | Yes |

**Key:**

* $H_0\ \bar{x}_d = 0\quad H_1\ \bar{x}_d \neq 0$ (Two-tailed test)
† Equal variances not assumed
Group 1 Area of maximum stress in vertebral column (C4-C6)
Group 2 Area of minimum stress in vertebral column (C7-T2)
Group 3 Area of maximum stress in vertebral column (T7-T9)
Group 4 Area of minimum stress in vertebral column (T11-L1)

**Table 7.8(viii) Independent samples t-test comparing means of groups for degenerative change associated with innominate measurements (contd.)**

| Innominate measurement | Vertebral area | Degenerative disease indicator | Groups tested | t-test for equality of means* | | | Difference in means |
|---|---|---|---|---|---|---|---|
| | | | | t | df | p value | |
| Right acetabulosciatic breadth (contd.) | Inferior body | Osteophytes (severity) | 1 and 2 | .013 | 4 | .990 | No |
| | | | 1 and 4 | -.078 | 4 | .941 | No |
| | | | 3 and 2 | -2.714 | 4 | .053 | No |
| | | | 3 and 4 | -1.705 | 4 | .163 | No |
| | | Osteophytes (extent) | 1 and 2 | -.061 | 4 | .955 | No |
| | | | 1 and 4 | -.919 | 4 | .410 | No |
| | | | 3 and 2 | -3.054 | 4 | .038 | Yes |
| | | | 3 and 4 | -1.199 | 4 | .297 | No |

**Key:**

* $H_0 \ \bar{x}_d = 0 \quad H_1 \ \bar{x}_d \neq 0$ (Two-tailed test)
Group 1 Area of maximum stress in vertebral column (C4-C6)
Group 2 Area of minimum stress in vertebral column (C7-T2)
Group 3 Area of maximum stress in vertebral column (T7-T9)
Group 4 Area of minimum stress in vertebral column (T11-L1)

**Table 7.8(ix) Mann-Whitney U test comparing medians of groups for degenerative change associated with innominate measurements**

| Innominate measurement | Vertebral area | Degenerative disease indicator | Groups tested | Mann-Whitney U test** | | Difference in medians |
|---|---|---|---|---|---|---|
| | | | | z | p value | |
| Left innominate breadth | Superior body | Osteophytes (extent) | 3 and 4 | -.218 | 1.000 | **No** |
| Left acetabulum diameter | Inferior body | Osteophytes (extent) | 3 and 4 | -.655 | .513 | **No** |
| Right pubic symphysis depth | Superior body | Osteophytes (extent) | 1 and 4 | -1.964 | .050 | **Yes** |

**Key:**

** $H_0$ $\theta_d = 0$ $H_1$ $\theta_d \neq 0$ (Two-tailed test)
Group 1 Area of maximum stress in vertebral column (C4-C6)
Group 3 Area of maximum stress in vertebral column (T7-T9)
Group 4 Area of minimum stress in vertebral column (T11-L1)



**Table 7.8(x) Effect size for the independent samples t-test (Eta squared vales)**

| Innominate measurement | Vertebral area | Degenerative disease indicator | Groups tested | t-test for equality of means | | | Eta squared |
|---|---|---|---|---|---|---|---|
| | | | | t | df | p value | |
| Left acetabulosciatic breadth | Inferior body | Osteophytes (severity) | 3 and 2 | -12.591 | 4 | <.001 | **0.9753 (97.53%)** |
| | | Osteophytes (extent) | 3 and 2 | -7.437† | 2.006 | .017 | **0.9326 (93.26%)** |
| Right acetabulosciatic breadth | Superior body | Osteophytes (severity) | 3 and 2 | -2.882 | 4 | .045 | **0.6750 (67.50%)** |
| | | Osteophytes (extent) | 3 and 2 | -4.204 | 4 | .014 | **0.8154 (81.54%)** |
| | | | 3 and 4 | -4.215 | 4 | .014 | **0.8162 (81.62%)** |
| Right acetabulosciatic breadth | Inferior body | Osteophytes (extent) | 3 and 2 | -3.054 | 4 | .038 | **0.6999 (69.99%)** |

*Summary of results for innominate*

Of the 93 'signpost' configurations examined, osteophyte development was the most frequently occurring manifestation observed. One hundred and seventy two (90.5%) of the configurations exhibited osteophytic change. Of these, 88 (51.2%) represented the severity of the osteophytic development and 84 (48.8%), the extent of the change. Porotic changes were noted in a total of 16 (8.4%) 'signposts', with nine (56.2%) and seven (43.8%) representing the extent and severity of the manifestation respectively. Two (1.1%) 'signposts' exhibited eburnation, with one (50%) representing the severity of the manifestation and one (50%) representing the extent of change.

With regard to the presence of any patterning observed in the presentation of the degenerative disease indicators, it can be suggested that the lower third of the thoracic spine and all of the lumbar area tended to generally exhibit the greatest correlation between the measurements concerned and the severity and extent of osteophytic change on the superior body surface. On the inferior body surface, degenerative change was mainly observed in the lower and upper halves of thoracic and lumbar regions respectively. Reports in the literature attest to this area of the spine exhibiting greater manifestations of pathological change (see Section 5.1.2). If correlations between innominate measurements and the severity and extent of osteophytosis reflect this fact, then this does suggest that pelvic size, as represented by the aforementioned innominate measurements, is contributing to this manifestation.

In the case of nine measurements (left and right maximum innominate length, left maximum innominate breadth, left iliac height, left and right acetabulum diameter, right pubis length and left and right acetabulosciatic breadth), a patterning in the areas of maximum and minimum correlation values could be discerned in the 'signpost' configurations. It has already been noted that the areas of maximum curvature in the human spine exhibit a predilection for the development of degenerative disease. If indeed the magnitude of a particular innominate measurement were contributing to the development of degenerative disease in the vertebral column as well, then it would be expected that the expression of the correlations comprising the 'signposts' would also reflect this pattern. That means that areas of maximum curvature and stress (C5, T8 and L4) should show larger correlations and areas of minimum curvature and stress (T1, T12 and L5/S1) should exhibit smaller ones. For the greater part, this is borne out in the 'signpost' configurations with respect to the severity and extent of osteophyte

development. On the superior body surfaces, smaller correlations were found for the left and right maximum innominate lengths at L1; for the left iliac height, at L5/S1; for the left and right acetabulum diameters and right pubis length, at L1 (for extent of affect only) and for the left and right acetabulosciatic breadths at T1, T12/L1 and S1. For the greater correlations on the superior body surface, the left and right acetabulum diameters exhibit these at T10 and L3; the right pubis length, at T6 (for extent of affect only) and the left and right acetabulosciatic breadths at C5-7, T10 and L4. On the inferior body surfaces, smaller correlations were found for the left and right acetabulum diameters at L1 and for the left and right acetabulosciatic breadths at T1 and L1. For the greater correlations on the inferior body surface, the left and right acetabulum diameters exhibit these at T9 and the left and right acetabulosciatic breadths, at C3, T9 and L3.

Those correlations not showing the expected patterning comprised the left innominate breadth, where a maximum correlation was noted at T11; the left iliac height, where a maximum correlation was observed at L2 and the right pubis length, where maximum correlation was seen at T12 (for severity of affect only) and a minimum, at T9 (for extent of affect only).

The data for porotic change and eburnation was very limited and exclusive to only four measurements (left and right pubis length, right pubo-sacroiliac diameter and right ischial spine to symphysion). Furthermore, each of these measurements was only assessed with respect to one area of the vertebra and so no general suggestions regarding the effect of those measurements on the expression of vertebral degenerative disease could be made.

