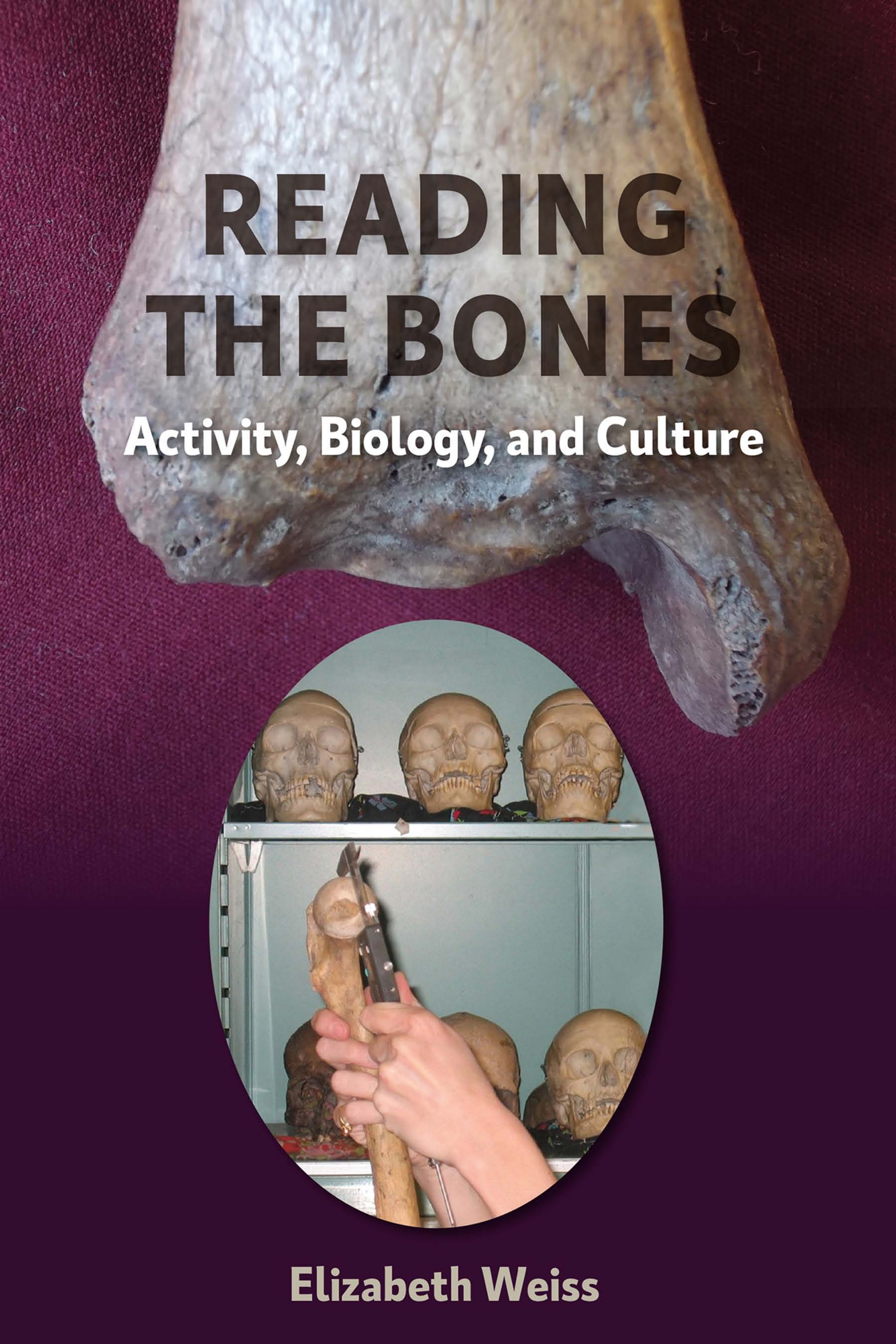

READING THE BONES

Activity, Biology, and Culture

Elizabeth Weiss

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ELIZABETH WEISS

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Dedicated to C. L. and N. P.

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PREFACE

Reading the Bones takes on one of the most debated topics in bioarchaeology. The question addressed in this book is, do skeletal activity indicators reveal past people's activity patterns, or do biological factors influence these markers in ways that make reconstructing activities impossible? Studies using activity indicators address fundamental questions regarding past lifestyles such as how agricultural adoption affected health, whether sex differences are more pronounced in agricultural cultures than in hunter-gatherer cultures, and whether class differences affect the activity levels of past peoples; however, activity indicators are not free of biological confounds such as hormonal effects on bone building, genetic adaptations to climate differences, and age differences in bone remodeling. Uniquely, this book reviews each of the main activity indicators from a variety of angles to attempt to understand which indicators can be used to reconstruct past lifestyles and which may be better retooled to answer other questions.

Throughout my career, I have been trying to answer this question by examining the main activity indicators, including osteoarthritis, cross-sectional geometries, entheseal changes, and stress fractures, and by looking for trends that transcend culture such as age and sex effects that are found throughout time and place. Considering that activity markers are perhaps the most commonly used skeletal traits analyzed in bioarchaeology and archaeology, this book provides a timely—and perhaps provocative—review of the usefulness of these traits when it comes to understanding the past.

For the last two decades I have been researching osteological activity markers. As a graduate student at Sacramento State University under the mentorship of Dr. Elizabeth Strasser, I embarked on the study of cross-sectional geometry to understand sexual division of labor in prehistoric Californian hunting and gathering Amerinds. My research concerned sex differences in mobility; I wanted to know whether sex differences were less pronounced within hunter-gatherers compared to agriculturalists or industrialists. Part of my question arose from the desire to understand whether adopting agriculture was beneficial to populations. Thus, I compared my CT-scanned femoral cross-sections, which were obtained through the generosity of the UC Davis Medical Center, to other preagricultural, agricultural, and industrial samples in an effort to discover whether sexual differences and, therefore, sexual division of labor may have been just as pronounced before the adoption of agriculture as after. My work was placed into context through my reading of many late-1980s works by Dr. Chris Ruff and the late Dr. Patricia Bridges. Ruff and Bridges came to different conclusions with their samples although both had looked at prehistoric Amerinds. Ruff, who focused on the lower limb, found a decrease in mobility in males within agricultural and industrial cultures compared to hunting and gathering cultures; he argued that as hunting decreased in importance for subsistence, males roamed less and their femoral cross-sections became more like the round female femoral cross-sections, which is arguably the natural human shape when low mobility is present. On the other hand, Bridges, who looked mainly at upper limb bones, emphasized the change in females' workloads with the adoption of agriculture, which would lead to grinding foods with mortars and pestles. She saw agriculture as increasing females' work and increasing sex differences, which is practically the opposite of Ruff's conclusions. Further, Bridges said that agriculture increased females' strength through their grinding of foods compared to processing gathered foods. Since my focus was on the lower limb, I tended to lean toward Ruff's view; yet the complexity of sex differences in activity patterns was not lost on me, and both Ruff and Bridges clearly saw this complexity as well.

My work, along with Ruff's and Bridges' work, made the assumption that bone shape is formed by activity rather than being mainly a result of biology. This assumption is based on the unification of biomechanical principles, such as in Dr. Sharon Swartz's 1993 work on understanding bones as beams with different forces acting on them, and Wolff's law of bone transformation, which states that when a force is placed on a bone, it will remodel to prevent breakage. Although Wolff's law was initially to be applied to trabecular or spongy bone (which is at the ends of long bones), anthropologists arguing that bone form is a result of activity patterns have extended Wolff's law to cortical or compact bone (which makes up the shafts of long bones). Anthropologists cited work on animals such as pigs and asymmetry studies on tennis and racket players to support the claim that activity was the main influence on bone form. To highlight anthropologists' assumptions of the power of activity is not to say that biological effects had been completely ignored; Ruff, for instance, did research on cross-sectional geometry and age effects.

After I finished my master's work, my PhD work led me to investigate upper limb morphology and activity pattern relationships. Being in a PhD program that was interdisciplinary (the Environmental Dynamics, or ENDY, program at the University of Arkansas at Fayetteville was a program that combined geology, geography, and anthropology), I was encouraged by my mentor, Dr. Peter Ungar, to include a physical environment aspect into my work. Once again, I was influenced by Ruff's work; he published two chapters in 2000 in which he looked at the effects of terrain type (e.g., mountainous, coastal, flatland) on lower limb cross-sections. Thus, I decided to examine the cross-sections of humeri and the effects of rowing on different water types (e.g., ocean and river) to determine if rowing in more difficult to maneuver waters may lead to stronger humeral cross-sections. I was able to draw together a great comparative sample due to the generosity of anthropologists Dr. Steven Churchill and Dr. Martin Solano, coupled with access to the skeletal collections at the Canadian Museum of Civilization in Ottawa, where Dr. Jerry Cybulski was the curator at the time. Mindful of the need not to ignore biological factors, I knew that certain measures to account for body types had to be taken. After a variety of controls, I found that the effects of rowing were muted by biology with cold-climate body types (along the lines of Allen's rule and Bergmann's rule) having cross-sections that were more robust than other populations.

In addition to this cross-sectional work, I also started my first research into entheseal changes (which at the time were known as muscle markers or musculoskeletal stress markers and are locations of muscle attachments on bones) as part two of my dissertation. In 1998, the same year as I entered into the PhD program, the *International Journal of Osteoarchaeology* published a special volume dealing with the fairly new technique of recreating activity patterns using entheseal changes. The attraction of determining activity patterns using entheseal changes was that, since these markers were external, no tools—just bones—were needed to collect the data. Scoring systems allowed anthropologists to assess bone morphology and draw conclusions about activity patterns related to division of labor, changes over time within a site, and even differences in activity between sites. Yet early on, researchers such as Dr. John Robb and Dr. Ann Stirland noted that trends not likely related to activities occurred, such as an increase in entheseal change formation with age. Thus, I endeavored to use aggregate entheseal change scores to find the best predictor of these markers; the best predictor was and still is age. This research won me my second student prize (the first was won for my cross-sectional master's work, mentioned above) and was published in the top physical anthropology journal, the *American Journal of Physical Anthropology*.

During those early days of my research, articles on whether activity indicators were actually biologically determined were common, as were articles that questioned the validity of applying Wolff's law to cortical bone; two of the articles that heavily influenced my work were John Bertram's and Sharon Swartz's 1991 article in *Biological Review* and Osbjorn Pearson and Daniel Lieberman's 2004 article in the *American Journal of Physical Anthropology*. Since those early years I have continued to investigate activity indicators, especially in terms of determining how much of the bone morphology examined by anthropologists studying human remains in archaeological settings can be attributed to activity compared to biology. Throughout my career I published on entheseal changes, cross-sectional geometry, stress fractures, and osteoarthritis. The only activity indicators that I have not published on are accessory facets, which are less commonly studied—with the exception of the numerous studies by students who present posters at conferences on kneeling facets.

What I have noticed since starting my career at San José State University a dozen years ago is that most fields of study in the sciences and many fields of study in the social sciences have become more accepting of genetic explanations for phenomena. In psychology, for instance, no longer is a mother's coldness blamed for a child's autism. Medical research has also looked to genetics to explain the risk of many health issues, such as osteoarthritis, obesity, and cancer. Yet anthropologists still seem to prefer environmental explanations over genetic ones—an assumption that will be challenged in this book. A few exceptions exist; for instance, forensic research on crania attribute the differences in bone morphology to race and yet forensic anthropologists are starting to dip their toes into the water of activity pattern traits to draw conclusions about victims' occupations and hobbies. For bioarchaeologists, the lack of emphasis on genetics has meant an emphasis on culture and activity rather than biology. I am not implying that these anthropologists completely ignore biological effects; rather, the research has been more often focused on activity patterns than biological trends. I think that we are missing a trick here.

Anthropologists use archaeological artifacts to bolster their reconstructions of activity patterns, which can and does lead to circular reasoning, some of which I have also been guilty of. For instance, looking at sex differences, I have hypothesized that males would have more robust entheseal changes in their upper limbs that would be indicative of spear throwing because arrowheads were found with males in the California Amerinds. When the data were collected, males' upper limbs were indeed more robust, especially along entheses that would be used for throwing. Hence, I concluded that the males had greater entheseal change scores compared to females as a result of spear throwing; but the muscles that would be used in throwing spears could also be used for many other activities. The reasoning is circular because I started with the information on spears and concluded that spear throwing caused the upper limb sex differences. The question that arises is, could I have predicted what activity males engaged in by just looking at the entheseal changes? The answer to that question is no; entheseal changes do not have that extent of predictive validity. Additionally, the reconstructions are often too simplistic (as my husband has pointed out when he proofreads my work—it seems that everyone either ground acorns or threw spears), but finer reconstructions would be reaching beyond what the data can tell us, which has led some anthropologists to suggest not making specific claims about activities but rather just drawing conclusions about general cultural trends (such as sex, class, and age differences).

In this book I examine each of the major activity indicators and explain the way data are collected, review the different research on the data that indicate biological influences, and cover possible activity and cultural effects. To do this, I most heavily relied on peer-reviewed journal articles (I have included less than a half dozen conference presentations that were in peer-reviewed published conference proceedings). I have also included some presentations from the Coimbra workshops on entheseal changes; these workshops have been influential in shaping entheseal change research in the past five years. Most of the research presented at the workshops has been published, but a couple of nonpublished works are included as well. I tried to strike a balance between anthropology journals (e.g., *American Journal of Physical Anthropology*, *International Journal of Osteoarchaeology*) and archaeology journals, which more often have a geographic focus (e.g., *African Archaeology*), and medical or biological journals. Some trends that I noticed were that in archaeology journal articles the researchers included activity markers and drew conclusions based on few remains and no statistical analyses, and they placed a lot of emphasis on artifacts to corroborate their skeletal findings. The authors often do not mention the controversies behind these skeletal traits, and they were less likely to use the newest techniques to collect or analyze the data. Anthropology or bioarchaeology articles (which are those in which the focus is on the remains rather than a specific site), on the other hand, often employ large samples and extensive statistical analyses, and they discuss the pros and cons of using activity markers in relation to the biology versus activity debate. Anthropologists are also still publishing articles on methods, terminology, and testing biological confounds. The nonanthropological and nonarchaeological articles are often experimental, which use nonhuman animals, or they focus on sports injuries (as opposed to nontraumatic bony changes). Looking at trauma compared to nontrauma changes is a prominent aspect of the entheseal change research debate into activity patterns.

I am sure my chosen references will not align completely with everyone else's due to the vast literature on activity markers; this is the nature of any text, and indeed it is my hope that my choices here will be distinctive. I have included a variety of sources and ensured that references that influenced my own work have been included to allow readers to see what has made me question the influence of activity on activity markers.

My first chapter on bone biology is deliberately concise because I suspect that most readers (whether they are researchers or students) have had some introduction to bone biology. Making this work unique compared to other works (including my previous work) has required a different set of references in chapter 1 than one might expect to see. I think the articles on bone biology that I have chosen will offer a fresh and challenging introduction to bones and a good foundation to understanding the following chapters, especially regarding the emphasis on bone remodeling in activity marker research.

My main purpose in writing this book, which is a theme found in each chapter, is to provide students and professors an alternative way to examine the genes-versus-environment debate. *Reading the Bones* is distinctive in that it has a unifying theme of addressing the nature-versus-nurture debate with an explicitly physical anthropology topic. In many anthropology departments the nature-versus-nurture debate is dealt with by using evolutionary psychology examples. Or, on the flip side, professors may employ Stephen Jay Gould's work (such as the *The Mismeasure of Man*) and focus on cranial measurements and race (although Gould's choice of Franz Boas' cranial studies is out of date now). Corey Sparks and Richard Jantz's (2003) re-analyses of Boas' work have shown that the cranial form is indeed largely due to genetics. Every day, forensic anthropologists successfully use craniometrics and nonmetrics to identify victims' race. Thus, it is time to hang up the cranial genes-versus-environment debate and time for a new take on it that still uses skeletal traits as opposed to behavioral traits. And the genes- or biology-versus-environment debate can be had superbly using activity indicators on bones; examining these skeletal traits and determining whether they can be used to reconstruct activity patterns truly is a topic of the environmental influence versus the biological influence. Thus, covering activity markers in a class can allow students of anthropology to address the nature-versus-nurture issue in a manner that is interesting to those planning on continuing their study of skeletal remains. Looking at activity indicators in this manner may lead to fruitful discussions on normal variation, population differences, effects of aging, and sex differences that are both cultural and biological. There is a complex interplay of factors here, and yet it will be clear from the comprehensive review and analysis in this book that this is not always appreciated by researchers, who may thus make assumptions on a fundamentally flawed basis. A much more interdisciplinary approach can be beneficial here, and this is one of the key messages in this book. Furthermore, these traits can be easily visualized, and even hands-on teaching can be incorporated into the lessons. I hope that this book is adopted by professors in capstone courses that discuss the various fields of anthropology or as an additional text in osteology, forensics, or bioarchaeology courses. Interestingly, most bioarchaeology texts on the market spend little time on activity indicators, and yet activity indicators are one of the most prominent areas of study in bioarchaeology, especially due to the ease of data collection (and yet easy data collection is not necessarily good data collection, as the meta-analysis in this book will show) and the ubiquity of osteoarthritis. In addition to being used as a textbook, this volume can be useful as a reference for researchers hoping to start collecting data on activity indicators (regardless of their hypotheses). In chapters 2 through 6, I provide guidance to those who wish to pursue research using activity indicators by going over various methods that I think improve predictive validity. Additionally, I have tried to indicate in various places where future research may be heading. Again, the benefits—not least in terms of critical thinking—of looking outside one's own specialist field and taking an increasingly interdisciplinary approach are highlighted.

In the end, I hope this work will inspire another generation of bioarchaeologists to delve deeper into understanding the complex factors that result in the beauty of the human skeleton.

Acknowledgments

The opportunity to write this book came as a pleasant surprise. After striving to find the right publisher for a bioarchaeology book looking at activity indicators from a variety of perspectives, Meredith Babb from University Press of Florida contacted me. Although we had initially planned to meet at a conference in San Francisco, our first discussion happened on the phone, where her excitement for my idea was evident. Without her help, I think this proposal would have just languished in my files.

I extend my gratitude to the Department of Anthropology at San José State University; the anthropology faculty and staff have provided a dynamic work environment that has enabled me to have a productive academic career.

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BONE BIOLOGY

Bioarchaeologists are anthropologists who study skeletal remains in the archaeological record to reconstruct past people's lives. Although there are many topics in bioarchaeology, such as dietary reconstructions, biological relatedness, and congenital diseases (diseases present at birth), reconstructing activity patterns is a key component of bioarchaeological research. Students have been especially keen on using macroscopic (visible to the naked eye) features on bones to determine whether past peoples had divisions of labor based on class or sex, whether past populations' shifts to agriculture from hunting and gathering were more or less laborious, whether the physical environment affected people's everyday activities, and many more activity related questions. For the most part, research has been helped along by the objects made by past peoples, known as artifacts; when artifacts corroborate the bioarchaeologists' activity reconstructions, the researchers think that their conclusions are even more valid. However, artifacts can be seen as crutches that allow for circular reasoning, and—perhaps even more troublesome—artifacts may affect the hypotheses that bioarchaeologists test. To determine whether skeletal remains can be used to reconstruct activity patterns, one needs to determine whether the traits examined are a result of activity or biology. In other words, as in many of the social sciences, the bioarchaeologists' main question should be "is it genes or environment?" As both social scientists (such as psychologists) and biological scientists (such as medical researchers) embrace the genetic revolution and start to answer questions about cause and effect with genetic information, bioarchaeologists often still seem to think that the answer lies in environment. Determining the cause or causes, which we call **etiology**, of bone traits used in activity reconstruction is the crux of this book. In order to answer the question of whether it is genes or environment, bioarchaeologists need to understand bone biology.

Bone is a complex material that is shaped by genetics and the environment. Understanding bone biology is essential in determining which features of bone are a result of genes, biology, or environment. In this book, the term "environment" refers to all nongenetic and nonbiological factors, such as activities and diet. Some factors do not fall neatly into the nature versus nurture or genes versus environment arguments; factors such as age are biological, but they may be impacted by external factors (such as cumulative wear or decreased activities). To examine which bony traits are a result of nonbiological factors, such as activity patterns or other cultural manifestations, one must first learn a little bit about bone biology.

Bone Basics

Bone Functions

Although bioarchaeologists use bones to understand activity patterns, bones have multiple functions throughout life. Bones act as a **calcium** reserve, which is essential for healthy organs, and help to maintain calcium **homeostasis**, which is a state of equilibrium in the body. Calcium is the most abundant mineral in the human body. When one has too little calcium (hypocalcemia), heart dysfunctions and seizures can occur; but too much calcium (hypercalcemia) can cause widespread organ damage. Bones also provide structures that help house disease-fighting cells; for example, sinuses are cavities that are surrounded by bones, and the sinuses house immune system cells. Plus, bones house and protect vital organs; for example, the brain is encased in the skull and the lungs are protected by the ribs (Frost, 2004; Pearson and Lieberman, 2004).

Perhaps most importantly for anthropologists examining remains to reconstruct activity patterns of past peoples, bones serve as attachment for muscles, and these anchors also play a role in movement (Frost, 2004; Pearson and Lieberman, 2004). Movement, whether it involves the entire body or just a part of the body (such as the arm), is accomplished through a lever system composed of muscles, tendons, and bones (Seeman and Delmas, 2006). In order to function as a muscle attachment system, bones need to be able to resist deformation in response to muscle use (which is considered an internal force) (Frost, 2004; Pearson and Lieberman, 2004). Also important to bioarchaeologists, bones attach to other bones at joints, which are covered with lubricated cartilage; degenerative joint disease (also known as **osteoarthritis**) is one of the most common forms of disease found in the bioarchaeological skeletal record, and it is used as an indicator of which joints were used in activities.

Bone Components

To accomplish its many functions, bone contains a variety of different materials. Thirty-five percent of bone is made up of **collagen**, which is a fibrous protein, and other similar proteins; these organic materials allow bone to retain some flexibility and stability (Pearson and Lieberman, 2004; Seeman and Delmas, 2006). The other components of bone are minerals; it is estimated that human bone is about 60% mineralized (Seeman and Delmas, 2006). Calcium in the form of hydroxyapatite crystals makes up most of the bone minerals, but bone also contains small amounts of fluoride, citrate, and magnesium (Pearson and Lieberman, 2004; Seeman and Delmas, 2006). The minerals in bone increase the stiffness whereas the collagen allows bone to maintain some flexibility, which prevents brittleness (Seeman and Delmas, 2006).

Bone Organization

At a macroscopic level, different bone structures, which are sometimes referred to as envelopes, serve different purposes and vary in the amount of stiffness and flexibility they exhibit (Frost, 1994; Robling et al., 2006). The four bone envelopes are **intracortical** (also known as **Haversian** bone or osteons), **trabecular** (also known as spongy bone), **endocortical**, and **periosteal** (Frost, 1994; Robling et al., 2006). All bones have these envelopes, but they contain different percentages of them. For example, long bones, such as the femur (thighbone) and humerus (upper arm bone), are mostly intracortical bone, which favors stiffness over flexibility since these bones are mainly used in the lever system that enables movement (Pearson and Lieberman, 2004; Seeman and Delmas, 2006). Vertebral bones, on the other hand, consist mainly of trabecular bone, which act as a spring to absorb shocks (Pearson and Lieberman, 2004; Seeman and Delmas, 2006). However, there is even variation in the same types of bone; the femur, for example, has a greater amount of intracortical bone

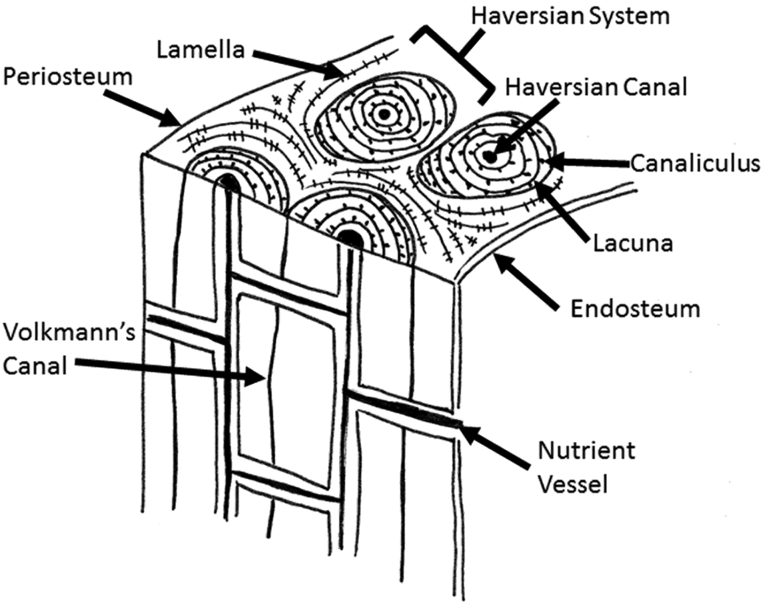

Figure 1.1. Haversian system. A cut-away that highlights some of the key features of mature bone.

than the tibia (or shinbone), which has a large **medullary cavity** (the marrow cavity located in the center of long bone shafts) and a great deal of trabecular bone.

The most common bone discovered in the bioarchaeological record is made of intracortical bone since it is the most mineralized. Looking at Haversian bone at a microscopic level, each single Haversian system has a tree-ring like appearance. Haversian bone, which is found throughout the shafts of long bones and covers the outside of other bones, contains interconnected osteons (a single set of the Haversian system) in which each osteon contains a cement-like lining and is connected to the other osteons through collagen fibers, known as **Volkmann's canals** (Seeman and Delmas, 2006). The spaces between the osteons are composed of **interstitial lamellae**, which are crack-resistant sheets of collagen fibers and remnants of previous osteons that were resorbed during **bone remodeling** (Seeman and Delmas, 2006). Bone remodeling is discussed in detail below. In addition, in between the lamellae are spaces or cavities called osteocytic **lacunae** that are filled with pre-bone cells that help in bone remodeling. These lacunae are distributed around each osteon (Seeman and Delmas, 2006). In Haversian bone, the overlapping parallel osteons limit fracture propagation in a similar way to how bricks are laid down to build a strong wall (Seeman and Delmas, 2006). Figure 1.1 illustrates the different components of osteons.

Trabecular bone is not as orderly as Haversian bone; commonly referred to as spongy bone, trabecular bone is porous and does not survive well in the archaeological record. Yet trabecular bone has the same components of Haversian bone. Instead of being organized in the Haversian system, trabecular bone is organized in packets of lamellae, which enable it to remodel faster. Trabecular bone is found at the end of long bones, such as the femoral head, and in bones that are not used in the lever system, such as the cranium (i.e., the skull minus the lower jaw). Plus, as mentioned earlier, it is found in places where energy absorption is required, such as in the vertebrae and the calcaneus (the heel bone) (Seeman and Delmas, 2006).

The endocortical envelope, which contains endocortical bone and endosteum tissue, lines the interior of the cortical bones and is the boundary between the bone and the medullary canal. Similarly, the periosteal envelope, which contains **periosteal bone** and periosteum tissue, lines the outside of all bone. The two tissues, which are typically only found in bone during life, are bone-forming tissues, which enable bone growth, modeling, remodeling, and repair.

Bone's Dynamic Changes: Growth, Modeling, Remodeling, and Repair

Although bone may seem stagnant, it is quite dynamic. These changes can be grouped into four categories: growth, modeling, remodeling, and repair. Growth and modeling occurs while an individual is developing and ceases or nearly ceases with the onset of adulthood. **Remodeling** occurs throughout one's life and maintains bone health. Remodeling has been said to provide one with a new skeleton every decade (Kushdilian et al., 2016). Research results vary in their assessment of bone remodeling speed and delays in remodeling seem to be normal (Chen-Charpentier and Diakite, 2016). **Repair** occurs when there is replacement of destroyed bone by new formations and occurs after a fracture or other injury. And, regardless of the type of bone, the same cells are responsible for the changes bones undergo throughout an individual's life; the community of these cells is called the **basic multicellular unit** (BMU). The Haversian system is one of the best known BMUs (Frost, 2004).

BMUs of bone consist of **osteoclasts** and **osteoblasts**. Osteoclasts, which consist of precursor cells, active cells, and dead cells, secrete an erosive substance to remove bone tissue that has been damaged (De Boer and Van der Merwe, 2016; Chen-Charpentier and Diakite, 2016; Frost, 2004). Osteoblasts, which deposit bone and add or maintain bone circumference, consist of responding cells, active cells, and differentiated cells (Frost, 1990, 1994). Differentiated cells include both **lining cells** and osteocytes (Chen-Charpentier and Diakite, 2016). Osteoblasts that do not become differentiated cells may be programmed to die (Bellido, 2014; Bonewald, 2011).

Bone Growth and Modeling

When looking at a person's entire life, bone removal through osteoclasts tends to occur first and to a greater extent than bone deposition through osteoblasts (Frost 1990, 1994). Growth occurs from before birth to maturity. Genes are heavily involved in the pattern, pace, and final outcome of bone growth (Frost, 1990, 2004; Robling et al., 2006). Modeling occurs both during the growth period of bone and involves genes and **mechanical loading**, which is the application of a push or a pull on an object. This push or pull is referred to as **force**; an example of a push force may be a weight placed on the bone, whereas a pull force might be a muscle contraction (Frost, 1990, 2004; Robling et al., 2006). Mechanical loading is found to affect not just weight-bearing bones, like the leg bones, but nearly all bones, with only the nasal bones and some cranial bones not experiencing mechanical loads (Frost, 1990, 2004). Mechanical loading can be weight-bearing, but it can also involve muscle use that strains the bone when the muscle is contracted.

Growth and modeling of bone are distinct from remodeling and repair (Frost, 1990). Unlike growth and modeling, remodeling and repair occur throughout life (Frost, 2004; Robling et al., 2006). In growth and modeling, baseline conditions, which are set by genes before birth, allow bones to change while also adapting to mechanical challenges. During growth and modeling, drift (or a gradual movement away from the original position) of bone cells allow bones to increase their cross-sectional strength.

Healthy, normal, growing bones can adapt their architecture through drift (Frost, 1990). Drift is a tissue-level response that can have profound consequences that change the size, content, and shape of a bone; however, drift occurs mainly during infancy and subsides after skeletal maturity (around the teen years) (Frost, 1990).

Evidence of mechanical loadings' effect on growth and modeling are especially evident when disuse occurs, such as in paralysis. When a child's bones are not used, the result is a small bone circumference and a round cross-sectional shape; these traits do not disappear in adulthood (Robling et al., 2006). When looking at outcomes of bone modeling, distal ends (the parts of bone that are furthest from the torso) are more affected by a lack of use or excessive use, which may be because the proximal ends (those that are close to the torso) are more tightly controlled by genetic factors. Regarding the humerus, the elbow end is distal while the shoulder end is proximal. Also, the proximal/distal difference may be a result of different mechanical loading on the bones (Robling et al., 2006).

Bone Remodeling and Repair

Although bone growth and modeling may be of interest to bioarchaeologists and osteologists looking at infant and child health, most bioarchaeologists are interested in reconstructing adult lives and, therefore, they focus on bone changes that they may assume tell the story of adult lives. In bioarchaeological terms, an adult is an individual who has reached skeletal maturity and is fully grown. The focus on adults is also in part because adult skeletons are more often recovered than children's skeletons, which are still in the process of growth and development. The small and unfused bones of children (who are also referred to as juveniles or subadults in the bioarchaeological literature) often fail to survive over the millennia in noncoffined graves. Additionally, adult bones seem to show more variation than children's bones; differences in areas where muscles attached, changes in joint surfaces, and distinctly shaped cross-sections are macroscopically visible on adult bones, whereas the bones of young individuals do not display great variation in these traits (see Gosman et al., 2013). Plus, it has been suggested that the insertion sites on children are independent of localized mechanical loads and are actually a result of the muscle–bone attachment forming (Enlow, 1976). The assumption has been that the differences in adult bones are a result of accumulated wear, bone remodeling, and repair; thus, understanding changes that adult bones undergo with use, remodeling, repair, and fractures (which occur when remodeling and repair fail to be effective) is essential to bioarchaeologists trying to reconstruct the activity patterns of past peoples.

Although bone remodeling follows some adaptation rules, what actually starts the bone remodeling process remains a mystery. Thresholds of bone strength against fractures are likely involved in starting up bone remodeling. Some clinicians have provided evidence that thresholds of bone strength are set by genes; once a threshold is surpassed, the bone should be at risk of a fracture (Frost, 2004). On the other hand, **microdamage** (which is usually thought of as resulting from everyday loads that can cause cracks that are invisible to the naked eye) may be the boundary between starting the bone remodeling and an actual fracture. It has been determined through clinical research that microdamage that is found in bone lies above thresholds for fractures (Frost, 2004; Seeman and Delmas, 2006). Hence, microdamage has been assumed to play a key role in bone remodeling, and it has been suggested that the damage is a result of mechanical overuse (Frost, 1990, 1994, 2004; Robling et al., 2006; Seeman and Delmas, 2006). The suggestion is that if bone remodeling is not effective and too much mechanical loading occurs, then this could lead to **fatigue fractures**, such as those found commonly in athletes (Frost, 2004).

Regarding bone remodeling, when microdamage has occurred, osteoclasts act to remove the damaged bone (Frost, 1990, 1994, 2004; Robling et al., 2006; Seeman and Delmas, 2006). When osteoclasts take this action, they resorb bone matrix and create tunnels in which new bone can be deposited. From experimental evidence, researchers have discovered that osteoclastic activity precedes osteoblastic activity in bone remodeling and repair (Frost, 1990, 1994, 2004; Robling et al., 2006; Seeman and Delmas, 2006). When bone remodeling is linked to the microcracks found in microdamaged bone, the remodeling is considered targeted. Research has shown that in dogs about a third of all bone remodeling was targeted (Pearson and Lieberman, 2004). Stochastic (or nontargeted) bone remodeling, which occurs when no known bone damage can be found and, thus, is not aimed at fixing the bone, is less well understood (Pearson and Lieberman, 2004). Some researchers have suggested that nontargeted remodeling is actually targeted, but the researchers did not find the microcracks because the slice of bone examined did not contain enough of the bone to see the microcrack; that is, the microdamage was in another section of the bone (Pearson and Lieberman, 2004).