Statistical analysis conducted on eight of the innominate measurements (see table 7.8(viii)) revealed that statistically significant differences, between the correlations observed between measurements and the severity and extent of osteophyte development observed at the points of maximum and minimum curvature, occurred in only three of these. These included right pubis symphysis depth and left and right acetabulosciatic breadths.

In the case of right pubic symphysis depth, there was a statistically significant difference between the correlation between this measurement and the extent of osteophytosis at the points of maximum and minimum curvature (centred around C5 and T12 respectively) on the superior body surface.

With left acetabulosciatic breadth, there was a statistically significant difference between the correlation between this measurement and the severity and extent of osteophytosis observed at the points of maximum and minimum curvature (centred around T8 and T11 respectively) on the inferior body surface.

With right acetabulosciatic breadth, there was a statistically significant difference between the correlation between this measurement and the severity and extent of osteophytosis observed at the points of maximum and minimum curvature (centred around T8 and T1 respectively) on the superior body surface. The extent of osteophyte development was also similarly affected between the levels of maximum and minimum stress centred around T8 and T12 respectively.

In the inferior body, right acetabulosciatic breadth also exhibited a statistically significant difference between the correlation between this measurement and the extent of osteophytosis observed at the points of maximum and minimum curvature (centred around T8 and T1 respectively) on the superior body surface.

### *c) The reconstructed pelvis*

From the 216 'signpost' configurations created for this skeletal element, six qualified for further examination and represented five of the measurements and eight degenerative disease indicators as detailed in Table 7.8(xi)

*Results based on visual appearance*

Of the eight degenerative disease indicators represented in the six 'signposts' examined, six were deemed amenable to visual interpretation only (all involving general area observations). Of the remaining two 'signposts', one was excluded due to the preclusive nature of data values comprising the horizontal axes and the other comprised negative values that were discussed separately (see table 7.8(xi)).

All values comprising the 'signposts', with the exception of those associated with the subpubic angle, were positive in nature, thus implying a positive correlation between the measurement observed in the reconstructed pelvis and the degree of degenerative change observed in the vertebral column. Therefore, as the measurements concerned increased in size, so did the severity and extent of the change observed in particular regions of the vertebral column. The subpubic angle data will be discussed separately later in this section.

**Table 7.8(xi) Significant 'signpost' configurations for reconstructed pelvis measurements**

| Reconstructed pelvis measurement | Vertebral area | Degenerative disease indicator | Interpretation |
|---|---|---|---|
| Greatest pelvic diameter | Right superior costal facet | Porosity (severity) | •G |
| | | Porosity (extent) | •G |
| Bi-tuberous width | Inferior body | Porosity (severity) | •P |
| | | Porosity (extent) | •G |
| Subpubic angle | Superior body | Osteophytes (severity) | •G * |
| Superior-anterior bi-iliac breadth of pelvis | Superior body | Osteophytes (severity) | ▲ |
| | Inferior body | Osteophytes (severity) | •G |
| Inferior-posterior bi-iliac breadth of pelvis | Left superior costal facet | Osteophytes (severity) | •G |

**Key:**

▲ Visual and statistical interpretation precluded

•G Visual interpretation possible. Observations made with regards to *general* areas affected, but no statistical analysis undertaken

•P Visual interpretation possible. Observations made with regards to actual *patterning* in presentation, but no statistical analysis undertaken

* Data consisted of negative values

Although it was possible to generally consider the measurements in three groups: medial-lateral (incorporating the superior-anterior bi-iliac breadth of the pelvis and the bi-tuberous width); oblique, orientated in the posterosuperior-anteroinferior plane (greatest pelvic diameter) and an angle (subpubic angle), the data was insufficient to make any generalizations. As such, visual assessments are briefly described here.

For those measurements categorised as medial-lateral, the correlation between the superior-anterior bi-iliac breadth of the pelvis and the severity of osteophytosis on the inferior body, mainly affected the levels extending from the lower quarter of the thoracic to the mid lumbar region. In the case of the bi-tuberous width, the correlation with the severity and extent of porosity on the inferior body, mainly affected the lower half of the cervical spine. None of the articular facets were represented by these measurements and only the left superior costal facet was assessed for the inferior-posterior bi-iliac breadth of the pelvis. This showed the correlations with osteophyte severity mainly being sited in the thoracic region generally.

With the oblique measurement, the correlation between the greatest pelvic diameter and the severity and extent of porotic change was noted to affect the thoracic area in the T5-T9 range. No other assessments of any other vertebral area of degenerative disease indicator could be undertaken with this measurement.

The subpubic angle was only assessed for correlation with the severity of osteophytosis on the superior vertebral body. All correlations were negative, but exhibited a general area of affect extending from the lower third of the thoracic region to L5. As with the previous measurement, no other assessments of degenerative disease in any other vertebral area could be undertaken with this measurement.

*Results based on statistical analysis*

Of the eight degenerative disease indicators concerned, none exhibited full data sets for at least one of each of the groups representing the maximum and minimum areas of stress in the vertebral column. This means that no statistical interpretation of results could be undertaken.

*Summary of results*

Of the eight 'signpost' configurations examined, osteophytic and porotic change was equally represented. Four (50%) of the configurations exhibited osteophytic change. Of these, two (25%) represented the extent of the osteophytic development and two 25(%), the severity of the change. Porotic changes were noted in a total of four (50%) 'signposts', with two (50%) and two (50%) representing the extent and severity of the manifestation respectively.

With regard to the presence of any patterning observed in the presentation of the degenerative disease indicators, it can be suggested that, once again, results have tended to highlight the lower half of the thoracic spine and lumbar area as those tending to generally exhibit the greatest correlation between the measurements concerned and the severity and extent of osteophytic and porotic change. In the case of the bi-tuberous width, the lower cervical area was also targeted. As previously alluded to, the lower cervical, lower thoracic and lumbar regions are those areas reported in the literature as demonstrating a greater affectation with degenerative disease (see Section 5.1.2). The findings with the reconstructed pelvis measurements, although extremely limited, do reflect this pattern of

affect, thus suggesting that pelvic size, as represented by the aforementioned measurements observed in the reconstructed pelvis, is possibly contributing to this manifestation.

The subpubic angle data was interesting in that it presented negative correlations for the severity of osteophyte development on the superior body surface. This would tend to suggest, therefore, that as the angle increased in size, the severity of pathological change observed in particular regions of the vertebral column would decrease. This is surprising, as a greater subpubic angle is associated with the more capacious and relatively unstable female pelvis and, as such, would be expected to incur greater referred stresses in the vertebral column as a result. In effect, therefore, this finding is completely opposed to what would be expected, especially as all other measurements in the pelvis and its constituent elements exhibited positive correlations in the data observed. Of the 12 'signposts' constructed for this particular measurement, only this one warranted further examination. However, if the data comprising the remaining 11 'signposts' is reviewed, it can be seen that correlations are mainly positive (in six) or mixed (in four) and only one other area (the left superior articular facet) produced negative results. However, it must also be remembered that none of these 11 'signposts' produced sufficient data to warrant further examination and so data contained therein must be treated with caution. Clearly this is an area that needs to be investigated further.

Statistical analyses conducted showed that there was no statistically significant difference between the site and severity of osteophytosis observed on the superior and inferior body surface.

***d) General summary***

The 'signpost' data that warranted further examination was extremely limited and the various problems associated with this have been discussed in section 7.8.3. Despite this limitation, however, it was considered prudent to at least make tentative exploratory assessments based on what was observed in these configurations, although caution was exercised in regard to any interpretations made. Any potential patterns identified could thus be subjected to further investigation to see if they did indeed reflect any relationships in the data.