Most research on microdamage is done on cortical bone, but trabecular bone actually remodels faster than cortical bone. In the trabecular envelope, bone remodeling may begin when **canaliculi**, which are little canals that connect the bone cells, are severed. This severance could result in **apoptosis** (or cell death), which may cause the body to send signals to lining cells to attract **osteogenic cells** (which are bone-forming cells, such as osteoblasts) from blood and marrow to the damaged area (Frost, 2004; Robling et al., 2006; Seeman and Delmas, 2006).

Another hypothesis on what starts bone remodeling posits that **extracellular fluid** (i.e., outside the cells) leaks during microdamage and that bone cells are sensitive to the leakage and create more bone to stop the flow of extracellular fluids (Seeman and Delmas, 2006). However, this may be more difficult to accept since, in bone remodeling and repair, it is clear that osteoclasts act first and then osteoblasts react; thus, the leakage may initially increase (Frost, 1990, 1994, 2004; Robling et al., 2006; Seeman and Delmas, 2006).

With bone remodeling and repair of microdamage, endocortical and trabecular envelopes do not increase naturally; rather, the changes occur on the periosteum, which results in larger cross-sections and stronger bones without increasing bone weight greatly (Robling et al., 2006).

Wolff's Law

Galileo Galilei may have been the first to suggest that mechanical loading changes bone shape, but Julius Wolff, a German surgeon, conceptualized the bone remodeling law most often cited today (Neve et al., 2012). In trabecular bone, it has been suggested that remodeling changes the orientation of the bony matrix; in 1896 **Wolff's law** of bone remodeling (which specifically states that every change in the form and function of a bone or in the function of the bone alone leads to changes in its internal architecture and in its external form) was initially applied to understand the orientation of trabecular bone cells and to determine whether the orientation corresponded to **stresses**, which are internal forces experienced by bone that can result in deformation. Wolff concluded that stresses caused bone remodeling that altered trabecular bone orientation to strengthen bones against specific loads without the requirement of microdamage or microcracks (Bertram and Swartz, 1991; Ruff et al., 2006); these cracks or other forms of damage are too small to see with the naked eye and appear to be the result of a variety of normal everyday mechanical loads. Wolff theorized that bone reacted to stress to prevent damage and, thus, saw remodeling as distinct from repair. Yet, osteologists who link bone remodeling to microdamage may be uniting repair and remodeling. Many anthropologists have extended the meaning of Wolff's law, perhaps incorrectly, to include cortical bone remodeling in response to stresses; functional bone adaptation may be a better way to describe changes in cortical bone as a response to mechanical loads (Ruff et al., 2006).

Bioarchaeologists frequently suggest that bone remodeling is mainly a result of bone's adaptation to mechanical loads to prevent damage and breakage (see Bertram and Swartz, 1991; Pearson and Lieberman, 2004; Ruff et al., 2006; Schlecht, 2012). Functional bone remodeling and Wolff's law both suppose that microdamage or repair is not necessarily a part of remodeling. The suggestion is that stimulant stress from mechanical loading is sufficient to cause bone remodeling prior to microdamage. External forces, such as those caused by walking on the ground, also place **strain** (an external change that is the result of force) on bones (Pearson and Lieberman, 2004). When bones cannot resist deformation, they break; fortunately, bones can repair themselves. A strong bone, which is usually measured through bone mineral density or cross-sectional shape, resists breakage from both internal and external forces (Pearson and Lieberman, 2004).

Bone cells seem to be strain-sensitive, and there is an elegant signal system in place that may cause some remodeling to occur (Robling et al., 2006). However, not all stresses will cause bone remodeling to fire up. When looking at adaptation in bones, researchers have found that stimuli need to be dynamic for bone remodeling to occur (Robling et al., 2006). In other words, the stresses cannot be constant; rather, they must be changing. A static load may be caused by standing for long periods of time whereas a dynamic load may be a result of running. Plus, bone cells become easily desensitized to stimuli; as a result, increasing loading does not result in stronger and stronger bones (Robling et al., 2006). Furthermore, mechanical loading seems not to produce remodeling in adult animals; the forces from the loads may too low in cortical bone of adult animals to produce a remodeling effect (Pearson and Lieberman, 2004).

Bone Remodeling Steps

Regardless of the initial cause of bone remodeling, bone remodeling and repair occurs within the packets of BMUs that consist of osteoblasts and osteoclasts. Osteoclast actions, which, as mentioned before, remove bone, are global or systemic; in other words, they occur throughout the skeleton and are not necessarily targeted. However, it has been suggested that osteoclasts do target damaged bone in order to start bone remodeling. Yet, even when bone deposition does not occur, osteoclastic activity continues throughout the skeleton. Osteoblasts, which seem to be more constantly site specific, lay down bone (Frost, 2004). Osteoblasts and osteoclasts act together but not in unison. Osteoclast activity starts before osteoblast activity; the osteoclast cells are in fact the first cells observed at the site of bone remodeling (Frost, 1994, 2004; Niedźwiedzki and Filipowska, 2015; Robling et al., 2006).

Bone synthesis during remodeling and repair occurs in two main steps. Osteoblasts, which actually come from fibroblasts, secrete initial collagen matrix; this lattice or mesh sets up the organization of the bone (De Boer and Van der Merwe, 2016; Pearson and Lieberman, 2004). Next the new bone is mineralized with crystalized needles, rods, and plates that are laid in between the collagen lattice (Pearson and Lieberman, 2004). Prior to mineralization, bone cells are known as **osteoids**, which are unmineralized organic components of bone. The final process of bone synthesis is to create an **anisotropic** material based on the loads the bone experiences. Anisotropy means that the material has different properties based on the direction of measurement; for instance, a bone cross-section can be stronger in the anteroposterior plane than in the mediolateral plane. If you picture bone as a pipe, a perfectly circular and even pipe would be isotropic, whereas a pipe that has a thicker layer in one section that prevents it from bending in that particular direction would be anisotropic. In experimental rat research, researchers have found that it can take up to four months for tibiae to become anisotropic as a result of mechanical loading (Takano et al., 1996); tibiae likely react faster than other long bones due to the high percentage of trabecular bone in tibiae. Additionally, this change in the shape of bone seems to be intricately linked with collagen fibers that are laid down in the new and disorganized woven bone (Takano et al., 1996; Pearson and Lieberman, 2004). According to Wolff's law of functional bone adaptation, bone should be stronger in the plane in which it was most stressed prior to remodeling to prevent breakage in the future.

Once bone remodeling is complete, osteoblasts morph into lining cells and osteocytes. Lining cells, which are flat in shape, regulate the passage of calcium in and out of bone, plus they respond to hormones by making specific proteins that activate osteoclasts (i.e., bone **resorption** cells). Lining cells cover the dormant bone surfaces (Xiong et al., 2015). Only 5% to 20% of mature osteoblasts become entombed in matrix and thus develop into osteocytes (Bellido, 2014; Neve et al., 2012).

Osteocytes, which are surrounded by new bone and have tendrils to sense cracks, are the longest lived and most abundant of any bone cells (De Boer and Van der Merwe, 2016; Neve et al., 2012). The tendrils are called dendrites, which lie inside canaliculi and reach to the periosteal and endosteal surfaces; dendrites are used to communicate with other cells, especially when they are mechanically loaded (Bellido, 2014; Neve et al., 2012; Niedźwiedzki and Filipowska, 2015). Canaliculi have the ability to release calcium from intracellular and extracellular stores; it has been suggested that osteocytes regulate this calcium flow (Neve et al., 2012). The same tendrils that sense cracks can also direct where osteoclasts should resorb bone (Frost, 2004; Nango et al., 2016). Osteocytes, which live in lacunae, are the least understood bone cells since they are hard to study due to their location in the bony matrix (Neve et al., 2012). Nevertheless, osteocytes seem key to bone remodeling. For instance, a protein RANKL produced by osteocytes is needed for osteoclast formation in trabecular bone (Xiong et al., 2015). Also, osteocytes may control the recruitment of osteoblast precursors (Bellido, 2014). Osteocytes, thus, could also play an important role in both bone deposition and resorption (the removal of mature bones) and in the maintenance of homeostasis, but how this is done is not well understood (Bellido, 2014). Most researchers have come to conclude that osteocytes sense mechanical loads and regulate bone remodeling through hormones, such as the parathyroid hormone's impact on the proteins SOST (which increases bone resorption) and RANKL (which increases bone deposition and produces osteoclasts) (Nango et al., 2016; Neve et al., 2012; Prideaux et al., 2016). For instance, when mechanical loads are placed on bones, osteocytes respond through the parathyroid hormones and decrease the amount of SOST proteins released (Neve et al., 2012).

When examining bone remodeling, factors other than mechanical loads need to be considered. Maturation affects whether bones will remodel effectively. Although bone remodeling is assumed to continue through life, bone remodeling occurs faster in children than in adults (Frost, 1994). In older people, osteoclast activity continues and osteoblast activity seems greatly diminished, which is in part a factor of changes in **estrogen** (which belongs to a group of hormones that promote the development and maintain the female characteristics of the body) and **testosterone** (which is a steroid hormone that stimulates development of male secondary sexual characteristics). Bone remodeling is controlled through the release, restriction, and loss of hormones (Niedźwiedzki and Filipowska, 2015). The imbalance of osteoclast and osteoblast activity can result in **osteoporosis**, a condition in which bones become weak, brittle, and are prone to fractures as a result of loss of bone mass and density (Pearson and Lieberman, 2004). The decrease in osteoblast activity may be the reason for the loss of osteocytes in older individuals; in individuals between 10 and 29 years old, nearly 90% of bone cells are osteocytes, but only 58% of bone cells are osteocytes in individuals between 70 and 89 years of age (Neve et al., 2012). Osteocytes do not proliferate, but they do die; since osteocytes develop from osteoblasts, less osteoblast activity will result in fewer osteocytes over time (Neve et al., 2012). Osteocytes are essential for healthy bones since they are rich in genes related to mineralization (Neve et al., 2012). Thus, even with increased loads, such as through exercise, bone deposition is not increased in older individuals but rather bone loss is slowed (Pearson and Lieberman, 2004).

Extrinsic (or nongenetic) factors and **epigenetic** factors, which relate to external modifications that can turn genes on or off, can also affect bone remodeling (Bertram and Swartz, 1991; Delgado-Calle et al., 2012). It appears that epigenetic factors are especially important in the changes in bone in older individuals; thus, osteoporosis and osteoarthritis are said to be influenced by epigenetic factors that turn off bone remodeling genes that activate osteoblasts (Vrtačnik and Ostanek, 2014). A multitude of factors other than mechanical loading seem to be linked to bone remodeling influences; blood flow, lack of nutrients, and even oxygen levels can decrease bone remodeling both extrinsically and perhaps epigenetically (Bertram and Swartz, 1991). And, even within a specific deficit, a variety of factors may influence the deficit. For example, vitamin D inhibitors—such as high adipose levels, low levels of sunlight, and veiling—can result in a decrease in bone remodeling since vitamin D is required to absorb calcium (Schlecht, 2012).

Genetic effects, it has been proposed, seem to outweigh the effects of mechanical loading. Many genes regulate the osteogenic cells of osteoblasts and osteoclasts (Pearson and Lieberman, 2004). Two dozen genes are associated with osteoclast activity (Pearson and Lieberman, 2004). Some mutations in these genes result in osteoporosis, which is bone loss to the extent that fractures can occur during normal activity, and other mutations have been found to result in excessive bone retention and hardening also known as **osteopetrosis** (which is a bone disease that makes bones abnormally dense and prone to fractures) (Pearson and Lieberman, 2004). Osteoblasts are sensitive to the endocrine system. Parathyroid hormones, vitamin D, calcitonin, and the sex steroids, all of which are part of the endocrine system, have been found to influence the actions of osteoblasts. The lack of estrogen after menopause is likely the best-documented of these relationships; the loss of estrogen after menopause has been linked to the high level of osteoporosis in postmenopausal females (Pearson and Lieberman, 2004).

Moveable Joints: Composition, Repair, and Remodeling

Joint Composition

Although bioarchaeologists usually focus on bone, understanding **synovial** (or **diarthrodial**) **joints**, which are moveable joints, is important since degenerative joint disease investigations play a key role in reconstructing activity patterns. At the end of a bone lies the articular endplate, which is the joint area that feels smooth when healthy and consists of **subchondral bone**, a thin layer of cortical bone; underneath the cortical bone lies trabecular bone (Hamill and Knutzen, 1995). These areas allow for smooth movement with low friction of our main joints (Hamill and Knutzen, 1995). Since these joints are involved in movement and some of them are weight-bearing, they experience mechanical loads (Grodzinsky et al., 2000).

Cartilage does not preserve and thus cannot be studied directly by bioarchaeologists, but during one's life **articular cartilage** (a flexible fibrous tissue that covers the ends of bones in joints to enable smooth movement)

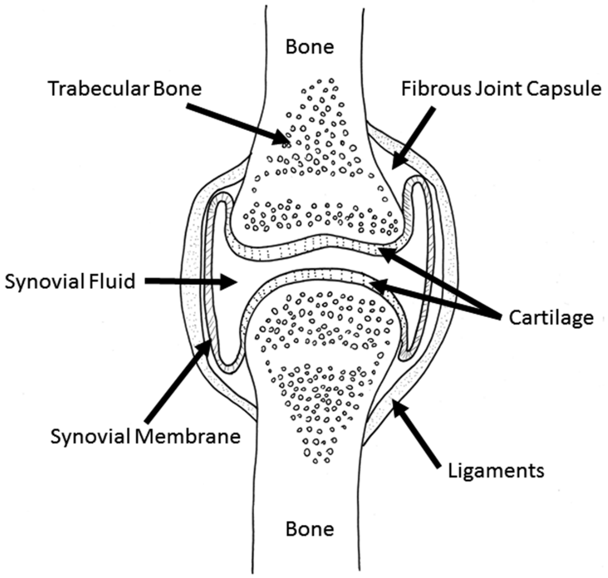

Figure 1.2. Synovial joint. A cut-away illustration highlighting the key features of synovial joint anatomy.

lays over all endplate. Cartilage distributes loads over surfaces, reduces bone-to-bone contact stresses, and reduces friction to allow for smooth and pain-free movement (Hamill and Knutzen, 1995). Articular cartilage is complex; it is composed of an organized network of extracellular matrix made up of collagen and noncollagen proteins, **proteoglycans**, and water (Suri and Walsh, 2012). Two-thirds of articular cartilage weight comes from the collagen proteins (Eyre, 2002). Articular cartilage can be between 1 to 7 mm thick depending on the anatomical location and the mechanical loads the joint experiences; for instance, knee joints have thicker cartilage than the ankle joint at the tibia and fibula (Hamill and Knutzen, 1995; Mow et al., 1984). Articular cartilage consists of white, dense connective tissue (Mow et al., 1984). It has two primary components: liquid, which is mainly water, and solids, which contain collagen and macromolecules of proteoglycan (Benjamini et al., 2014; Hamill and Knutzen, 1995; Mow et al., 1984). Proteoglycans are polysaccharide proteins that have conjugated and that are present in connective tissue and have a lubricant quality. The synovial membrane, which contains the fluid part of the articular joint, is a capsule with interstitial fluid that is mainly water.

Up to 80% of the synovial membrane fluid that lubricates the joints may be water (Mow et al., 1984). There are four zones of articular cartilage, with the calcified zone being the deepest zone and of most importance to bioarchaeologists; each zone has the same basic components but in different amounts and organization (Eyre, 2002; Mow et al., 1984). The calcified zone lies right at the tidemark between articular cartilage and bone, and the subchondral bone is where cartilage and bone come together. Overall, articular cartilage is a relatively ordered tissue in which the collagen fibers form meshes or lattices in various directions (Benjamini et al., 2014; Nukavarapu and Dorcemus, 2013). Collagen fibers thus provide the structure for the articular cartilage. In this mesh of collagen, the proteoglycan macromolecules are trapped (Mow et al., 1984). Figure 1.2 illustrates some of the key components of a synovial joint.

Joint Repair and Remodeling

Although articular cartilage is resistant to **shear** forces, which are forces coming from two directions, and its **viscoelasticity** allows temporary shape changes, articular cartilage is also prone to wear and microtears (Nukavarapu and Dorcemus, 2013). Viscoelastic materials are both viscous, which means that they are thick and sticky, and elastic, which refers to the ability to return to their original shape after forces are applied to them. Having the combination of viscous and elastic properties means that the application of stress may cause temporary deformation if the stress is removed quickly, but permanent deformation can occur if the stress is maintained. Thus, viscoelastic materials exhibit time-dependent strain. The proneness to wear is likely a result of the lack of repair and remodeling; instead of remodeling, cartilage swells and deforms. Like bone, cartilage experiences microdamage (Suri and Walsh, 2012). These changes in joint thickness and shape help to distribute mechanical loads and help to prevent breakage. For example, in order to resist compression, the cartilage's ionic properties attract water, and its porous quality allows the water to enter into various aspects of the cartilaginous matrix; these result in the cartilage becoming swollen and resistant to compressive loads (Mow et al., 1984). The lack of remodeling is likely because cartilage is **avascular** (and thus is not associated with a blood supply), but it is nourished by the joint fluid, which is found in the synovial membrane that serves to secrete fluids and lubricates surfaces (Hamill and Knutzen, 1995).