In summary, the data could thus be examined with regard to three aspects: 1) the type of degenerative disease indicator observed; 2) the general area of vertebral affectation and 3) any possible patterns in the spread and magnitude of pathological manifestation.

*The type of degenerative disease indicator*

The frequency of degenerative change type observed in the 'signpost' configurations is presented, by pelvic area, in Table 7.8(xii). This shows that for all areas of the pelvis, osteophyte development was the most frequently observed, with 76.7%, 90.5% and 50% of 'signposts' configured for the sacrum, innominate and reconstructed pelvis respectively exhibiting this manifestation. The severity and extent of the affect were represented almost equally in the three pelvic areas. Porosity was also noted, but to a much lesser extent, with 23.3%, 8.4% and 50% of 'signposts' configured for the sacrum, innominate and reconstructed pelvis respectively displaying this pathological change. The severity and extent of the affect were again represented almost equally in the three pelvic areas. Eburnation was only recorded in one case and accounted for 1.1% of pathological change observed in the innominate.

It is perhaps not surprising that osteophytosis should be the most frequently observed degenerative disease indicator, as it is part of a normal degenerative process that affects joint margins generally (see Section 5.1.2a). Stresses and damage sustained to the cartilaginous intervertebral joints may predispose to osteophyte development, either as a result of intervertebral disc degeneration, or subsequent to traumatic and infectious processes (see Section 5.2.1). The degree of spinal curvature is also considered a predisposing factor (see section 5.2.1c) and age plays a part too, with an increase in severity being observed with time. Essentially, the osteophytes serve to redistribute abnormal loads acting through the spine, in very much the same way as capitals and bases of architectural columns serve to support and transmit forces through their shafts.

*Area of vertebral body affected*

The vertebral areas affected by degenerative change in the 217 'signposts' constructed are presented, by pelvic area, in Table 7.8(xiii). Please note that percentages have been rounded up to one decimal place. The areas that tended to be mainly affected were the superior and inferior body surfaces and as previously noted, it was the severity and extent

**Table 7.8(xii)** **Degenerative change type observed in 'signposts' by pelvic area**

| Pelvic area | Osteophytes | | | Porosity | | | Eburnation | | |
|---|---|---|---|---|---|---|---|---|---|
| | Total (%) | Severity (%) | Extent (%) | Total (%) | Severity (%) | Extent (%) | Total (%) | Severity (%) | Extent (%) |
| Sacrum | 76.7 | 36.7 | 40 | 23.3 | 10 | 13.3 | 0 | 0 | 0 |
| Innominate | 90.5 | 51.2 | 48.8 | 8.4 | 43.8 | 56.2 | 1.1 | 50 | 50 |
| Reconstructed pelvis | 50 | 25 | 25 | 50 | 25 | 25 | 0 | 0 | 0 |

**Table 7.8(xiii) Area of affectation by degenerative change type observed in 'signposts' by pelvic area (Expressed as a percentage of the total number of 'signposts' constructed)**

| | Superior body | | | | | | Inferior body | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pelvic area** | **os** | **oe** | **ps** | **pe** | **es** | **ee** | **os** | **oe** | **ps** | **pe** | **es** | **ee** |
| **Sacrum** | 1.8 | 2.3 | 0.5 | 0.5 | 0 | 0 | 2.3 | 2.3 | 0.5 | 0.5 | 0 | 0 |
| **Innominate** | 16.1 | 15.2 | 0.9 | 0.9 | 0 | 0 | 12.4 | 9.7 | 0.5 | 0.5 | 0 | 0 |
| **Reconstructed pelvis** | 0.9 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 | 0.5 | 0.5 | 0 | 0 |

| | Left Superior Articular Facet | | | | | | Right Superior Articular Facet | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pelvic area** | **os** | **oe** | **ps** | **pe** | **es** | **ee** | **os** | **oe** | **ps** | **pe** | **es** | **ee** |
| **Sacrum** | 0 | 0 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Innominate** | 1.8 | 1.8 | 0.5 | 0.5 | 0 | 0 | 3.2 | 3.7 | 0 | 0 | 0 | 0 |
| **Reconstructed pelvis** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Key:**

| | | | | | |
|---|---|---|---|---|---|
| **os** | Osteophyte (severity) | **ps** | Porosity (severity) | **es** | Eburnation (severity) |
| **oe** | Osteophyte (extent) | **pe** | Porosity (extent) | **ee** | Eburnation (extent) |

**Table 7.8(xiii)** **Area of affectation by degenerative change type observed in 'signposts' by pelvic area (contd.) (Expressed as a percentage of the total number of 'signposts' constructed)**

| | Left Inferior Articular Facet | | | | | | Right Inferior Articular Facet | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pelvic area** | **os** | **oe** | **ps** | **pe** | **es** | **ee** | **os** | **oe** | **ps** | **pe** | **es** | **ee** |
| **Sacrum** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0.5 | 0 | 0 |
| **Innominate** | 3.7 | 3.7 | 0.9 | 0.9 | 0.5 | 0.5 | 1.8 | 1.4 | 0.5 | 0.5 | 0 | 0 |
| **Reconstructed pelvis** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | Left Superior Costal Facet | | | | | | Right Superior Costal Facet | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pelvic area** | **os** | **oe** | **ps** | **pe** | **es** | **ee** | **os** | **oe** | **ps** | **pe** | **es** | **ee** |
| **Sacrum** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Innominate** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 | 0 |
| **Reconstructed pelvis** | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | 0 |

**Key:**

| | | | | | |
|---|---|---|---|---|---|
| **os** | Osteophyte (severity) | **ps** | Porosity (severity) | **es** | Eburnation (severity) |
| **oe** | Osteophyte (extent) | **pe** | Porosity (extent) | **ee** | Eburnation (extent) |

**Table 7.8(xiii)** **Area of affectation by degenerative change type observed in 'signposts' by pelvic area (contd.) (Expressed as a percentage of the total number of 'signposts' constructed)**

| | Left Inferior Costal Facet | | | | | | Right Inferior Costal Facet | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pelvic area** | **os** | **oe** | **ps** | **pe** | **es** | **ee** | **os** | **oe** | **ps** | **pe** | **es** | **ee** |
| **Sacrum** | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Innominate** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Reconstructed pelvis** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | Left Transverse Process Facet | | | | | | Right Transverse Process Facet | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pelvic area** | **os** | **oe** | **ps** | **pe** | **es** | **ee** | **os** | **oe** | **ps** | **pe** | **es** | **ee** |
| **Sacrum** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Innominate** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Reconstructed pelvis** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Key:**

| | | | | | |
|---|---|---|---|---|---|
| **os** | Osteophyte (severity) | **ps** | Porosity (severity) | **es** | Eburnation (severity) |
| **oe** | Osteophyte (extent) | **pe** | Porosity (extent) | **ee** | Eburnation (extent) |

of osteophyte development that was most frequently represented in the 'signpost' configurations.

These results may simply reflect the fact that it is the bodies of the vertebrae that tend to survive fairly well and provide material for examination, whereas articular and transverse process facets are susceptible to loss through post-mortem erosion as a result of their somewhat 'exposed' positions. Costal facets, on the other hand, tend to survive fairly intact on the lateral aspects of the thoracic bodies, but exhibit less evidence of degenerative change simply because affectation is far less marked. Therefore care must be taken not to interpret a lack of pathological change as an absolute actual absence.

*Patterns of affect*

The patterns of affectation observed in the 'signpost' configurations were all tentatively made. However, it could be suggested that correlations between the measurements in the sacrum and the severity and extent of osteophytosis and porosity tended to be concentrated in the lower half of the thoracic column, on both superior and inferior body surfaces. In the innominate, the correlations between measurements and the severity and extent of osteophyte development were found to mainly affect the lower third of the thoracic through lumbar region and lower thoracic through upper lumbar area, on the superior and inferior body surfaces respectively. Correlations between the measurements in the reconstructed pelvis and the severity and extent of osteophytosis and porosity tended to be concentrated in the lower half of the thoracic column and throughout the lumbar region, on both superior and inferior body surfaces

As previously noted, reports in the literature have attested to the lower cervical, lower thoracic and lumbar regions (which experience maximal spinal motion), demonstrating greater affectation with degenerative disease (see Section 5.1.2). The findings from this study support this and, as correlations are being examined, also suggest that the measurements themselves are contributing to the development of the pathological change.

If it is hypothesized that a more capacious pelvis is more likely to predispose individual to developing degenerative change and if, from literature, this pathological change is found to manifest at levels of maximum curvature preferentially, then expect to see a greater level of correlation between measurements and degenerative disease indicator at that particular vertebral level if the pelvic size is playing a part in the overall development. That tended to be borne out by the results examined here.

With the exception of one measurement (subpubic angle in the reconstructed pelvis) all correlations were found to be positive. This suggests that as the measurements increase in size, a concomitant increase in the severity and extent of the affect of the degenerative change will be expected. Although the subpubic angle produced negative correlations, this was not felt to reflect expected results and it is difficult to offer any anatomical explanation for such an expression anatomically. As previously noted, it may simply be that the data comprising the 'signpost' under study in this case is not representative of the relationship between the measurement and development of degenerative change, but may have evolved as a result of sampling variation. Clearly further examination of this particular measurement is warranted.

Statistical analyses were also undertaken to see if differences between correlations at levels of maximum and minimum curvature were statistically significant. The inadvisability of employing such small group sizes for this analysis has already been highlighted, as groups of this size, generally speaking, would not be expected to exhibit any significant differences. However, it was felt that it would be interesting to run the tests anyway and explore any results generated.

Forty-three tests were carried out (representing one measurement in the sacrum and eight in the innominate) and of these, four produced significant results. The measurements concerned were all from the innominate. The right pubis symphysis depth showed a significant difference in the correlations between the extent of osteophytosis observed at the levels of maximum and minimum curvature on the superior body surface at C5 and T12 respectively. The right acetabulosciatic breadth exhibited a significant difference in the correlations with the osteophytosis (severity and extent) observed at the levels of maximum and minimum curvature on the superior body surface at T8 and T1 respectively. Similar differences were found between correlations with the extent of osteophytosis at the levels of maximum and minimum curvature on the inferior body surface at T8 and T11 respectively.

The left acetabulosciatic breadth showed a significant difference in the correlations with the osteophytosis (severity and extent) observed at the levels of maximum and minimum curvature on the inferior body surface at T8 and T1 respectively. These significant differences suggest that the measurements concerned are playing a role in the expression of degenerative change at the different vertebral levels representing maximum and minimum curvature and that the curvature itself is not wholly responsible.

### 7.8.4 Hypothesis testing and predictive approaches to assessment of development of degenerative disease in the vertebral column

In Section 7.8.1, it was noted that, due to constraints with the present study, each of the pelvic measurements would only be considered in isolation and not in combination. This approach was adopted to potentially highlight those individual measurements (if any) that could be more likely to contribute to the development of degenerative change in the vertebral column.

Any such measurements thus identified could then be further examined (for example, by employment of discriminant function analysis), to explore the predictive ability of a combination of measurements to predispose to the development of the three degenerative disease indicators (osteophytes, porosity, eburnation) in a particular vertebral area. The results obtained, however, have been extremely limited. Despite this, it was felt that a few measurements could prove to have some promising possibilities. If these measurements were then examined in combination, could they possibly predict the level of degenerative change expected in a certain area of the vertebra? In order to answer this question, a number of parameters had to first be considered. In the first instance, a particular area of the vertebra had to be selected. As the superior body surface exhibited the greatest involvement (see Table 7.8(xiii)), this was selected. Secondly, a degenerative disease indicator had to be chosen and as the severity of osteophytosis was the most frequently observed manifestation, generally speaking, on the superior body surface, this was selected for examination. Finally, a set of measurements had to be decided on and these were made from those comprising the 'signposts' that were both visually and statistically assessed. In the sacrum, the maximum depth of curvature was selected. Although this did not produce any statistically significant results, the data presented in the 'signpost' configuration was extensive enough to warrant inclusion for this parameter. In the innominate, three measurements were selected and all of these produced statistically significant results for tests of differences in the areas of maximum and minimum curvature in the spine. These measurements included the right pubis symphysis depth and the left and right acetabulosciatic breadths.

With the selection of variables complete, a model was constructed and sought to examine how well this set of measurements was able to predict the severity of osteophytosis on the superior vertebral body surface. In order to undertake this analysis, a new variable had to be created that would reflect the magnitude of osteophyte severity in this particular area. As each individual in the sample could potentially express a different grading for this

manifestation at each of the vertebral levels form C3 to S1, it was not considered appropriate to assign any type of 'average' score for the superior body surface generally. Instead, a cumulative score was calculated by adding all of the grades recorded for the superior body surfaces from C3 through to S1. This new variable was named the 'osteophyte severity score for the superior body surface' and coded as 'ossbs' in the SPSS data editor. Values for this new variable ranged from 0 to 54. This variable was then recoded into three separate groups, which represented a different magnitude of affectation. Group 1 was identified as minimal expression of osteophyte severity and 'ossbs' values falling in the range from 0 to 18 were recoded as such. Group 2 was classified as moderate expression of osteophyte severity and 'ossbs' values falling in the range from 19 to 37 were included in this category. Finally, Group 3 was labelled as severe expression of osteophyte severity and 'ossbs' values falling in the range from 38 to 56 were recoded as such. These three groups were identified as the 'osteophyte severity grouping' variable and were listed under the variable title of 'osgroup' in the SPSS data editor. Discriminant function analysis was then undertaken, utilising the 'osgroup' variable as the dependant one and the four measurements as the independent ones. The output generated by this analysis is presented in Appendix 11, Volume 2.

The Eigenvalue (Table 7.8(xiv)) presents the ratio of importance of the measurements that classify the grading of the osteophyte severity and reflect the percentage of variance explained in the degenerative disease indicator. In this case, the first discriminant function value accounts for 93.2% of the variance, or about 13 times the percentage of variance of the second discriminant function (6.8%). Examination of the relative percentages of variance accounted for by each discriminant function provides useful information and here suggests that only the first is likely to discriminate between the groups (level of severity of osteophytosis) with any accuracy.

**Table 7.8(xiv) Summary of Canonical Discriminant Functions - Eigenvalues**

| Function | Eigenvalue | % of Variance | Cumulative % | Canonical Correlation |
|---|---|---|---|---|
| 1 | 1.472 [a] | 93.2 | 93.2 | .772 |
| 2 | .107 [a] | 6.8 | 100.0 | .311 |

[a] First 2 canonical discriminant functions were used in the analysis.

The Wilks' lambda value (Table 7.8(xv)) indicates if there is any statistical difference among the groups and results show that one does exist (Wilks' lambda =.365, p=.001).