Even though cartilage is avascular, there is evidence that cross-talking between cartilage cells and bone cells may enable cartilage repair and remodeling. Cartilage cells, which are called **chondrocytes**, are usually thought of as static with little ability for repair and remodeling (Burt et al., 2013; Eyre, 2002). But researchers have recently questioned whether cartilage may be more active than previously thought. Chondrocytes and subchondral bones perceive stresses (Benjamini et al., 2014; Grodzinsky et al., 2000; Lories and Luyten, 2011). Responses to stress seem similar to responses to stress in bone; in other words, dynamic loads, for instance, create a greater response than static loads (Lories and Luyten, 2011). Subchondral bone, which lies under the calcified cartilage, is composed of bony lamellae of cortical bone and trabecular bone. Subchondral bone is strong but not uniform in thickness, and it goes through bone remodeling as other bone does (Nukavarapu and Dorcemus, 2013). Upon stresses on the cartilage, researchers have found that **proinflammatory** cells called **cytokines** are released; unfortunately, this response is destructive to cartilage (Lories and Luyten, 2011). Chondrocytes, which lie in the lacunae of the Haversian system and in trabecular bone, have also been linked to interactions with bone cells. Chondrocytes, it seems, cross-talk with osteoblasts and osteoclasts, which may initiate remodeling and repair (Lories and Luyten, 2011). Microcracks or lesions, especially those deep in the cartilage such as in the calcified zone, likely increase cross-talk between chondrocytes and bone cells (Lories and Luyten, 2011; Suri and Walsh, 2012). When microlesions are found, it appears that osteocytes, osteoblasts, osteoclasts, and bone-lining cells engage with subchondral bone (Suri and Walsh, 2012). Consequently, it has been suggested that cartilage remodeling is actually repair but that the repair is insufficient to make significant changes in joint health (Lories and Luyten, 2011). Some researchers have suggested that this is because chondrocytes' response to synthesizing the complex matrix of cartilage occurs too slowly (Sandell and Aigner, 2001). This cross-talk with bone cells, however, is not well understood; how chondrocytes respond to stresses is still unknown (Grodzinsky et al., 2000).

Summary

Throughout this book changes in bone are discussed to determine whether bioarchaeologists can use bone traits to reconstruct past lives.

The features examined in this book include cross-sectional geometries, entheseal changes, osteoarthritis, stress fractures, and facet extensions. These features, all of which are macroscopic and most of which do not need any technology to assess, are currently used to reconstruct activity patterns of past peoples with little attention paid to the possible biological confounds. The main arguments are that these bony features are a result of remodeling, nontraumatic stress fractures, or even just wear and tear in tissues that do not change. For instance, cross-sectional geometries are usually interpreted as a result of bone remodeling whereas osteoarthritis emphasizes wear-and-tear etiology and spondylolysis (a type of stress fracture) has been said to be related to nontraumatic stresses. In each subsequent chapter, a different type of bony trait will be reviewed. The anthropological research on cross-sectional geometries, entheseal changes, osteoarthritis, stress fractures, and facet extensions are reviewed to see what activities have been linked to these features. Instead of stopping at the anthropological explanations, research from clinicians and experimental researchers are reviewed to determine whether any of these variations can be better explained through biological factors. In short, the question asked is whether bone traits are a result of activity or biology.

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CROSS-SECTIONAL GEOMETRIES

Cross-sectional geometry is one of the most well-studied ways to reconstruct activity patterns. Experimental animal research and clinical sports literature support the connection between long-bone diaphyseal shapes and activity patterns. Many of these studies support the use of cross-sectional geometries to reconstruct activity patterns of past populations; however, the question of biological influences, especially in terms of growth and sex differences, is still being discussed prominently in relation to cross-sectional geometries.

Biomechanics of Beam Models

Long bones can be conceived of as pipes or beams from which, by calculating the deviation from perfect roundness and uniformity, anthropologists can determine the direction of stresses the bone experienced, the bone remodeling responses to the stresses, and the activities which may have caused the stresses (Bridges, 1995). However, anthropologists also understand that the beam model is not perfect since, as mentioned earlier, bone is anisotropic and thus resists certain stresses naturally better than other stresses, even without directed bone remodeling. Furthermore, bone cross-sections are never perfectly round; evolutionary pressures have ensured that bone cross-sections most often fit their purpose without threat of fractures. Yet studying cross-sectional geometry can let anthropologists see where stresses have placed undue strains on bones that have led to cross-sectional shape differences that arise throughout an individual's life. Stresses that are said to be caused by mechanical loads, such as weight-bearing or muscle use, can be divided into strains and forces. Loads are weights or pressures borne by something. Strains are stresses experienced by bones that come from external sources, such as the surface one walks on. Forces, on the other hand, are stresses experienced by bones that come from muscle use, such as when one throws a spear or grinds acorns. Thus, in accordance with functional bone remodeling theory (and Wolff's law), bone remodels to prevent breaking from its most significant stresses (Swartz, 1996).

Stresses

There are five stresses that can affect a beam or a long bone. These strains and forces are tension, compression, bending, shearing, and torsion (Swartz, 1996). In most cases, tension and shearing only occur in a very localized manner whereas compression, torsion, and bending are experienced either by the entire bone or by a bone region. **Tension** is mainly a force at the muscle insertion sites. Tension is force that pulls the beam and creates an elongating force (Swartz, 1996). Muscle insertion sites are addressed in the next chapter.

Compression is the strain bones experience most often, especially weight-bearing bones (Swartz, 1996). Since compression is such a regular strain, bone biology is adapted to this strain. The Haversian system, described in chapter 1, is ideal for preventing breaks due to compression, especially when the compression loads are coming from the same direction as the Haversian systems. Bones that are susceptible to compression fractures are those that are mainly composed of trabecular bones, such as vertebral (or back) bones. Vertebral bone collapses are especially common in osteoporotic and elderly individuals (Weiss, 2014c). This is likely a combination of being recently bipedal (which refers to moving around on two limbs rather than four) and, consequently, vertebral bones being still mainly configured for non-weight-bearing stresses, coupled with a recent increase in longevity that has enabled females to have postreproductive years. In postmenopausal years, females experience hormonal changes such as a loss of estrogen (i.e., a hormone that helps regulate healthy bone remodeling) that, consequently, leads to bone loss (Frost, 1990). Haversian bones, such as femoral shafts, also experience bone loss with age but, having been adapted to compressive loads, do not fracture frequently from bearing weight.

Shearing stresses occur when loads come from two different directions. Shearing stresses are rare and usually result in a fracture. The most common form of shearing stresses result from high-impact incidents, such as when one is moving forward and is hit head on, such as in contact sports. These types of events usually lead to an injury.

The most common forms of stresses are from **torsion** (or twisting) and bending loads. Torsion occurs near the joint surfaces especially and is usually a force rather than a strain (Alexander, 1968). For example, torsion is common near the hip joint, which affects the upper part of the femur, and near the shoulder joint, which affects the proximal humerus. Bipedal mobility and throwing both result in torsional stresses and are activities often examined in the anthropological literature (e.g., Bridges, 1995; Sládek et al., 2006; Sparacello et al., 2011).

Bending stresses are actually composed of tension on one side of the beam and compression on the other side (Alexander, 1968). Bending stresses are usually a result of bone strain and muscle force. The femur, which is the most commonly examined bone for bending strength, experiences bending stresses from the muscles used in walking that attach mainly on the back (or posterior) of the femur and to the ilium region of the pelvis and tibia. These muscles pull the femur back and cause stresses along the shaft. But the femur also experiences bending strains from the ground because when compression impacts long bones, bending also usually occurs. Due to the high degree of bending and torsional stresses on the limb bones, anthropologists have surmised that these strains should result in the greatest amount of bone remodeling to prevent breakage from the stresses. A way to calculate bending strength is to look at the ratio of minimum and maximum moments of inertia. **Moments of inertia** represent the bone's ability to resist changes in angular velocity; thus, moments of inertia give an indication of how much the bone has remodeled in a response to bending stresses.

Measuring Bone Strength: Variables and Standards

In biomechanical studies of cross-sectional properties, only a handful of geometric values need to be considered to determine how bones have reacted to the above discussed strains and forces. Regardless of the hypotheses and the materials used to examine cross-sectional data, nearly all cross-sectional studies use the geometric properties of total area, cortical area, moments of inertia, and polar moments of inertia (e.g., Hansen et al., 2009; Maggiano et al., 2008; Marchi et al., 2006; Ruff and Hayes, 1982;

Table 2.1. Cross-sectional geometry properties and the strengths they measure

Cross-Sectional Property	Strength Measurement
Cortical area (CA)	Compression and torsion
Total area (TA)	Compression
Moments of inertia (*I*)	Bending
Polar moment of inertia (J, Zp)	Torsion

Weiss, 2003a). In short, there are areal and inertial (or second moment of area) values (see Table 2.1).

The areal values include **total cross-sectional area** (TA), which is the measure of the cortical area plus the medullary area, and **cortical cross-sectional area** (CA), which is a measure of the total amount of **cortical bone** in a cross-section. Both TA and CA measure compressive strength; that is, the bone's resistance to breaking from compression is also known as compressive strength. A larger CA or TA value indicates a bone that has remodeled to prevent fractures from compressive loads.

Inertial values are measured through the center of gravity and address issues of bending and torsional strength. Bending stresses, which are the stresses most likely to cause fractures in bones, can be assessed in the direction of the bending strains. Ergo, measurements for bending strength are expressed as *I*ap (for inertial strength in the anteroposterior plane) and *I*ml (for inertial strength in the mediolateral plane); *I*x and *I*y are sometimes used in place of *I*ml and *I*ap. A ratio of *I*ml to *I*ap allows researchers to calculate where bone remodeling has deposited new bone to prevent breakage from bending stress. For instance, if the strain comes from the anteroposterior plane, then the bone should have a cross-section that is long front to back.

Finally, **polar moment of inertia**, which is abbreviated as J and Zp (when raised to 0.73 for standardization), is used to determine torsional strength. J can be calculated by adding *I*ap and *I*ml together; thus, J is also used to determine overall bone strength (sometimes called **robusticity**) (Runestad et al., 1993).

Because the number of variables are few, most studies can be easily compared, so cross-sectional studies sometimes use previously published data to compare with new data (e.g., Trinkaus et al., 1994; Weiss, 2003a). Additionally, the cross-sectional data are standardized by where the information is gathered from on the bone; for example, the most common humerus location is 35% of bone length with 0% being the elbow end and 100% being the humeral head (e.g., Fresia et al., 1990; Rhodes and Knüsel, 2005; Stock and Pfeiffer, 2004; Weiss, 2003a). The locations are standardized to avoid major muscle insertion locations (Ruff and Larsen, 1990). The locations are also chosen where stresses may be highest (Ruff and Larsen, 1990). Common locations for the femur and tibia include the midshaft (or 50% of bone length) and 80% of bone length (e.g., Bridges et al., 2000; Holt, 2003; Stock and Pfeiffer, 2004; Trinkaus and Ruff, 1999).

Standardization for body size, which is also referred to as correcting for or controlling for body size, is common in cross-sectional geometry studies (e.g., Bridges et al., 2000; Holt, 2003; Maggiano et al., 2008; Stock and Shaw, 2007; Trinkaus and Ruff, 1999; Weiss, 2003a, 2005; Wescott and Cunningham, 2006). Chris Ruff and colleagues (1993) provided formulae for standardizing by humeral length. However, standardization can also be completed with body mass, and this may be preferable when comparing groups with different body types as a result of climatic adaptations (Weiss, 2003a, 2005). Limb length, which is shorter in cold-climate populations compared to hot climate populations as a result of natural selection (a trend known as Allen's rule), can result in exaggerated robusticity values in short-limbed populations. Furthermore, body mass calculations use the ends of long bones (such as the femoral head) or pelvic breadth, and these features are less likely to be altered by growth interruptions such as nutritional deficiencies and childhood diseases. To calculate body mass in individuals who have long since passed away, one uses measures from the femoral head or bi-iliac breadth and calculations based on **regression formulae** (Ruff et al., 1991; Ruff, 2000b).

Not all variables need to be standardized by body size; ratios, including measures of asymmetry, do not need to be standardized by body size. Many researchers use bilateral asymmetry to determine whether activities were **bimanual** or **unimanual** (e.g., Rhodes and Knüsel, 2005, Weiss, 2009a). Asymmetry compares left-side and right-side values within a single individual, and the product is a percent difference; since the value is standardized as a percentage and the comparison to find the percentage is within an individual, no body size standardization is required. Most asymmetry studies involve research on the upper limb since most people have a hand preference; most people are right-handed. Therefore, certain tool use may result in great asymmetry. Forensic anthropologists have looked at asymmetry to determine handedness, but they used external measurements as opposed to cross-sectional asymmetry (see Ubelaker and Zarenko, 2012, for a review of forensic studies of asymmetry and handedness).

Data Collection

Although cross-sectional geometry variables, anatomical locations of data collection, and body-size controls are very uniform and standardized, there are a variety of ways to collect the data. Early research on cross-sectional geometries employed saws to literally slice through bones (e.g., Ruff and Hayes, 1982, 1983), but even recent studies have employed this method (e.g., Hansen et al., 2009; Maggiano et al., 2008). This method allows for accurate measurements, but it is obviously destructive and thus not desirable on rare or culturally sensitive collections. Many studies employ medical imaging technology, such as radiographs (e.g., Marchi, 2008; Marchi et al., 2006; Trinkaus and Ruff, 1999; Trinkaus et al., 1994, Weiss, 2005) and computer tomography scans (e.g., Bridges et al., 2000; Gosman et al., 2013; Niinimäki, 2012; Sládek et al., 2006; Stock, 2006; Wescott, 2006), to obtain cross-sectional information. Computer tomography scans (CT scans) and quantitative computer tomography scans (qCT scans or pQCT scans) are 360° radiographs that use computer software to put together the cross-sectional image. CT scans are expensive and not universally available, but traditional radiographs (X-rays) are often available even in anthropology departments. To calculate cross-sectional variables from X-rays, the X-rays need to be taken in two planes (therefore, one may see the term biplanar X-rays), and the cross-sectional geometries are calculated with Pi formulae (Fresia et al., 1990; Biknevicius and Ruff, 1992; Weiss, 2003a). If X-rays are taken with a stationary X-ray machine as opposed to one with a moveable arm (like a dentist's X-ray), then a magnification factor formula must be used to remove any magnification error (Weiss, 2003a). X-rays are inexpensive, easily available, and nondestructive, but recent research has suggested that there is a slight bias in X-rayed values. X-rayed cross-sectional values are about 5% greater on average than CT-scanned values even after corrections (O'Neill and Ruff, 2004); why this is the case is still unknown and, thus, worthy of further investigation. X-rayed data accuracy can be improved with subperiosteal molds (Stock and Shaw, 2007). Nevertheless, even with these little variations, cross-sectional data collected in multiple methods are still comparable, and the data from any of these images can be either calculated with formulae or entered into computer software programs, like SLICE (see Doube et al., 2010).

The standardization of cross-sectional geometries has allowed anthropologists to compare data from previously published sources, including sports literature (e.g., Trinkaus et al., 1994). Cross-sectional geometry is likely the most uniform data anthropologists use to reconstruct activity patterns.

Activity Pattern Reconstructions

Subsistence Pattern Changes

Anthropologists' main interest in cross-sectional geometries of long bones has been to reconstruct activity patterns of past populations. The combination of Wolff's law, early animal research, and asymmetry studies on tennis players has led anthropologists to conclude that cross-sectional bone morphology (or shape) is an outcome of biomechanical loads linked to activity patterns that cause stresses that bone responds to by remodeling (Bertram and Swartz, 1991; Ruff et al., 2006). Although cross-sectional research started in the late 1960s with John R. Dewey and colleagues' (1969) work on Nubians in relation to age-related changes in bone, physical activity research blossomed in the 1980s and continues to this day.

Research looking at changes in mobility in relation to the transition to agriculture from hunter-gatherer subsistence and the shift from agricultural populations to industrial populations was one of the early uses of cross-sectional geometries and activity pattern reconstruction. In one of the first temporal views of mobility and subsistence using cross-sectional geometry, Tasuku Kimura and Hideo Takahashi (1982) looked at femoral cross-sections of Japanese hunter-gatherer populations dating more than 5,500 years ago compared to more recent Japanese populations (a 2,000-year-old agricultural sample and a modern sample) to document that femora have become rounder over time in males whereas female femoral cross-sections were always round. Kimura and Takahashi surmised that the cross-sectional changes were a result of increasing sedentary behavior in males who once walked many miles to hunt game; the lack of mobility decreased bending stresses, thereby keeping the femoral cross-sections round in later populations. This article influenced many subsequent researchers interested in mobility in relation to subsistence patterns. For example, Ruff and colleagues (1984) and Ruff (1987), citing Kimura and Takahashi (1982), came to similar conclusions when examining cross-sectional shape in Southwestern hunter-gatherers, agriculturalists, and a modern industrial sample.