**Table 7.8(xv) Summary of Canonical Discriminant Functions - Wilks' Lambda**

| Test of Function(s) | Wilks' Lambda | Chi-square | df | Sig. |
|---|---|---|---|---|
| 1 through 2 | .365 | 25.679 | 8 | .001 |
| 2 | .903 | 2.600 | 3 | .457 |

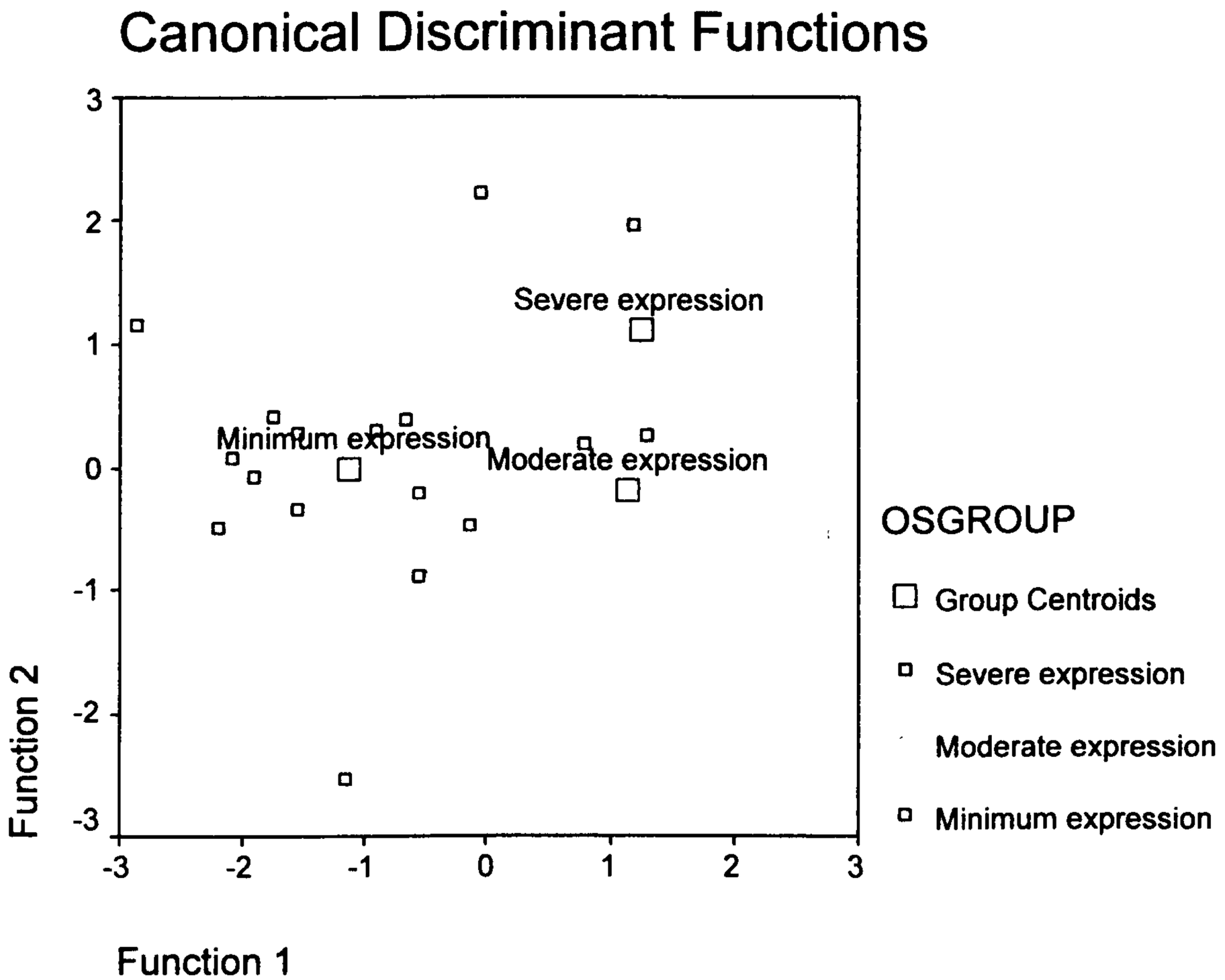
The standardized canonical discriminant function coefficients (Table 7.8(xvi)) indicate which of the four measurements is most important in the model and is identified by the largest value, irrespective of whether it is positive or negative. In this case, S1_BG (the right acetabulosciatic breadth) is the most important (value of .572) with regard to function 1 (plotted on the x-axis) and S1_BF (the left acetabulosciatic breadth) the most important (value of –1.690) with regard to the function 2 (the y co-ordinate).

**Table 7.8(xvi) Summary of Canonical Discriminant Functions - Standardized Canonical Discriminant Function Coefficients**

| | Function | |
|---|---|---|
| | 1 | 2 |
| S1_T | .276 | .535 |
| S1_AU | .371 | .379 |
| S1_BF | .213 | -1.690 |
| S1_BG | .572 | 1.162 |

The resulting discriminant function can then be plotted in a scatter plot (Figure 7.8(x)) to give a visual representation of the results. In this case, the large mauve squares indicate the centroids, or means, of each of the three groups on the computed discriminant function variables. Group membership is indicated by the use of different markers and colours for each subject as detailed in Figure 7.8(x). By projecting these points onto the x-axis, it is possible to see how the first discriminant function works to discriminate between the levels of severity observed for osteophytosis on the superior body surface. Here minimum expression scores the lowest and can be differentiated between moderate and severe expression. However, the centroids of the latter two project to pretty much the same value on the x-axis and so may not be differentiated between. Similarly, if points are projected onto the y-axis, it is possible to see how the second discriminant function serves to

**Fig 7.8(x) Canonical discriminant functions for grading of expression of osteophyte severity on the superior vertebral surface**




discriminate between the levels of severity observed for osteophytosis on the superior body surface. In this function, severe expression can be distinguished from minimum and moderate grading levels, but the latter two may not be differentiated as the centroids of these project to similar values on the y-axis.

These discriminant function coefficients thus allow for computation of a new variable that can be used to discriminate between each of the three groups representing degree of pathological manifestation. Because the new variable is standardized, the first step in computation is to convert all the dependent variables to standard scores. This is easily accomplished in SPSS, with new standardized z score variables being added to the data editor. The second step is the multiplication of the standardized canonical discriminant function coefficients with each of the standardized z scores and then summing of those results.

To plot a new variable from a new set of measurements taken of the four analysed here, values for function 1 and function 2 thus need to be calculated as follows:

For function 1 (x axis co-ordinate), the following equation is employed:

(.276 x standardized z score for maximum depth of curvature) + (.371 x standardized z score for right pubic symphysis depth) + (.213 x standardized z score for left acetabulosciatic breadth) + (.572 x standardized z score for right acetabulosciatic breadth) = New function 1 value

For function 2 (y axis co-ordinate), the following equation is employed:

(.535 x standardized z score for maximum depth of curvature) + (.379 x standardized z score for right pubic symphysis depth) + (-1.690 x standardized z score for left acetabulosciatic breadth) + (1.162 x standardized z score for right acetabulosciatic breadth) = New function 2 value

The new function 1 and function 2 values can then be plotted on the preceding scatter plot (Figure 7.8(x)) and the predicted level of expression for osteophyte severity deduced. As an example, say that an additional individual from another 18$^{th}$-19$^{th}$ century North-west European sample has been found. What level of severity of osteophytosis on the superior body surfaces would be expected? Values for the four pelvic measurements would need to be recorded and standardized z scores calculated for those values. Contrived data has been utilized for this purpose and entered as burial 104 on the SPSS data editor. The standardized z scores are presented as variables zs1_t, zs1_au, zs1_bf and zs1_bg. Relevant data is shown in Table 7.8(xvii).

**Table 7.8(xvii) Contrived data for predicting severity of osteophytosis on the superior body surface**

| Measurement | Value | z score |
|---|---|---|
| Maximum depth of curvature of sacrum | 18.92 mm | -1.06244 |
| Right pubic symphysis depth | 35.27 mm | -0.71513 |
| Left acetabulosciatic breadth | 32.91 mm | -0.94098 |
| Right acetabulosciatic breadth | 34.35 mm | -0.49904 |

Calculation of the new functions for this individual are undertaken as follows:

For function 1 (x axis co-ordinate):

(.276 x -1.06244) + (.371 x -0.71513) + (.213 x -0.94098) + (.572 x -0.49904) = -1.04

For function 2 (y axis co-ordinate):

(.535 x -1.06244) + (.379 x -0.71513) + (-1.690 x -0.94098) + (1.162 x -0.49904) = 0.17

If the two functions generated were then plotted in the scatter plot, the resulting co-ordinate would lie within the area of minimum expression for osteophytosis severity and lie fairly close to the centroid for that group. Thus, from the measurements of this additional individual, one could predict that only minimal pathological change associated with this degenerative disease indicator would be observed on the superior vertebral body surfaces.

As noted at the start of this section, this analysis was only intended to be exploratory, as constraints of the current study preclude further expansion with this analysis. However, this initial examination has revealed the usefulness of discriminant function analysis with this data set and how combinations of pelvic measurements may possibly be employed to predict the level of degenerative disease development in particular areas of the vertebral column. It would certainly be interesting to see what other sets of selected measurements could reveal. This initial evaluation has identified an important area for further research.

# CHAPTER 8 CONCLUSIONS AND FURTHER RECOMMENDATIONS

## 8.1 Conclusions

This study sought to make an initial evaluation of the relationship between human pelvic size and shape and the distribution, type and severity of vertebral degenerative disease in archaeological material. The material comprised four archaeological skeletal samples and represented an eighteenth to nineteenth century, North-west European, middle-class documented population.

Many factors are thought to contribute to the development of joint disease, with ethnic group, sex, age, genetic predisposition, pre-existing or intercurrent disease, occupational practices and diet all being influential factors. In this current study, two further elements (pelvic size and shape) were evaluated as potential compounding factors. Given the constraints of this thesis, it was not possible to control for all of the above mentioned factors in this study and that needs to borne in mind with any interpretations that are made.

An additional issue with any type of research of this nature is how the quality and quantity of material available for examination tempers the extent to which interpretation of any results can be made. This raises the question as to whether a dearth of significant results actually reflects the fact that there simply is no correlation, or whether it merely informs about the preservation of the material under examination (and subsequent dearth of data recorded).

The anatomical structure of the human vertebral column also predisposes to the development of degenerative disease in the structure. On lateral view, the human vertebral column is seen to consist of four curves. Those in the thoracic and sacral areas are concave anteriorly (or kyphotic) and represent the primary curvatures that develop *in utero* and are present at birth. Those in the cervical and lumbar regions are convex anteriorly (or lordotic) and comprise the secondary curvatures. These develop postnatally and confer flexibility and support to the structure and enable humans to efficiently balance their weight over their feet. The latter curvatures are an adaptation to the demands of erect bipedal posture, but such biomechanical modifications are not without their disadvantages.

The habitual force of gravity acting on this structure stretches it to its functional extreme and renders it susceptible to tremendous stresses and subsequent pathological manifestations. Points of maximum (C5, T8 and L4) and minimum (T1, T12 and L5/S1) stress occur within these curvatures and these are suggested as agents responsible for the variation of pathological change observed in the spine. This hypothesis is certainly borne out in a number of anthropological studies, with the lower cervical, lower thoracic and lumbar regions (which experience maximal spinal motion), demonstrating a greater degree of affect.

Although the vertebral column tends to reflect biomechanical stresses placed on it by bipedalism and bipedal posture over extended periods, there has never been any consideration of whether pelvic size and shape may be contributing to this situation. It is already acknowledged that a compromise has been reached between efficient upright posture/bipedal locomotion and the size and shape of the female pelvis in relation to its role in parturition. What was considered interesting to explore, therefore, was whether a difference would exist between the rates of degenerative disease exhibited between the two sexes. As the female pelvis tends to be more capacious than the male counterpart, this theory was initially explored by examining the general effect of size itself and the pelvic shape on the total sample. The former necessitated the measurement of 93 dimensions within the pelvic girdle and its separate components. The severity and distribution of osteophytes, porosity and eburnation in the vertebral column was established at 24 levels (seven cervical, twelve thoracic and five lumbar) in addition to the first sacral vertebra and occipital condyles. These attributes were also ascribed, when present, to the costal facets in the case of the thoracic vertebrae. Statistical analysis was then employed to test for any relationship between pelvic measurements and the sex and age at death of the individual as well as any correlations between each of the measurements themselves. The relationship between pelvic shape and degenerative disease was investigated by the utilization of 'signpost' configurations. The correlation between measurements in the sacrum, innominate and reconstructed pelvis and degenerative disease in the vertebral column were examined for and an appropriate 'signpost' mechanism was created to effectively display this relationship.

An extremely large data bank was thus amassed. The magnitude of this alone produces its own inherent problems, both from the recording and analytical perspective. In the case of the former, a variety of reasons (see Table 6.1.), not least of all post-mortem erosion, precluded data from being collected (see below). In the latter, the risk of generating type 1

errors during statistical analysis was increased due to the larger data set. However, given the nature of the material under study, the author considered it prudent to record as much data as possible, particularly in view of the fact that the condition of many osteological collections is compromised with time due to the tremendous pressure placed on them by continued examination by scholars and curators (Caffell *et al.*, 2001). Janaway and colleagues (2001:202) noted that the 'reliability of information derived from skeletal collections is directly related to their condition' and with the passage of time, it becomes almost inevitable that opportunities for recording specific data will diminish due to the damage, loss or mixing of material.

A further concern, with regard to data manipulation, was the issue of subjectivity with pattern recognition in, and interpretation of, the 'signpost' configurations. To a certain extent the employment of t-tests and Mann Whitney U tests served to examine any perceived patterns between areas of maximum and minimum curvature statistically. However, in practice, this only involved a very small number of 'signposts' overall and those that could be examined in this way only required three data points in their grouping variable. Although, in practice, it would not normally be advisable to use such small group sizes for analysis, the author thought that it would be interesting to run the tests nevertheless and just explore any results generated.

Associations and correlations were therefore examined for between a) pelvic measurements and sex, b) pelvic measurements and age, c) pelvic shape and sex, d) pelvic shape and degenerative disease and e) pelvic size and degenerative disease. Results are summarised as follows.

**a) Relationship between pelvic measurements and sex**

This relationship was examined to demonstrate that the sample under study exhibited significant dimorphic differences in the pelvic measurements between the sexes. Eight (53%) sacral, 23 (74%) innominate and 15 (94%) reconstructed pelvis measurements did show significant differences, with the female structure being larger. The female pelvis is described as being more capacious than the male and this attribute was certainly reflected in this sample.