Yet not all studies looking at the transition from hunting and gathering to agriculture found only male changes in cross-sectional properties. Patricia Bridges (1989a) studied populations that went from hunting and gathering to agriculture in the Tennessee Valley and found that although lower limbs became less resistant to bending stresses, female cross-sections showed an increase in resistance to stresses, which may indicate that females did most of the agricultural labor. The upper limbs of females increased in strength, which Bridges attributed to grinding corn. She found similar patterns in West-Central Illinois Amerinds. The upper limb is used in more ways than the lower limb; thus, Bridges' work integrated artifactual analyses, such as mortars and pestles as burial goods, to support her activity reconstructions. In a 2000 study, Bridges and coresearchers hypothesized that an initial increase in female humeral strength related to the difficulty in processing natural seeds, but once agriculture was fully adopted, female humeral strength decreased again, likely because the domesticated corn involved breeding a plant that was easier to process and grind than the naturally occurring seeds. Bridges and colleagues also suggested that the decrease in male humeral strength may have been related to replacing the **atlatl** (which is a device for throwing spears that consists of a board with a projection at the rear to hold the weapon in place until released) with bows and arrows. Atlatls require more strength, which places more stress on bones, than bows and arrows. Bridges' work on the upper limb helped her and subsequent researchers focus on female labor, which is often overlooked.

Examining sex differences in activity continues in cross-sectional research. In a recent study on the transition to agriculture in the Southwest, Marsha Ogilvie and Charles Hilton (2011) looked at Pecos foragers compared to pottery mound farmers to determine patterns of sexual division of labor. Looking at humeral cross-sections, TA increased in farmers, but CA did not. In humeri, bending strength as measured by I_x/I_y was found to be higher in males of both populations. Although asymmetry decreased in the farming Amerinds, male asymmetry was higher than female asymmetry, which may have been due to tool making. In general, Ogilvie and Hilton (2011) found, similar to Bridges (1989a), that females underwent more changes than males, likely because females engaged in farming activities and were presumably the ones grinding maize.

In an interesting article on subsistence coupled with European contact, Anne Fresia and colleagues (1990) examined cross-sections of Georgia coast Amerinds using biplanar X-rays. Fresia and colleagues looked at these Georgia coast Amerinds who, unlike the previously mentioned hunter-gatherers, were hunter-fisher-gatherers who transitioned to agriculture before European contact but upon contact became more dependent on agricultural foods. Fresia and colleagues found that asymmetry of humeral cross-sections at 35% of bone length decreased over time. Overall, female cross-sectional geometries changed more than did male cross-sections. Yet males' asymmetry decreased most dramatically at the time of contact with Europeans; thus, sex differences initially increased with the onset of agricultural practices but then decreased again with contact as agriculture became the main source of food and hunting decreased dramatically.

Across the ocean in the Old World, effects of subsistence pattern changes with an adoption of agriculture have also been examined in relation to mobility, upper-arm cross-sectional strength, and sexual dimorphism. For example, Damiano Marchi and colleagues (2006) looked at late Upper Paleolithic hunter-gatherers from Europe compared to Mesolithic hunter-gatherers and Neolithic Italian farmers to examine activity pattern shifts. The **Paleolithic** period extends from 2.6 million years ago to right before 10,000 years ago; the **Mesolithic** period falls between 10,000 years ago to 2,000 years ago, but varies in different locations; and the **Neolithic** period tends to be the last 5,000 years, but once again it varies from one location to another. This study is unique in its expansive time period coupled perhaps with a sample of homogenous peoples. Many prehistoric populations are assumed to be homogenous, but this assumption is often not thoroughly tested. Although the sample sizes were small (for example they had only 16 Neolithic Italian farmers), cross-sectional data on humeri and femora revealed some interesting trends. In the humerus, Marchi and colleagues (2006) found a decrease in asymmetry that was linked to less unimanual work, like throwing for hunting, and more bimanual work, such as grinding. This trend has been found in other studies, such as the Bridges' (1989a) study mentioned earlier. In the femora, Neolithic farmers' cross-sections had greater bending strength than the hunter-gatherer populations, which is the opposite of what one might expect. But the authors suggested this is a consequence of the Italian sample coming from a mountainous terrain. In the first study to highlight how terrain can affect cross-sections, Ruff (2000a, 2000c) looked at various Amerind populations and found that populations in mountainous terrain had more robust femoral cross-sectional shapes than flatland or coastal populations. Thus, Ruff provided good evidence with large samples that physical terrain can effect femoral shape.

Not all anthropologists are convinced that lower-limb cross-sections are so easily affected by activity patterns. Daniel Wescott (2006) studied femoral cross-sections over time in a large sample to assess mobility effects on bone shape, and he concluded that strong anteroposterior-oriented cross-sections are not clearly linked to mobility. Wescott posited that genes may play a greater role in cross-sectional shapes than previously assumed.

Mobility and Cross-Sections

Mobility is one of the most studied activities in cross-sectional research. **Mobility** can be defined in multiple ways (see Carlson and Marchi, 2014, for a full discussion), but for our purposes here mobility is defined as using the limbs to move the entire body from one location to another location. A strong anteroposteriorly oriented femoral cross-section is suggestive of bending strength and, thus, mobility. Figure 2.1 illustrates a strongly anteroposteriorly oriented femoral cross-section. Mobility changes have been examined in the transition to agriculture (see earlier discussion of Kimura and Takahashi, 1982; Ruff, 1987; and Bridges, 1989a) as well as in cases that are not related to agriculture adoption.

Therefore, although the transition to agriculture from hunting and gathering is an essential topic covered by anthropologists, some studies have looked at mobility in terms of local phenomena to reconstruct past activities. In the New World, for instance, Isabel Maggiano and coresearchers (2008) used a small sample of Yucatan individuals from AD 250 to AD 550 compared to a later sample, which dated between AD 550 to AD 770, to examine the effects on past people living in a coastal city that changed from a localized salt production center to a major salt exportation hub. Maggiano and colleagues reported on extensive archaeological evidence to support the transition of this location into a single-industry

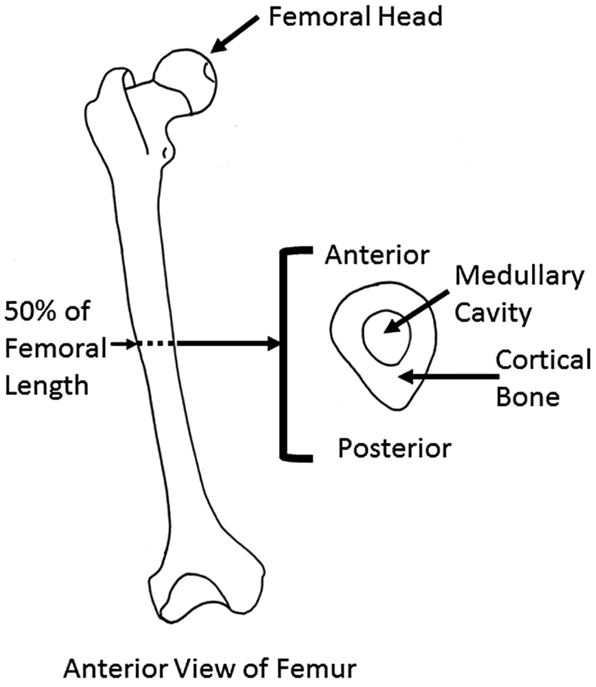

Figure 2.1. Femoral cross-section. An illustration of a cross-section of an individual that had a strong anteroposteriorly oriented femoral midshaft, which would be suggestive of high mobility or difficult terrain.

town. Salt production and exportation presumably led to an increase in administrative labor in the city; thus, this increase in non-labor-intensive work should be visible in the people's cross-sectional shapes. It appears that femoral cross-sections did get rounder over time, and sex differences decreased in femoral shape; as a result, males became more sedentary likely as a result of their new positions in society as administrators. This research is notable for its look at how a single industry can shape human lives, which is analogous to our current construction of thinking of certain cities linked to manufacturing hubs, such as with Detroit and cars. But we may ask, even in single-industry cities, what proportion of the population actually worked in the industry? In other words, Detroit was known for cars, but what proportion of Detroit's maximum postwar population actually worked in a car factory? Does our perception match with reality?

Another example comes from Michael Ledger and colleagues (2000), who used CT scans of South African free blacks, slaves, and hunter-gatherers to examine mobility differences. They found that male hunter-gatherers had femoral cross-sections that were indicative of high mobility, but the females' round cross-sectional femora may have related to a decreased emphasis on mobility with an emphasis on obtaining foods, such as tubers, through digging. The South African slaves had femoral cross-sections to indicate a low mobility, but their femora were still more anteroposteriorly oriented than the free-black, modern South African sample. Although it is possible that the low bending strength in slave populations was related to a lack of mobility, it could also be that these individuals were not healthy enough for bone remodeling to occur effectively; their socioeconomic status was extremely low, and their diet may have been restricted. However, the diet in this population is not known for certain, and historians who research the African diaspora may be better suited to answer questions about diet among slave populations. Lack of good diet, as mentioned earlier in chapter 1, can have a negative effect on bone remodeling; plus, this dietary effect can be epigenetic if the diet impacts mothers-to-be. Nevertheless, the slave population had very robust upper limbs, which may be suggestive of a different type of labor for them compared to the other populations examined.

Jay Stock (2006), who examined CT-scanned cross-sections of hunter-gatherers, found that the trend in circular femoral diaphyses (or shafts) may relate to decreased mobility, but he also noted that populations that depend on water transportation have less anteroposteriorly oriented femora than more terrestrial or inland populations. Stock's (2006) work on coastal compared to inland populations corroborated similar studies by Stock and Susan Pfeiffer (2001, 2004). Yet Stock (2006) and Stock and Pfeiffer (2001, 2004) accepted that they could not exclude genetic adaptations to explain the diaphyseal differences. This point is especially poignant for the articles by both Stock and Stock and Pfeiffer, referenced earlier, since they are comparing different populations, but sometimes anthropologists may not even consider genetic variation since there is cultural continuity at a location that spans a considerable length of time. Furthermore, Stock (2006) noted that climate influences cross-sections; Elizabeth Weiss (2003a) found this to be the case as well in a cross-cultural study of upper-limb bones in rowing populations. Interestingly, in the lower limb, climate—most specifically cold climate and northern latitudes—affects the distal element most, but in the upper limb the humerus is more affected by climate than the bones of the forearm (Stock, 2006).

Wescott (2006) examined mobility over time and found that femoral shape and robusticity are not clearly linked to mobility. For example, when sex differences in femora are noted and tied to mobility changes, the difference is not always due to an increase in male anteroposterior orientation; sometimes, the changes are an unexpected increase in female mediolateral orientation, which may not relate to activities at all. Sex differences in femora are likely related to genetic and biological differences, such as pelvic shape and hormonal cycles (Wescott, 2006). This point is especially important in lower-limb studies since females were invariably found to have rounder cross-sections than males, which is usually attributed to more mobility among males than females. Yet the genetic factors Wescott brings up suggest that the sex difference is not in activity patterns but in our genes. Thus, lower-limb shape may in large part be regulated by genes and not environment. Evidence from earlier peoples, such as Neanderthals, supports the genetic perspective too; Neanderthals were likely very mobile, yet their femoral cross-sections were not anteroposteriorly oriented as might be expected (see Lieberman et al., 2004; Trinkaus, 1997).

Upper-Limb Studies

Even though lower-limb studies seem to be important to understanding mobility, there are complications regarding sex differences, especially if the lower-limb cross-sections are affected by pelvis shape, so perhaps the upper limb can give us a greater understanding of whether activities or genes shape cross-sections. Upper limbs are used in a variety of manners and thus may even be useful in reconstructing specific activities if mechanical loadings shape them. Studies on asymmetry are especially useful since body shape and size will not need to be considered in these intra-individual variables.

In a site-specific study that examined the cultural differences between monks and lay persons, Simon Mays (1999) used biplanar humeral X-rays to understand activity patterns. Mays studied a sample of eleventh- to sixteenth-century English people and compared the lay persons to monks. He found that monks had lower values for polar moment of inertia, which measures torsional and overall bending strengths, compared to the other males. Although some monks engage in hard labor, the Gilbertine Order, which these monks belonged to, was an intellectual order belonging to the Augustinian Rule; thus, the lack of robust cross-sections was likely a result of a less labor intensive life than the average males at the time. Another possibility is that the monks had a restrictive diet that would have prevented them from growing strong bones, but Mays dismisses this since once again the order these monks belonged to was not one that practiced an austere diet. Mays' work is an especially good example of where historic cultural information can lead anthropologists to understanding population differences even within a site. Yet Mays conceded that one cannot rule out genetic differences between the two groups of males or other factors such as diet throughout life. In the past, careers were more likely passed on from one generation to the next, so laborers may have belonged to a different genetic stock than those individuals who entered into the brotherhood. Interestingly, osteoarthritis, another activity pattern indicator, did not differ between the two groups, which led Mays to surmise that osteoarthritis may be a less reliable activity indicator than cross-sectional geometries.

Some activity pattern research has focused on weaponry and the effects of different weapons used on humeral asymmetry. Although subsistence pattern studies have also been examined using asymmetry (as discussed earlier), not all of the research regarding weapons focuses on the effects of adopting agriculture. Weaponry research is intriguing because it claims it can possibly distinguish differences that may seem minute to the layperson. In an innovative look that combines evidence of injuries with combat information and artifacts, Jill Rhodes and Christopher Knüsel (2005) examined two British sites, Towton, which is a historic battle site from the Wars of the Roses with many blade-injured individuals, and Fishergate, which was split into two groups—a group of blade-injured individuals and a group of non-blade-injured individuals—for comparative purposes. Fishergate is a medieval site with three separate burial areas that contain different socioeconomic groups. One of the areas consists of a monastic cemetery from early thirteenth to fourteenth century whereas the blade-injured individuals come from the other two secular areas. Both sites had evidence of sword use and histories of war. Looking at patterns of robusticity and asymmetry, Rhodes and Knüsel came to some thought-provoking conclusions; for instance, they found that the individuals with the greatest robusticity as measured by J did not necessarily have the greatest levels of cortical bone. Furthermore, the comparative sample had lower levels of J than the Towton sample, but the Towton sample had lower directional bending strengths measured by using *I*x/*I*y than the Fishergate blade-injured sample. Additionally, the Towton group displayed the greatest levels of asymmetry in directional bending strength. These variances suggested to Rhodes and Knüsel (2005) that even similar weapons do not lead to the same cross-sectional properties; differences may be due to training differences or the age at which training begins. Age at which an activity begins is essential to how much difference in bone remodeling occurs, as you will see in the following sports section.

In another weapon study, Vitale Sparacello and colleagues (2011) also found links between high levels of asymmetry in humeral cross-sections and sword use. In their Italian sample, males had higher levels of asymmetry than females, and the levels of asymmetry were in the same range as the Towton sample found in Rhodes and Knüsel's work. Accordingly, Sparacello and colleagues have suggested that the asymmetry is a result of weaponry use that started at a young age.

In a 2006 study by Daniel Wescott and Deborah Cunningham, CT scans of humeri from the Arikara South Dakota Amerinds were examined to look for temporal changes that may have occurred between the sixteenth century and the nineteenth century. After standardizing for body size, Wescott and Cunningham noted that male humeral cross-sections changed likely as a result of the switch from bows and arrows to firearms; female humeral cross-sections experienced no changes over time. Yet it must be remembered that the upper arm is used for many activities; thus, these weaponry studies sometimes seem to be implying that the action of using blades, swords, or bows and arrows is outweighing all other activities that the males engaged in.

Perhaps one of the most famous examples of asymmetry comes from Erik Trinkaus and colleagues' (1994) work on Neanderthals; this research is highlighted in the following section on sports literature.

Research on the Cross-Sectional Geometry Determinants

Sports Literature

Anthropologists commonly cite evidence from studies on athletes to support the cause-and-effect relationship between cross-sectional geometries and activity patterns (e.g., Bridges, 1995; Fresia et al., 1990; Ledger et al., 2000; Maggiano et al., 2008; Mays, 1999; Rhodes and Knüsel, 2005; Ruff et al., 2006; Sládek et al., 2006). Much of the sports literature covers asymmetry of the upper limbs in tennis and racquetball players. The following reviewed studies have been frequently cited by anthropologists as evidence that activity, and not genes, is the most important factor in shaping cross-sectional shapes.

Pekka Kannus and colleagues (1995) used bone mineral content rather than traditional cross-sectional geometry measures to examine asymmetry in tennis players. They detected that female tennis players from Finland had two times the amount of asymmetry than nonplaying female controls. Bilateral asymmetry, the authors noted, is especially pronounced in athletes who started to play before puberty. In another asymmetry study, Heidi Haapasalo and colleagues (2000) looked at a relatively small number of tennis players and a control sample of nonplayers; with their two dozen subjects, the authors found that tennis players had greater asymmetry than nonplayers. The asymmetry was most pronounced in inertial values where the players' asymmetry was over twice as high as in nonplayers and the cross-sections of the dominant playing hand was strongest. In an early multinational study that attracted the attention of anthropologists, Henry H. Jones and colleagues (1977) examined asymmetry in professional tennis players from 18 nationalities; they discerned that the tennis players consistently had more robust and more asymmetrical humeri than nonplayers. The fact that this study included people who would be genetically distinct helped bolster the argument that the environment and not genes determined the final shapes of diaphyses. Hartmut Krahl and colleagues (1994) corroborated these findings using a mixed-sex sample, which may have helped allay concerns that the sex differences in the archaeological samples were due to biology and not activities. Ruff (2000b) incorporated some of this sports evidence and found that tennis players had higher levels of asymmetry than preagricultural Amerinds, agricultural Amerinds, Aleut whalers, and Neanderthals.