**b) Relationship between pelvic measurements and age**

If a relationship exists between the age of an individual and the size of their pelvis, then it follows that age will be a confounding variable in any association found between the pelvic size and degenerative disease development. This was explored in the current study and significant correlations were found between age and pelvic dimensions in five (33%) sacral, 29 (94%) innominate and four (25%) reconstructed pelvis measurements. In the sacrum and innominate, the significant correlations were small, but positive, in both the female and male groups, suggesting that larger measurements are associated with older individuals. In the reconstructed pelvis, the significant correlations were small, but positive in the female group. However, they were negative in the male group. This suggests that although a larger pelvis may be selected for in the older females, the opposite is occurring with the male. This finding certainly supports the theory of an evolutionary effect naturally selecting for females expressing a genetic predilection for larger dimensions. This makes biological sense, as parturition is facilitated by a more obstetrically efficient (i.e. more capacious) pelvis. Likewise, in the male, a more compact and stable pelvic structure is favoured and, with respect to those measurements examined in the reconstructed pelvis, members of this sex with a genetic predilection for smaller dimensions are being selected for.

**c) Relationship between pelvic shape and sex**

Tests of association between the pelvic shapes recorded in the sample and the sex of the individuals under study showed that the gynaecoid and android configurations were significantly associated with the female and male sex respectively. This attribute certainly supports the classifications most frequently assigned in the literature.

**d) Relationship between pelvic shape and degenerative disease in the total sample**

Statistical tests undertaken to explore this relationship revealed that only 0.5% of the results were significant. Given that 5% of results would be expected to produce significant results by chance alone, then this result could not be deemed to have any statistical merit and was therefore disregarded. Categories of degenerative effect were then combined to see if any benefit could be gained, but only 0.9% of results with this approach produced significant results, so these had to be disregarded as well.

As a result, no significant evidence of an association between pelvic shape and the magnitude of degenerative disease could be demonstrated in this sample. Likewise, there was no significant association found between pelvic shape and the presence/absence of degenerative change.

**e) Relationship between pelvic size and degenerative disease**

In order to initially explore the relationship between these parameters, a 'signpost' configuration was created. Using this model, the significant correlations found between measurements and degenerative disease where presented at particular levels of the vertebral column. A number of provisos were mentioned in relation to this and as a consequence, any interpretations were tentatively made and tempered with caution. Furthermore, given the constraints of the present study, it was not possible to explore any relationships in the female and male groups individually. Instead the total sample was utilized with the intention that any significant findings should be further investigated between the sexes.

Generally speaking, results tended to suggest that osteophytosis was the most common type of degenerative disease encountered. Porosity was present to a much lesser extent and eburnation was almost absent. As a result, data for these latter two manifestations was too limited to allow any interpretation. The superior and inferior body surfaces were the main areas of the vertebrae exhibiting change, with the lower half of the thoracic and lumbar regions demonstrating most affect. Correlations, with the exception of one 'signpost' constructed, were positive in nature, implying a positive association between the measurement observed and the degree of degenerative change observed in the vertebral column. Therefore, as the measurements concerned increased in size, so did the severity and extent of the change observed in particular regions of the vertebral column. The only exception to this was the subpubic angle, which presented negative correlations for the severity of osteophyte development on the superior body surface. This suggests that as the angle increases, the severity of pathological change observed would decrease. This is surprising, as a greater subpubic angle is associated with the more capacious and relatively unstable female pelvis and, as such, would be expected to incur greater referred stresses in the vertebral column as a result. In effect, therefore, this finding is completely opposed to what would be expected, especially as all other measurements in the pelvis and its constituent elements has exhibited positive correlations in the data observed. However, as discussed in the preceding chapter, other data for this particular measurement (which did

not produce sufficient data to warrant further examination) presented either positive or mixed correlations and so maybe the results here are simply a reflection of sample variation. Clearly this is an area that warrants further investigation.

The acetabulosciatic breadth produced the most complete data sets for the severity and extent of osteophytosis observed on both the superior and inferior body surfaces. It is interesting to speculate as to why this should be so. Is this dimension reflecting a major role in an individual's predisposition to developing degenerative disease in the spine, or are the results simply reflecting the robust nature of the structure and that it is therefore possible for measurements to be taken of it? Either way, a definite pattern, in the correlations displayed across the levels comprising the 'signpost' configuration, was evident. The question, therefore, is why should this be? If the anatomy of the skeleton is reviewed with respect to stresses acting across joints, then forces being exerted superiorly from the lower limbs to the vertebral column will act through the hip and sacro-iliac joints. In the anatomical position, the acetabulosciatic breadth lies directly on the chord linking these two areas. It may simply be that any measurement involved in the direct transfer of stresses will be more positively correlated with degenerative disease development. If that is the case, then it would be expected that the acetabulum diameter, sciatic notch width, sciatic notch height, sciatic notch position and auricular surface measurements should exhibit similar patterns in their 'signpost' configurations. This was not found to be the case. However, as previously alluded to, this may not be a reflection of the measurements' lack of affect on the development of degenerative change itself, but rather an indicator of preservational status of the innominate bone generally. The acetabulum, anatomical boundaries of the greater sciatic notch and the auricular surface were all frequently found to be affected by post-mortem erosion. Furthermore, indistinct landmarks in the latter area also precluded auricular surface profiling. As a result, 'signposts' configured for these measurements only displayed limited data and of those that did warrant further examination, most could only be described with respect to general areas of affect. Consequently, if it is postulated that these areas in the direct line of force are expected to exhibit more accentuated correlations with degenerative disease in the spine, other ways (other than examining archaeological skeletal material), need to be found that would allow them to be explored scientifically before any final conclusions can be drawn.

Statistical differences between correlations at levels of maximum and minimum curvature were examined for. Only four (9%) of the 43 tests conducted in this manner produced significant results and these represented three of the measurements from the innominate

(the right pubic symphysis depth and the left and right acetabulosciatic breadths) (Table 8.1). The right pubic symphysis depth showed a significant difference in the correlations with the extent of osteophytosis observed at the levels of maximum (C5) and minimum (T12) curvature on the superior body. The left acetabulosciatic breadth exhibited a significant difference in the correlations with the severity and extent of osteophyte development at the levels of maximum (T8) and minimum (T1) curvature on the inferior body. The right acetabulosciatic breadth showed a significant difference in the correlations with the severity and extent of osteophyte development at the levels of maximum (T8) and minimum (T1) curvature on the superior body and at the levels of maximum (T8) and minimum (T11) curvature on the inferior body. These significant differences suggest that these measurements are playing a role in the expression of degenerative disease at maximum and minimum levels of curvature and that curvature itself is not acting alone in predisposing to the development of these manifestations.

Discriminant function analysis was employed to explore the predictive ability of combinations of measurements to predispose to the development of these three degenerative disease indicators at a particular vertebral area. Four measurements were selected for this purpose and comprised the maximum depth of curvature, the right pubic symphysis depth and the left and right acetabulosciatic breadths. In the model the inter-relationship of these four variables to the expression of severity of osteophytosis on the superior body surface was explored. The right acetabulosciatic breadth was found to be the most important parameter in this model, with the left acetabulosciatic breadth being second. The discriminant function coefficients produced allowed computation of a new variable that could be employed to discriminate between each of the three groups representing level of severity of osteophytosis. Contrived data was then used to test this model and was successful in predicting an expected level of expression of the pathological change.