Although asymmetry is important, age at which the athlete starts to engage in the activity is also very important to examine. Saija Kontulainen and colleagues (2003) examined female racquetball players using traditional cross-sectional geometries. They discovered that long-term racquetball players had an increase in CA, but the medullary area did not differ from that in nonplayers or short-term players. Young starters (or long-term players) were defined as those who started to play before puberty; these young starters had two times the asymmetry as later starters. The age of onset in activity is one that anthropologists realize may play a great role in the final changes on the bone; anthropologists, as mentioned earlier, often assume that the daily activities (such as hunting, gathering, and grinding food) of past peoples started early in life. This assumption was explicitly made, for example, with the use of swords among the Iron Age Italians studied by Sparacello and colleagues (2011). Yet, in both of these studies, researchers note that between 60% and 80% of the variation is likely to be genetic. Plus, there may be a selection bias on who becomes an athlete in the first place. For instance, larger and more muscular girls may be singled out by coaches early in life, or these girls may also be drawn to sports more so than other girls. Plus, height may also be a factor, especially for running, where a longer stride has an advantage.

Perhaps one of the most famous comparisons with sports comes from Trinkaus and colleagues (1994) who compared Jones and colleagues' (1977) tennis player data on asymmetry with Neanderthal humeri. Trinkaus and colleagues found that Neanderthals were nearly as asymmetrical as tennis players in cross-sectional geometry, and both groups were more asymmetrical than other comparative groups, such as the Pecos Amerinds, who were agriculturalists. The asymmetry of Neanderthals, the authors surmised, was likely a result of biomechanical load since the articular surfaces displayed no greater asymmetry than comparison groups. Articular surface metrics are thought to be nonchanging throughout adult life and controlled by genetics. Articular surfaces, hence, are used to reconstruct body size and are used for standardizing measures. Neanderthals likely experienced great forces when thrusting spears into large game animals. In a rare bioarchaeological experimental study, Daniel Schmitt and colleagues (2003) conducted experiments that illustrated that, although thrusting engages both arms, unlike throwing, the force is asymmetrically applied and thus can cause asymmetry to humeral cross-sections. The question also arises whether Neanderthal bone remodeling may differ from that of *Homo sapiens* and, thus, equal actions may result in different cross-sectional outcomes. We are not, in other words, comparing like with like.

Although most sports literature concentrates on the upper limbs, Riku Nikander and colleagues (2010) looked at how sports affects cross-sectional geometries of tibiae. The use of the lower limb in sports research can help us understand the effects of mobility on cross-sections; unfortunately, the femur was not included in this study. They used a sample of 204 competitive female athletes compared to 50 female nonathletes to look at which loads caused cross-sectional changes. They divided their sports into high impact (such as high jumps, hurdles, and triple jumps), odd impact (such as soccer and racquet games), repetitive low impact (such as running), high magnitude (such as powerlifting), and nonimpact (such as swimming). The authors found that most of the cross-sectional differences in TA, CA, and J were found in the high-impact, repetitive low-impact, and odd-impact athletes. Nonimpact and high-magnitude athletes did not differ much from their nonathlete comparison. The strongest tibiae were found in the high-impact athletes, which fits in with some of the literature on bone remodeling mentioned in chapter 1 in which Robling and colleagues (2006) noted that, for bone remodeling to occur, stimuli need to be dynamic. A nondynamic load may be caused by standing for long periods of time, whereas a dynamic load may be a result of running or other high-impact sports. Robling and colleagues also mentioned that bone cells can become desensitized to stimuli, which may occur if the activity is done too often. In short, nonimpact and high-magnitude sports did not cause cross-sectional changes. Although the authors suggested these differences are related to loads, they did point out that genetic differences have not been accounted for, and, thus, there may be a selection bias with large-muscled and big-boned females choosing to become athletes. Furthermore, age differences were present and may have affected the outcome; for example, the repetitive low-impact and the high-magnitude groups were significantly older than the high-impact group. Plus, many athletes do a wide range of activities that are designed to raise fitness, strength, and stamina across the board. So, for example, tennis players will do a wide range of gym and pool training and not just training to boost arm strength. Not taking this cross-training into consideration is another example of how activity assumptions can be too one-dimensional. Finally, the comparison sample was older than the high-impact group. Age is a well-known determinant in bone remodeling, which is discussed in detail later in this chapter.

Not all researchers are convinced that the sports literature reveals that activity patterns cause bone remodeling to prevent bones from fracturing against stresses. For example, John Bertram and Sharon Swartz (1991) argue that the sports literature should not be used to fully support the use of cross-sectional geometries to reconstruct activity patterns; they point out that athletes often start their sport early in life and at an intensity that would not be seen in everyday activities. Furthermore, they suggested that the diaphyseal differences are often a result of injuries; for that reason, what is considered remodeling is actually repair.

Animal Studies

Animal research provides another avenue to understanding the influence of stress on bone remodeling. Unlike research on athletes, animal experiments eliminate selection bias—the animals have not chosen whether to engage in the particular activity. Additionally, animals can be controlled to a greater extent, with some being exercised daily and others being in a sedentary or inactive cage environment. Anthropologists have frequently cited animal research to support the use of cross-sectional geometries to reconstruct activity patterns (e.g., Fresia et al., 1990; Marchi et al., 2006; Maggiano et al., 2008; Pomeroy and Zakrzewski, 2009); one frequently cited article comes from Savio Ly Woo and colleagues (1981), who examined the effects of exercise on swine femoral cross-sections. Woo and colleagues compared five one-year-old swine who were exercised for a year with four non-exercised control swine. After the researchers sacrificed the swine, they reported that the femoral cross-sections of the exercised swine had 17% greater cortical thickness, 23% greater CA, and 20% increase in bending strength compared to the control group. Woo and colleagues concluded that the exercise changed the size and shape of the cross-section without changing bone density or bone biochemical composition.

Later studies, such as those by M. R. Forwood and colleagues (1996) on rat tibiae, corroborated Woo and colleagues' work. Forwood and colleagues looked at eight groups of rats who were subject to different bending loads. The bones, which were chemically marked to detect bone deposition, were examined after the rats were sacrificed on the sixteenth day of the experiment. The authors found that even a single loading episode created bone formation, and the more the bone was loaded with bending stresses, the more bone was deposited.

In an applied case, Prafulla Regmi and colleagues (2015) looked at how chickens housed in aviaries (rather than conventional farming cages) differed in bone strength from their caged peers. Chickens in aviaries could perch, move about, and flap their wings, whereas conventional cages for chickens provide no such room for exercise or activity. Regmi and colleagues found that the aviary chickens' tibiae did not differ in TA compared to the conventional cage chickens, but the aviary chickens' tibiae did have higher values for CA, and they also had reduced medullary canals compared to the other chickens. Furthermore, in the aviary chickens, the humeri had increased TA and *I* values compared to the conventionally caged chickens. Regmi and colleagues concluded that the stronger bones were directly linked to mechanical loads, and they advised that aviaries rather than conventional cages should be used in farms to reduce bone fracture rates, which are excessively frequent in conventionally caged chickens.

Other animal studies have taken a different approach by looking at bone strength after no mechanical loading. Perhaps the best known of these is a series of studies on rats in space. In one of these studies, Arthur Vailas and colleagues (1990) considered the effects of non-weight-bearing during 12.5 days of space flight. Since while in space the rats would have been in a near zero gravity environment, no weight-bearing loading could occur. The researchers had five rats go into space, and they had comparison groups that included rats who were subjected to similar environmental factors to the space rats. For example, some of the lab rats were subjected to similar vibrations that the space rats would have felt upon take off, and similar foods were fed to the lab rats. Vailas and colleagues reported that flight affected long-bone growth and remodeling; the rats who were in space had lost bone strength, and this decline in bone strength was greatest in weight-bearing bones. The authors suggested that the space flight caused a lack of stresses on the bones, and this resulted in continual bone resorption with no bone remodeling. Mechanical loads, it seems, are essential to healthy bones.

Not all researchers are convinced that the animal research provides ample evidence that cross-sectional geometries are linked to activities, especially since some studies have failed to show that activities can change bones (e.g., Pearson and Lieberman, 2004; Zumwalt, 2006). Osbjorn Pearson and Daniel Lieberman, for example, found that body mass accounts for most of the variance in sheep diaphyseal shape. Furthermore, Bertram and Swartz (1991) suggested that some of the bone loss in space rats, for example, was a result of mental distress and hormones associated with that stress, such as cortisones. In studies that look at Amerinds' first contact with Europeans, such as in Fresia and colleagues' (1990) work on the Georgia coast Amerinds, stress may have affected bone remodeling; anthropologists have evidence of contact being a time of stress. Furthermore, the animals in the study were likely the same age and had been cared for in a similar manner; thus, some nonactivity related noise, such as different diets that could affect bone remodeling, is eliminated. In archaeological samples, age is estimated rather than known, and diet may be clouding the true reasons for differences.

Some research has established that, although activity may seem to play a role in cross-sections, evolutionary selection for specific types of environmental niches may also play a role in bone strength. Alison Doherty and colleagues (2012) looked at hibernating woodchucks with pQCT-scanned cross-sections. Using skeletons from animals who either died right before hibernation or right after hibernation, the authors found that posthibernation tibial cross-sections were actually stronger than prehibernation cross-sections. But in the mandible, femur, and humerus, no significant differences in bone strength could be detected in prehibernation and posthibernation skeletons. This lack of bone loss may relate to genes that have been selected for in animals who hibernate (Doherty et al., 2012). In other words, through evolutionary processes such as natural selection, perhaps hibernating animals who better retain bone strength have been selected for, so when they exit their hibernation the animals can survive the stresses that would be placed on their bones. A broken bone could, after all, result in the death of a wild animal.

In a look at animals more closely related to us, Heather Hansen and colleagues (2009) found that baboon cross-sectional geometries were best explained by age, sex, and genes. And Naoki Morimoto and colleagues, in a 2011 study, looked at chimpanzee diaphysis and wrote that Wolff's law did not explain the similarities and differences between captive and wild chimpanzee bones; rather, **ontogeny** (i.e., the development of an individual from embryo to adulthood)**,** which is mainly controlled by genes, best explained cross-sectional shape.

Jon Wergedal and colleagues (2005) decided to tackle the question of whether genes determine bone strength by looking at lab mice. Using 29 strains of inbred mice, Wergedal and coresearchers studied both bone composition and femoral cross-sections standardized by length. The authors concluded that cross-sectional geometry is an important factor in determining bone strength but that genetic factors highly influence the cross-sectional geometry. Although the environmental conditions were identical for all the mice, there was as much as 40% difference between the mice cross-sectional geometries (Wergedal et al., 2005). Bone cross-sectional geometries, the authors surmised, are strongly influenced by parathyroid hormones, growth hormones, insulin-like growth factor hormones (i.e., IGF-I and IGF-II) and bone **morphogenetic proteins**, which are proteins that promote the formation of bone and help mend broken bones. These biological factors are considered response genes; in other words, they determine the rate and degree to which the body responds to stresses, and, therefore, they also determine rates and degrees of bone repair and remodeling. The same type of genetic responses may be seen in humans: parathyroid hormones may especially influence sex differences in bone shape, and medical research has found that the parathyroid hormones influence female bone health to a greater extent than they do male bone health (see Calvo et al., 1991).

Age Factors

Although anthropologists may disagree on the strength of sports and animal research to provide support to cross-sectional geometries' link to activity patterns, most (if not all) anthropologists looking at cross-sections accept that there are other factors at play besides activity patterns. Nearly all studies at least mention factors such as age, genes, body size, and hormones (e.g., Bridges, 1995; Maggiano et al., 2008; Marchi, 2008; Ruff and Hayes, 1982; Ruff et al., 2006; Stock, 2000; Stock and Pfeiffer, 2001; Trinkaus et al., 1994; Weiss, 2003a). For example, Weiss (2003a) explained that ocean-rowing populations' humeri may have been robust due to the cold-climate body type. Additionally, sex differences in the pelvis have been suggested to affect cross-sectional geometries of the lower limb (Ruff and Hayes, 1982).

One nonactivity pattern factor that is well-studied is age; growth and aging have been shown to affect cross-sectional geometries. As previously mentioned, insulin-like growth hormones have been found to play a role in bone remodeling that may affect cross-sectional geometries. In one of the first big-sample age examinations of cross-sections, Chris Ruff and W. C. Hayes (1982) discovered that apposition of bone on the subperiosteum may compensate for endosteal resorption that occurs with aging. Examining diamond-bladed saw-cut cross-sections of more than

100 Pecos Pueblo, New Mexico, Amerinds, Ruff and Hayes (1982) found that CA decreased as one aged while, at least in this population, TA and medullary area increased in older individuals. Bending strength also increased in males at the midshaft of the femur in older individuals. In a later study, Ruff and Hayes (1983) also noted that males reach their peak cortical bone amount about a decade later than females, and cross-sections get larger in both sexes, which increases inertial values and, therefore, torsional and bending strengths. The longer bone deposition in males may better explain the male strength difference in bones more than activity. Ruff and Hayes' 1980s work has been extremely influential and continues to be cited by anthropologists to this day (e.g., Agarwal, 2016; Sumner and Andriacchi, 1996; Wescott, 2006).

S. A. Feik and colleagues (1996, 2000) found a similar increase in cross-sectional size over an adult's life in 20- to 100-year-old Anglo-Celtic Australians with known ages. Thus, it appears that ontogenetic changes are cross-cultural and, ergo, likely linked to genes that control for growth. They also noted that, in the femur, the linea aspera, which is most pronounced at midshaft, becomes less pronounced with age, resulting in a more circular cross-section. The authors attributed this change to postural changes that occur with age in both sexes and during menopause in females, but it is likely biological changes rather than posture that influence the cross-sectional differences, especially since Mays (2000) corroborated these results in an English sample from the eighteenth and nineteenth centuries.

Recently, James Gosman and colleagues (2013) examined tibiae and femora of Oneota Amerinds dating back to 1300 AD with X-rays and CT scans and found evidence that contradicts previous studies. By looking at many locations on the bone, Gosman and colleagues were able to assess which parts changed most as a result of ontogenetic growth. Unlike previous studies that found the greatest changes at midshaft, Gosman and colleagues found the midshaft unchanged throughout one's life and found other locations changed far more as a result of ontogeny. The authors also suggest that the tibial and femoral midshafts in adults may have a high threshold to change.

Although age is estimated in archaeological samples, such as the Pecos Pueblo sample, there are benefits in examining age effects in these past peoples; for instance, the genetic makeup of the population is likely homogenous and, thus, genetic confounds are likely reduced (Ruff and

Hayes, 1982). Environmental conditions were also likely more homogenous than in later populations. Nevertheless, it may be erroneous to assume homogeneity since many of these archaeological samples span hundreds or even thousands of years; homogeneity of genetics is often based on artifactual evidence rather than DNA studies.

Summary

In summary, osteologists—whether they are anthropologists, primatologists, or medical researchers—acknowledge that nonmechanical factors influence cross-sectional geometries (e.g., Bertram and Swartz, 1991; Bridges, 1995; Gosman et al., 2013; Morimoto et al., 2011; Pearson and Lieberman, 2004; Ruff et al., 2006; Wergedal et al., 2005; Wescott, 2006). Yet some anthropologists think that enough variation is caused by mechanical loads that cross-sectional shape can be used to determine activity patterns (e.g., Maggiano et al., 2008; Marchi, 2008; Rhodes and Knüsel, 2005; Ruff et al., 2006; Stock and Pfeiffer, 2001; Trinkaus et al., 1994). Others are skeptical that, even after standardizing for body size, the effects of stresses will be significant enough to outweigh the effects of genes, body size, age, and other biological factors (e.g., Bertram and Swartz, 1991; Morimoto et al., 2011). In order to move forward with cross-sectional research, some anthropologists have called for more accurate measures (e.g., Stock and Shaw, 2007). Others have recommended using only the best variables in activity research; it appears that J may be more strongly correlated with activity patterns than areal measures (e.g., Lieberman et al., 2004; Weiss, 2005). Many researchers have called for a greater understanding of cross-sectional geometries and their formation (e.g., Demes, 2007; Gosman et al., 2013; Sumner and Andriacchi, 1996; Wescott, 2006; Wergedal et al., 2005). Cross-sectional studies are an example of the varied approaches researchers have undertaken to comprehend bone morphology's usefulness in reconstructing activities. As one can see, the multidisciplinary approach has led to much knowledge and even more questions.

3

ENTHESEAL CHANGES

When one looks at a human bone, one may notice areas that have raised ridges and depressed pits; the complex topographical areas on bones are usually from muscle insertions. Muscles attach to bone to enable movement; thus, when muscles contract, the bone is moved. This action causes force on the bone in question. Anthropologists have been using muscle insertion osteological landmarks to determine which muscles have been frequently or intensely used and, with the help of artifacts, to thereby reconstruct activity patterns of past populations. Yet researchers have also noted cross-cultural patterns, such as correlations with age and consistent sex differences, that suggest variation in these bony landmarks may be regulated by biological effects (and therefore by genes) rather than activity patterns (or culture).