One of the main hypotheses made as part of this research was that if a capacious pelvis is more likely to predispose an individual to developing degenerative disease in the spine, and if this pathological change is found to manifest at levels of maximum curvature preferentially (as supported in the literature), then a greater level of correlation between the measurements and the degenerative disease indicator(s) at any particular vertebral level should be expected if the pelvic size is playing a part in the overall development. This tended to be borne out by the results produced here. When combined with further extensive research, as detailed in the next section, the current results should enhance our

**Table 8.1 Measurements in the innominate showing statistical differences between correlations at levels of maximum and minimum curvature**

| Measurement | Degenerative disease indicator | Vertebral area | Areas of maximum and minimum curvature showing significant differences in pathological manifestation | | | |
|---|---|---|---|---|---|---|
| | | | C5 and T1 | C5 and T11/T12 | T8 and T1 | T8 and T11/T12 |
| Right pubic symphysis depth | Osteophytes<br>- extent | Superior body | | • | | |
| Left acetabulosciatic breadth | Osteopytes<br>- severity<br>- extent | Inferior body | | | • | |
| Right acetabulosciatic breadth | Osteopytes<br>- severity<br>- extent | Superior body | | | • | |
| | Osteopytes<br>- severity<br>- extent | Inferior body | | | | • |

understanding of this particular pathological process and the factors responsible for its development, thus determining to what extent pelvic size does play a role in its occurrence. This could potentially be of great importance clinically. At the beginning of this thesis, it was noted how back pain is reported as the most common orthopaedic complaint, being responsible for a considerable loss of time from work each year as a result. In addition to the astounding annual loss of working days, there is also the financial implications of treatment to consider. If the mechanisms for the development of this disease can be deduced and better understood, then preventative measures could be established earlier and the management of the condition enhanced. As a consequence, the serious drain on the resources of both clinicians and employers alike could potentially be diminished.

## 8.2 Further Recommendations

This study has conducted an initial evaluation of the relationship between pelvic size and shape and the site, severity and distribution of degenerative disease in the vertebral column. There is much further work that still needs to be undertaken in this area and this can be broadly classified into one of two categories: continuing research on the current sample and other related research.

### 8.2.1 Continuing research on current sample

1) A relationship between age and pelvic size was discovered in the total sample as well as the female and male groups studied. Evolutionarily speaking, if females with a larger pelvis are being selected for, and larger pelvic measurements are positively correlated with the development of degenerative disease in the vertebral column, then will females be affected by more extensive pathological change at a younger age? Conversely, if smaller pelves are being selected for in the male, will the extent of degenerative change be reduced? These questions need to be addressed with further research.

2) The examination of the relationship between pelvic size and degenerative disease was only examined in the total sample in the current study. Clearly the female and male groups need to be evaluated separately as well. It is hypothesized that any significant correlations currently observed in the 'signpost' configurations would be more accentuated in the female group simply because of the more capacious nature of their pelvic anatomy. The results of the current study could form a starting point for this, by highlighting which

potential measurements should be further investigated in each of the sex groups to see if there is a significance difference between them.

3) The discriminant function analysis undertaken on this sample produced promising results and it would be interesting to test other combinations of pelvic measurements, from the total sample, in the same way. Furthermore, this analysis would also need to be undertaken separately on the female and male groups to see if the predictive ability of a combination of measurements on the expression of degenerative disease would be different between the sexes.

4) The development of degenerative disease has a multifactoral aetiology and it would be beneficial to be able to disengage the various contributing factors. For this reason, partial correlation could be employed to control for the possible effects of other confounding variables.

5) One question regarding the observed data is how can one organize it into meaningful structures, that is, to develop taxonomies? For example, perhaps the measurements recorded have to be organized before a meaningful description of the differences between them, and their subsequent effect on the development of degenerative disease in the spine, can be made. Clustering techniques have been applied to a wide variety of research problems such as this, whenever it is necessary to classify a "mountain" of information into manageable meaningful piles. It could potentially place pelvic measurements into groups, or clusters, so that the degree of association is strong between members of the same cluster and weak between members of different clusters. Each cluster thus describes, in terms of the data collected, the class to which its members belong, and this description may be abstracted through use from the particular to the general class or type. The members of these cluster groups may then be utilized for further statistical analyses.

6) Paired measurements in the innominate and reconstructed pelvis were also investigated, although results for analyses conducted on these were limited, particularly with respect to pathological change. However, it would be interesting to examine any degree of asymmetry noted in greater detail and to see if this possibly affects the degree to which degenerative disease manifests in the vertebral column. Furthermore, on a non-pathological note, does the level of any asymmetry found reflect the side preference (leggedness) of an individual? If handedness and leggedness are correlated in any way, then possibly determining the former could also allow inference of the latter. However, it

would be extremely difficult to answer the aforementioned question, as information pertaining to an individual's preference for leg use would have to be known and for archaeological material, that would not be the case. Utilization of modern samples and medical media may be able to further address this issue (see section 8.2.2).

7) Further pelvic measurements could also be identified and examined. For instance, given the importance of the maximum depth of curvature, the sacrum could be extensively profiled. The resulting extent and depth of curvature could then be expressed as a graph and the area under it calculated. This value could then be examined for any evidence of a relationship with sex, age, and degenerative disease.

8) Only three degenerative disease indicators were examined in this study – osteophytes, porosity and eburnation. Other pathological manifestations, such as Schmorl's nodes, could also be evaluated to see how their expression is influenced by pelvic size and shape. Schmorl's nodes could be recorded with respect to status, position on the vertebral body, depth and shape. Saluja and colleagues (1986) have presented a very concise and easy scheme for indicating the position of a node on the vertebral surface and this could be employed for assessment of that parameter. Measurement of the greatest depth could be achieved by employment of the depth measurer on a set of digital sliding callipers. A new system for recording the status and shape of the node could also be devised.

9) In the current study, only individuals with anatomically normal pelves and vertebral columns were selected for inclusion in the sample. It would be interesting to see how anatomical variants in the pelvis (e.g. sacralization, lumbarization) could affect development of degenerative disease in the vertebral column.

10) Although this current research examined pelvic measurements, the effect of vertebral measurements on the site, severity and distribution of degenerative disease could also be explored. All of the analyses undertaken in this thesis (and comprising the further recommendations as well) could then be undertaken on a number of vertebral dimensions. It is suggested that three measurements (the anteroposterior diameter, posterior transverse diameter and anterior transverse diameter) be recorded for both the superior and inferior body surfaces. The anterior sagittal height, posterior sagittal height, spinal canal width and spinal canal length would then comprise four other measurements. These ten measurements could be taken from each vertebra in the thoracic and lumbar regions (T1-

L5). It is suggested that the cervical, sacral and coccygeal elements be omitted due to peculiarities in their structure.

The curvature of the vertebral spine is also a function of vertebral body morphology, and so the relationship between these two parameters could also be investigated, as well as the impact that that may have on any subsequent expression of degenerative disease.

Finally anatomical variants in the vertebral column (e.g. block vertebrae, hemivertebrae, hypoplasia and aplasia of the centrum) could also be investigated to see if they affected development of degenerative disease in the vertebral column.

11) Finally, the data collected for this current study could be employed to re-evaluate existing methods used in anthropological analyses e.g. the metrical determination of sex using measurements in pelvis (and spine).

### 8.2.2 Other research

1) The current research was undertaken on skeletal sample of material from an eighteenth to nineteenth century, North-west European, middle-class documented population. It would be interesting to undertake the same type of study utilizing medical media. Particular measurements of the pelvis could potentially be observed from radiographic, CT, MRI and ultrasound media and employed in two ways. In the first instance to explore any relationship between these measurements and degenerative disease in the vertebral column and secondly, to see how such results would compare to those obtained on the dry bone specimens employed in the current study.

2) The measurements obtained from medical media (as described above) could also potentially be used for studies in asymmetry. For instance, is sidedness in the lower limb (leggedness) reflected in the measurements themselves? If so, then how would this affect the site, severity and distribution of degenerative disease, if at all? Clearly a modern sample would be required for this, as archaeological ones would not have any documented information regarding sidedness preference.

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