Defining Entheses

Anthropologists have used many terms for evidence of muscle insertion sites, such as musculoskeletal stress markers, muscle markers, and occupational stress markers, but the current terminology used is **entheseal changes** (Jurmain and Villotte, 2010). Entheseal changes are changes at muscle attachment sites that consist of ridges, bony spurs, and pitting into the bony cortex. The new terminology is based on our current understanding regarding muscle insertions from a biological perspective, but going back to Ancient Greece the term "enthesis" has been used (Claudepierre and Voison, 2005; Jurmain and Villotte, 2010). The new term, "entheseal changes," Robert Jurmain and Sebastien Villotte (2010) correctly surmise is free of etiological assumptions. Thus, the new term frees anthropologists who wish to examine these markers without misleading readers into thinking that activity pattern reconstructions are always the goal of the research. In Ancient Greece, **enthesis** was the term used to designate structures that attach ligamentous tendons and joint capsules to bone; currently enthesis is more generally defined as a muscle attachment (Claudepierre and Voison, 2005). Diane Hawkey and Charles Merbs (1995), whose work has defined a great deal of the subsequent anthropological entheses research, described an entheseal change (which they called a musculoskeletal stress marker) as "a distinct skeletal mark that occurs where a muscle, tendon, or ligament inserts on the periosteum and into the underlying bony cortex." However, in some medical reference books, **ligaments** are connections that unite bone to bone, whereas **tendons** anchor muscles to bone (e.g., Vorvick, 2015). More recently, M. Benjamin and colleagues (2002) have defined an enthesis as "the region where a tendon or joint capsule attaches to bone; i.e., an 'attachment site' or 'insertion site.'" They further add that these muscle attachment or insertion sites ensure that forces from the muscle's belly are sent to the skeleton in a way that avoids excessive stresses that are referred to as peak stresses (Benjamin et al., 2002). Although entheses include joint capsule attachments, anthropologists only examine entheses that involve muscle attachments; thus, entheses in the anthropological literature are generally understood to mean the muscle attachment sites only.

Entheseal Changes: Robusticity, Stress Lesions, and Enthesophytes

Entheseal changes, as described earlier, are areas where muscle attachments occur and where these attachments have resulted in changes on the bony cortex. Entheseal changes are macroscopically visible. They appear as three-dimensional changes on bone. Depending on the location and type of enthesis, the entheseal change site may have proliferative changes or erosive changes or both (Weiss, 2015b). **Proliferative changes** are raised areas that can be in the form of mounds or crests (Foster et al., 2014). Many anthropologists attribute the proliferative changes to the result of bone remodeling action (e.g., al-Oumaoui et al., 2004; Chapman, 1997; Eshed et al., 2004; Hawkey and Merbs, 1995). The assumption is that the bone experiences stress from the muscle pull, which triggers bone deposition to prevent breaking from these stresses (Molnar, 2006; Ruff et al., 2006; Stefanović and Porčić, 2013). These ridges and mounds, which are sometimes referred to as rugosity or **robusticity** (e.g., Hawkey and Merbs, 1995; Peterson, 1998; Weiss, 2003b), are most commonly found in areas where muscles insert into the periosteum directly (rather than through a tendon or ligament), which are discussed below (Benjamin et al., 2002).

Erosive changes are sometimes called stress lesions or pitting; these changes are pits and cysts into the bony cortex (Henderson et al., 2013; Hawkey and Merbs, 1995; Peterson, 1998). These changes cause a discontinuity in the bony cortex (Henderson et al., 2013). Erosive changes are sometimes also linked to remodeling but are more often associated with **microtrauma** (which is usually thought of as a small insignificant injury that can lead to a more major injury later) or with overuse of muscles (Hawkey and Merbs, 1995). Hawkey and Merbs (1995) saw proliferative and erosive changes as being on a continuum where stress lesions are evidence of greater muscle use than robusticity alone. However, some anthropologists disagree with this perspective of stress lesions and argue that stress lesions are caused by distinct microtrauma rather than nontraumatic bone remodeling and, thus, should not be scored on a continuum (e.g., Mariotti et al., 2007; Nolte and Wilczak, 2013; Villotte, 2009).

A third bony feature is an **enthesophyte** (also called an entheseal osteophyte); an enthesophyte, quite simply, is a bony spur. This may seem to be a proliferative trait, but most anthropologists and clinical researchers tie it to overuse or microtrauma (e.g., Benjamin et al., 2006; Dutour, 1986; Lai and Lovell, 1992; Weiss, 2015b). Some anatomical sites are especially prone to enthesophytes, such as the calcaneus (the heel bone) and the elbow (when spurs occur on the elbow, clinicians use the colloquial term "tennis elbow") (Abreu et al., 2003; Benjamin et al., 2000; Dutour, 1986; McConkey, 1981; Weiss, 2012a).

Types of Entheses: Fibrous and Fibrocartilaginous

Although one may think that these proliferative and erosive changes appear on all entheses equally, there are differences in their distribution depending on the type of muscle insertion. There are two main types of entheses: fibrous and fibrocartilaginous. Figure 3.1 shows how these different types of muscle attachments anchor muscle to bone. Robusticity, or the raised ridges and mounds, are most prevalent in entheses that attach directly onto bone into the periosteum; these entheses are called **fibrous entheses** (Benjamin et al., 2002). An example of a fibrous entheses is the attachment for the deltoid on the humerus. The supinator and pronator teres of the forearm are also fibrous entheses (see Fig. 3.1).

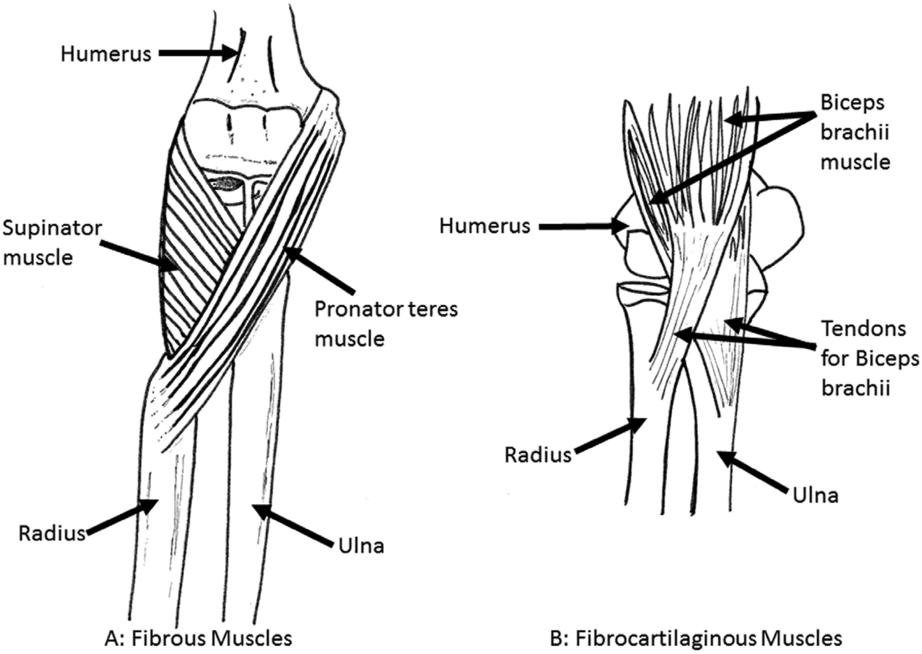

Figure 3.1. Fibrous and fibrocartilaginous muscles. Upper-limb entheses that display the difference between fibrous muscles (*a*, in this case the supinator and pronator teres), and a fibrocartilaginous muscle (*b*, in this case the biceps brachii, the long tendon of which inserts to the radial tuberosity).

Fibrous entheses occur on long bone shafts (or diaphyses) and are associated with our body's largest and most powerful muscles (Benjamin et al., 2002; Shaw and Benjamin, 2007). Fibrous entheses are broad and cover a great amount of surface area on the bone (Benjamin et al., 2002). The large surface area employed for the fibrous muscle insertion dissipates stress and, hence, reduces the chance of injury (Benjamin et al., 2002; Schlecht, 2012). Fibrous muscle insertions are also associated with areas of thick cortical bone (Benjamin et al., 2002; Schlecht, 2012).

Fibrous entheses may move throughout the growth of an individual (Benjamin and McGonagle, 2009). Furthermore, fibrous entheses seem to be formed postnatally, and they are regulated by the parathyroid hormone–related protein that controls entheseal change development through osteoclast activities (Djukic et al., 2015). Fibrous entheses vary greatly in their morphological expressions, and the fleshy fibers of fibrous entheses are sometimes referred to as **Sharpey's fibers**, which anchor tendons, ligaments, and periosteum to bone (Benjamin et al., 2002; Claudepierre and Voison, 2005). From a clinical perspective, fibrous entheses are not well understood (Benjamin et al., 2002; Shaw and Benjamin, 2007). The other type of enthesis, **fibrocartilaginous enthesis**, is better understood because of associated diseases; fibrous entheses seem less involved with diseases than fibrocartilaginous entheses (Claudepierre and Voison, 2005; Henderson, 2008). Consequently, fibrous muscle insertion sites have received less attention than fibrocartilaginous from the medical community (Benjamin et al., 2002). Moreover, fibrous entheses also have fewer enthesophytes than fibrocartilaginous entheses. Enthesophytes, according to the sports literature, are thought to cause pain and therefore have been of greater interest to clinical researchers compared to fibrous entheses (Benjamin et al., 2000; Shaw and Benjamin, 2007).

Fibrocartilaginous muscles insert on bone via a tendon or ligament. Tendons come in many shapes and sizes (Benjamin et al., 2006). Fibrocartilaginous entheses that occur in areas of thin cortical bone have been said to grow through endochondral (within cartilage) sites (Benjamin et al., 2002; Schlecht, 2012; Shaw and Benjamin, 2007). Hence, fibrocartilaginous entheses are close to joints and near the ends of bones as well as on small bones and throughout the vertebral column (Benjamin et al., 2002; Claudepierre and Voison, 2005). Therefore, fibrocartilaginous entheses are more numerous in the body, but they are associated with less powerful muscle attachments (Benjamin et al., 2002; Shaw and Benjamin, 2007). An example of a fibrocartilaginous entheseal site is the insertion of the biceps brachii on the radial tuberosity, as seen in Figure 3.1.

In fibrocartilaginous entheses, the stress is not dissipated by surface area alone but also by the elasticity of the tendon, which absorbs some of the muscle force (Benjamin et al., 2006; Schlecht, 2012). Fibrocartilaginous entheses are more circumscribed than fibrous entheses (Schlecht, 2012; Shaw and Benjamin, 2007). The tendons of fibrocartilaginous entheses anchor the muscle at four points (Schlecht, 2012). And although the tendon attachment is smaller in area than in fibrous entheses attachments, the tendon flares out close to the bone, which aids is dissipating stresses (Benjamin et al., 2002; Shaw and Benjamin, 2007).

Fibrocartilaginous entheses are less prone to proliferative changes, and they are more likely to have stress lesions and enthesophytes (Benjamin et al., 2000; Villotte, 2009). These changes are often considered pathological or traumatic in sports or clinical research, so sometimes entheseal changes on fibrocartilaginous entheses are termed **enthesopathies** (Abreu et al., 2003; Benjamin et al., 2006; Dutour, 1986). A healthy fibrocartilaginous enthesis should be smooth and free of stress lesions or vascularization, which is the development of blood vessels in a tissue and may be visible as small stress lesions on a bone (Benjamin et al., 2006). As Villotte (2006) noted, fibrous entheses, on the other hand, often display changes even when they are healthy. In short, fibrocartilaginous entheses are better understood because they have been studied in relation to diseases and sports injuries (e.g., Henderson, 2008; Benjamin et al., 2002, 2006). Since fibrocartilaginous attachments are normally avascular, when an injury occurs, healing tends to be poor and leaves visible marks of the injury.

Fibrocartilaginous entheses are sometimes referred to as organs with four zones (Benjamin et al., 2004). The zones go from the end of the muscle to the attachment at the bone. Throughout these zones, the enthesis becomes less fibrous and more bone-like (Apostolakos et al., 2014; Benjamin et al., 2004; Claudepierre and Voison, 2005). The **tidemark** of the entheseal organ is the site where the entheseal fiber and bone meet; in other words, the tidemark is a transitional zone that appears as a wavy line and marks the junction between calcified and uncalcified cartilage (Apostolakos et al., 2014; Claudepierre and Voison, 2005). This combination of an elastic fibrous tendon and hard bony cortex allows for a stable attachment that prevents injuries, and yet both wear and tear and injuries do occur (Shaw and Benjamin, 2007). Heel spurs, as mentioned earlier in reference to calcaneus enthesophytes, are an example of an injury. Enthesophytes, as previously stated, most commonly arise in fibrocartilaginous entheses.

Charlotte Henderson (2008) also pointed out that **rheumatic diseases** (diseases that affect joints and muscles), such as rheumatoid arthritis and diffuse idiopathic skeletal hyperostosis, are common at fibrocartilaginous entheses sites. **Rheumatoid arthritis** is a chronic inflammatory disease that is thought to be inherited; typically, rheumatoid arthritis initially affects the small joints of the hands and feet. **Diffuse idiopathic skeletal hyperostosis** (also known as DISH) is a form of arthritis that is inherited and is associated with flowing calcification along the sides of the vertebrae. Yet not all fibrocartilaginous entheseal changes are explained by pathologies or injuries; M. Benjamin and Dennis McGonagle (2009) point out that fiber tendons react much like bone, with the arrangement of fibrous tissue being much like the arrangement of bone. Also, **fibroblasts** become harder **fibrocartilage** through exposure to loads. Interestingly, research has revealed that when mice are inflicted with **botulism toxins**, the toxin-induced paralysis delays fibrocartilage formation (see Benjamin and McGonagle, 2009). Thus, muscle use may result in more bony entheses even without injury.

Some researchers have suggested that the division between fibrous and fibrocartilaginous entheses is overly simplistic (Shaw and Benjamin, 2007). H. M. Shaw and Benjamin (2007) highlight some of the ways in which insertion sites can vary and therefore depart from the standard definitions of fibrous and fibrocartilaginous entheses. For instance, many fibrocartilaginous entheses do not have fibrocartilage across the entire attachment site. And some attachments are composed of both fibrous and fibrocartilaginous entheses. Plus, some fibrocartilaginous sites do not have all four zones. And some fibrous muscle insertions have some ligaments or tendons associated with their attachments and when they insert directly into the periosteum, the muscle closest to the bone has fleshy fibrous ligaments within it.

Researchers have also shown that entheses are especially strong and well designed to dissipate stress; thus, entheseal changes resulting from normal, everyday activity seem unlikely (Benjamin et al., 2000, 2002; Schlecht, 2012; Shaw and Benjamin, 2007). This suggests that the variations are inherited rather than related to activity patterns; this point is readdressed in the summary. Unfortunately, genetic research has been lacking in entheseal change studies, and it seems to me that such research would be highly desirable to help resolve the issue. Nevertheless, the fibrous and fibrocartilaginous entheses division allows for better data collecting methodologies by anthropologists since the bony changes vary greatly—as mentioned above—fibrous entheses tend to have greater proliferative changes while fibrocartilaginous entheses are more likely to develop stress lesions and bone spurs (e.g., Henderson et al., 2013; Mariotti et al., 2007; Villotte, 2006, 2009).

Collecting Entheseal Change Data

Capturing entheseal change data in a way that is meaningful and comparable to other researchers' data has been a challenge. Entheseal changes are complex, irregular, three-dimensional landmarks of bones, shown in the entheseal change photos of Figure 3.2.

Early methods to capture evidence of entheseal changes were mainly descriptive, such as J. Lawrence Angel's (1952) work on Iranian remains from Hotu Cave. Entheseal change research has grown in popularity since the 1980s. Part of the popularity of entheseal change research lies in the methodologies employed; since entheseal changes are macroscopic and on the surface of bones, there is no need for expensive technology to gather data. Therefore, a greater variety of anthropologists have undertaken entheseal change data collection to understand past populations. For archaeologists and forensic anthropologists, for instance, the ease of collecting entheseal change data may enable them to include the data in site analyses, whereas this is less frequent for cross-sectional data, which requires either X-rays or CT scans. The same trend is present in osteoarthritis, stress fractures, and accessory facets, as is discussed in later chapters.

In a groundbreaking 1995 article, Hawkey and Merbs provide a method to collect data on entheses that is relatively easy to learn and required only direct observation. Their ordinal (or rank) method does not distinguish between fibrous and fibrocartilaginous entheses because this information was not available to them at the time. It is based on scoring robusticity such as ridges and raised mounds, stress lesions such as pits, and ossification, which is now called enthesophytes. These three types of traits are scored separately; Hawkey and Merbs, however, propose that robusticity and stress lesions can be viewed as being on a continuum, but that enthesophytes are evidence of trauma and perhaps even a singular event. According to Hawkey and Merbs, robusticity and stress lesions are from muscle use over time, and bone remodeling explained robusticity, whereas fatigue or overuse are the causes of enthesophytes. Hawkey and Merbs's (1995) method remains the most commonly employed methodology (e.g., Eshed et al., 2004; Molnar, 2006; Schrader, 2012; Wilczak, 1998). One reason for continuous use of this method is that researchers wish to compare their data with previously published data (e.g., Schrader, 2012), but the days of using the Hawkey and Merbs (1995) method may be limited due to

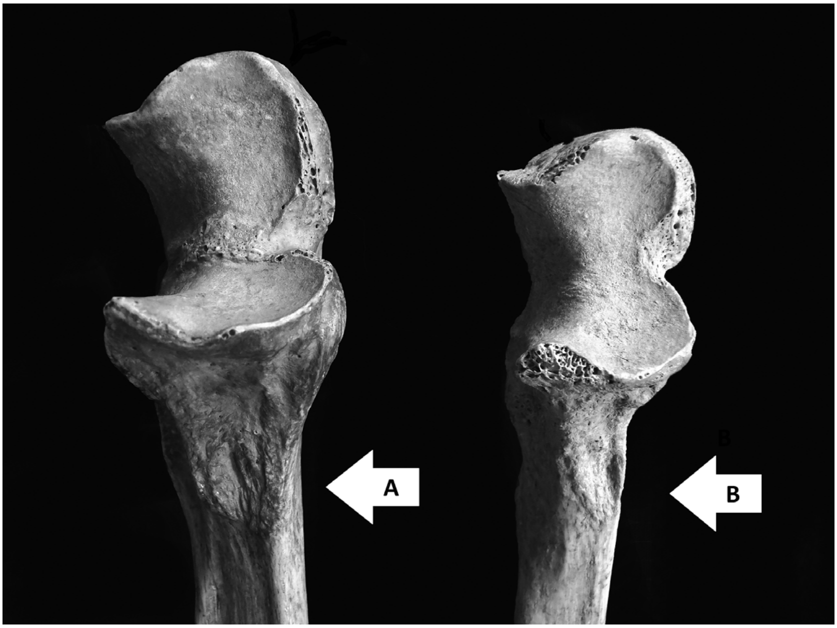

Figure 3.2. Entheseal changes. Variation of the brachialis entheses of the ulna; the brachialis is a flexor of the elbow. The ulna on the left side (*a*) has greater entheseal changes than the ulna on the right side (*b*).

our greater understanding of entheseal changes, especially the difference between fibrous and fibrocartilaginous entheses. The apparent advantages of the method (e.g., its ease of use) are now a disadvantage. As researchers cling to this method when better methods are available, we need to challenge the use of outdated methodologies if we are to drive forward our understanding of the issues.

Other ordinal methods have proliferated (e.g., Villotte, 2006; Mariotti et al., 2007). Some ordinal methods, like that of Villotte (2006, 2009), separate fibrous and fibrocartilaginous entheses and even require scoring edges of the enthesis separately from the entheseal center but unify the scores to give one score for each site. Recently, ordinal methods have come under fire for their high interobserver and intraobserver error rates (e.g., Davis et al., 2013). **Interobserver error** rates determine how frequently different researchers will score the same enthesis differently and **intraobserver error** rates determine how frequently the same researcher will score the same enthesis differently. Hence, low error rates are indicative of variable reliability; that is, the entheseal changes are consistently scored regardless of who scores the bone or how many times the bone is scored. Although some researchers have published low error rates with ordinal data collection techniques (Havelková and Villotte, 2007), others have found consistently unacceptable error rates (e.g., Davis et al., 2013; Henderson et al., 2013). C. B. Davis and his colleagues (2013) found error rates as high as 20% in their research of ordinal data collection of entheseal changes, whereas Henderson and her colleagues (2013) reported error rates as high as 33%. Robusticity is the most frequently scored entheseal change (since it appears to occur more often than enthesophytes or stress lesions), and it also has the highest error rates (Davis et al., 2013). These high error rates are especially disconcerting since published data are often compared to new data. Additionally, error rates suggest that training researchers to collect entheseal change data may be necessary, which could deter forensic anthropologists and archaeologists from incorporating entheseal change data into their reports.

One way to reduce error rates is to use a binary data collection method; binary methods rate entheseal changes as present or absent. These methods have been employed by many anthropological researchers (e.g., Cashmore and Zakrzewski, 2013; Djukic et al., 2015; Villotte et al., 2010a); the analyses of these methods are often simple, such as reporting frequencies and chi-squares, since the data are not considered statistically powerful (Wilczak, 1998). Yet Villotte and colleagues (2010a) have employed more sophisticated methods in their research. One complicating factor is that binary methods (and, to a lesser extent, ordinal methods) hide entheseal change complexities (Weiss, 2015b).

Another way to reduce error rates is through **aggregation**, the act of combining units or parts into a mass. In a much-cited article, Elizabeth Weiss (2003b) has argued for aggregating entheseal change data since muscles work in groups and aggregating scores reduces error and increases **construct validity**, or the degree to which a variable measures the characteristic being investigated. Since errors are random, multiple scores will cancel out errors; some entheses are also more likely to be susceptible to high error rates. Further evidence from the clinical literature reveals that entheses overlap, which strengthens the anchors; thus, treating each enthesis as independent from another does not make biological sense (Shaw and Benjamin, 2007). However, other anthropologists have argued against this approach since there is normal variation (which is not the result of disease or trauma) between entheses and their responses to stresses (Nolte and Wilczak, 2013).

To improve entheseal change research, some anthropologists have employed metrics and three-dimensional metrics; perhaps the earliest attempt to measure entheseal changes came from Cynthia Wilczak (1998). For the most part, these methods have yet to be fully explored. Weiss (2015b) provided a review of these methods and found that the variables tended to be simple measures, such as area and volume. Perhaps the earliest use of three-dimensional laser analyses of entheses comes from Ann Zumwalt (2005, 2006), who examined sheep entheses with archaeological geographic information system technology to view muscle insertions **topographically** (which reveals the relief features or surface configuration of an area), but her research failed to link increased exercise with entheseal changes. This research, which is mentioned in chapter 2, has been cited as evidence that activity does not play a large enough role in bone remodeling to use external bone morphology to reconstruct activity patterns; however, Zumwalt herself suggested that the lack of results may have been due to the short experimental period of only 90 days.

In her review of entheseal change methodologies, Weiss (2015b) reported that researchers who employed three-dimensional methods of data collection took much longer to collect their data; consequently, the sample sizes were negatively impacted. Three-dimensional technologies, furthermore, may be out of reach for many researchers in terms of expense (Weiss, 2015b). Finally, choosing the part of the bone to include in the analyses—outlining the borders of the entheses—is somewhat subjective. Therefore, error rates continue to be high in three-dimensional analyses of entheses (Noldner and Edgar, 2013). Nevertheless, three-dimensional analyses of entheseal changes may be the only way to capture the true complexity of these osteological landmarks. If entheseal change research takes this high-tech path, we may see fewer entheseal change articles and especially a drop in entheseal change data collected as an addition in archaeological reports and articles. Another possibility is that those who incorporate entheseal changes into site analyses will continue to use less sophisticated methods while researchers who specialize in entheseal change studies will engage in high-tech data collection methods. This potential disconnect is difficult to resolve.

Reconstructing Activity Patterns

Regardless of the methodology employed, most anthropologists research entheseal changes to reconstruct activity patterns of past populations. In their book on occupational stress markers, Capasso and colleagues (1999) highlight a variety of entheseal change research linked to specific activities, such as enthesopathies on the femur linked to cart-driving and horseback riding in the predynastic Ur of Iraq; bilateral biceps brachii entheseal changes on the radius linked to carrying heavy loads with bent elbows, such as water carrying during **medieval** (from AD 1000 to AD 1500) times in Europe; high rates of entheseal changes in the clavicle's (or collarbone's) pectoralis major site and the humerus's deltoid tuberosity site associated with slinging in Mediterranean Minorcan males between the eighth and fifteenth centuries; and phalanx (or finger) flexor hypertrophy among Egyptian scribes from Thebes. Even though some anthropologists have suggested that specific activity reconstruction may not be possible with entheseal change studies, many archaeologists and anthropologists who emphasize archaeological integration with skeletal materials still cite Capasso and colleagues' (1999) book as an example of specific activity reconstructions. I think drawing conclusions about specific activities may lead to an overly simplistic view of past peoples' lives, often defining the broad range of their lives to a single activity, for example, carrying water.

The Archaeological Research

Although there are themes in entheseal change research, the reconstructions of activity are more geographic and site specific since the hope has been that entheseal changes can help to detail specific activities of past peoples. Thus, the review of activity pattern research is organized by geographic regions: Arctic regions, New World, Europe, the Middle East, and Africa. In many of the following articles, there is a great deal of emphasis on artifactual evidence; yet one must wonder whether entheseal change data provide any information over and above the information provided by the artifacts. One way to determine this is to see if activity reconstructions would be possible without the artifacts. In a blind test where artifacts were unknown, I would hypothesize that activity patterns could not be reconstructed; thus, we would have to conclude that entheseal change data has little predictive validity.

Some of the earliest entheseal change research using ordinal scaled data comes from Hawkey and Merbs; their methods have greatly influenced entheseal change research for over two decades. In their seminal work, Hawkey and Merbs (1995) look at entheseal changes, which they call musculoskeletal stress markers, from 75 male and 61 female **Thule** (an Eskimo culture that dated from AD 500 to AD 1400 and extended throughout the Arctic, Greenland, and Alaska) whale hunters from Hudson Bay. The examined population had lived through a mini Ice Age 750 years Before Present (with present being 1950), which changed their diet. The frozen waters made kayaking impossible, and this resulted in a decrease in entheseal changes in the clavicles of males. In a couple of studies on Alaskan Eskimo sex differences, Steen and Lane (1998) found that in a sample of nearly 240 individuals, males had greater entheseal change scores than females, which the authors attribute to male activities of rowing and harpoon throwing. Although Steen and Lane do not include artifacts in their study, they note that the purpose of their entheseal change research was to evaluate evidence from the ethnoarchaeological record to determine activity patterns. In 2001, D. C. Cook and S. P. Dougherty corroborated Susan Steen and Robert Lane's (1998) work by looking at eighteenth-century Alaskans and found again that males had greater upper-limb entheseal change scores, especially in terms of robusticity and enthesophytes, than females. In these studies, the lack of sex differences in lower limb entheses compared to the sex differences in upper limb entheses suggests to the authors that the sex differences are related to activities that involve using upper-limb muscles such as rowing and hunting with harpoons rather than to biological sex differences, which should be present throughout the body.

Looking at population differences rather than sex differences, Ping Lai and Nancy Lovell (1992) found that Native Albertans who were fur trading had greater upper-limb entheseal changes than a European who may have worked in less strenuous conditions; they suggest that the Native and mixed-race individuals gained their upper-limb robusticity through paddling and lifting while engaging in the fur trade as long-distance canoeists called voyageurs. Comparing Aleuts to Russians, W. S. Laughlin and colleagues (1991) found that Aleuts had more pronounced entheseal changes, which they attribute to kayaking, compared to the Russians. In both of these studies, it was also noted that the Europeans and the Russians had longer limbs than the Native populations. These studies are interesting since the samples were from genetically distinct populations and yet both populations were cold-climate populations. Taller individuals seem to have less robust bones; thus, the differences noted by Laughlin and his colleagues may actually be related to genes, especially those involved with growth, rather than activity patterns.

In a small study, Lovell and Aaron Dublenko (1999) looked at three males and one female who were involved in the Canadian fur trade of the nineteenth century. The study was published as a case study in the *International Journal of Osteoarchaeology*, which allowed researchers more opportunities for case studies than does the *American Journal of Physical Anthropology*, especially in its early days. Now anthropologists are often encouraged to use larger samples and be less descriptive. The female had prominent hand entheseal changes, which may have been a result of milking cows and churning butter. The males, on the other hand, had **hypertrophic** upper limbs, which means that the entheseal changes on their upper limbs were extremely well developed in terms of robusticity; they likely engaged in rowing and carrying fur bundles that weighed around 40 kgs (or about 90 lbs.). Additionally, it appeared that the use of **tumplines**, straps attached at both ends to a sack and used to carry objects by placing the straps across the forehead, gave them well-formed cranial entheses in the form of prominent superior nuchal lines from the use of the trapezius muscle. Even though this study was small, the authors emphasized that entheseal changes information was corroborated by archival documents and artifacts associated with the site.

Moving south, using a large California hunter-gatherer sample, Weiss (2007) found that entheseal changes in the deltoid, pectoralis major, latissimus dorsi, and teres major sites were higher in males than in females even after controlling for body size differences. Weiss (2007) and Weiss and her colleagues (2012) tentatively suggested that these sex differences in entheseal changes may be related to males' use of atlatls during hunts, but female activity patterns remained elusive. Their conclusions were drawn in part by the knowledge that males were often buried with projectile points while females were not. Yet females were buried with mortars and pestles, and mortar and pestle use should have produced significant entheseal changes in female upper limbs. It may be argued that grinding foods is more labor intensive than hunting and, thus, entheseal changes did not corroborate with the most likely activities.

Nancy Chapman (1997) looked at maize agricultural intensification in New Mexico in relation to sex differences and found that the latissimus dorsi and anconeus sites of the upper limb in males increased with maize agriculture, which may have been due to hoeing the field and chopping wood. Grinding maize, it seemed to Chapman, led to an increase in entheseal changes related to the upper-limb deltoid and rotator cuff muscles in females. One may notice that the muscles noted by Chapman for agricultural activities overlap with those for hunting, mentioned earlier. One criticism regarding entheseal change research can be that entheseal changes cannot be used to reconstruct specific activities since most muscles, especially in the upper limb, are involved in many activities. Hence, the reconstructions are really based on the artifacts and not the entheseal changes. This use of entheseal changes coupled with artifacts can lead to circular reasoning. Anthropologists look at what artifacts are in the record, then score entheseal changes and match them with the artifacts to reconstruct activities, but the researchers could not reconstruct the activities without the artifacts.

Entheseal change research has blossomed in Europe. European researchers, such as Sebastien Villotte, Christopher Knüsel, Valentina Mariotti, and F. Alves Cardoso, to name only a few, have been holding and attending workshops to enhance our understanding of entheseal changes so that they can be used more effectively in research, such as in cases without rich artifactual materials or archival documents.

In 2006 and 2010, while looking at sports literature, Petra Molnar found that harpooning, archery, and kayaking employed some overlapping muscles and some distinct muscles. Using this biological muscle-use information, coupled with artifactual evidence, Molnar examined a Scandinavian prehistoric site from Sweden and reported that males had greater upper-limb entheseal changes and more asymmetry than females. She concluded that these entheseal changes were likely linked to harpoon use, but archery uses many of the same muscles as harpoon use and so could not be ruled out.

In a complex five-population study by Ihab al-Oumaoui and colleagues (2004), entheseal changes from Spanish sites were studied to look for differences between sexes that resulted from terrain types, subsistence patterns, and culture. In the 342-individual sample, the authors note that male and female patterns tended to cluster regardless of the population, but those living in hills and tending to livestock had greater sex differences in lower-limb entheseal changes than in the other populations. This sex difference, al-Oumaoui and colleagues decided, was because males were more mobile than females—that is, males walked more than females. However, it could also be because any walking difference between the sexes would make a greater impression on mountainous terrain population's bones than on flat terrain population's bones. In the other populations, such as the flat land or river land agricultural populations, no lower-limb sex differences occurred; the exception to this pattern was in the Muslim population, where lower-limb entheseal changes were prominent and again males' entheseal changes seemed to suggest greater mobility. The cultural practices of Muslims likely restricted female mobility.

In another look at mobility, Angela Lieverse and colleagues (2009, 2013) examined aggregate entheses (using a method that separates fibrous and fibrocartilaginous entheses) of two groups, one with skeletal remains dating from 8,000 to 7,000 years old, and another with 6,000- to 4,000-year-old remains, with a hiatus dividing the two groups. Lieverse and colleagues examined upper- and lower-limb entheses of prehiatus and post-hiatus individuals to see how activity patterns may have been affected by the time gap; it appeared that prehiatus individuals had greater mobility (as indicated in both their lower-limb and upper-limb entheses, which was tied to use of watercrafts) than the post-hiatus individuals. They argued that these data provide evidence that microenvironmental changes can lead to activity changes visible in entheses. However, it is possible that the populations were from different gene pools; Lieverse and colleagues entertain this possibility and note that biological and cultural discontinuity is present at the location. Nevertheless, the detailed pattern in their results led them to conclude that the variation was a result of activities rather than biology.

In another study employing recent ordinal scales that separate fibrocartilaginous and fibrous entheses, Petra Havelková and colleagues (2011) examined sexual division of labor in Greater Moravia, which is the eastern part of the Czech Republic. With nearly 200 individuals from a castle site and a hinterland site, the authors found sex differences in the upper-limb entheses. The hinterland population had greater degrees of sex differences, which may have been related to agricultural work load distribution. Overall, female entheseal changes at the elbow region were more pronounced whereas males had greater forearm entheseal changes.

Surprisingly, at the castle site, females had higher entheseal change scores than males; this, the authors state, may be because the castle males were from privileged homes and thus did not engage in manual labor. However, as mentioned in chapter 2, in past cultures, trades and class were often inherited, so these differences could be related to genetic differences.

In the **Levant**, which is a region on the eastern coast of the Mediterranean Sea north of the Arabian Peninsula and south of Turkey, at one of the earliest sites of agriculture, Vered Eshed and colleagues (2004) looked at upper-limb entheses using the Hawkey and Merbs (1995) method so that the data were comparable to earlier work by Jane Peterson (1991). Eshed and colleagues found that early agriculturalists had greater entheseal changes than the last hunter-gatherers, called the **Natufians** (who were semisedentary and lived in the Levant between 12,500 and 10,200 years ago). Tree-felling, wood-working, and mud-brick-building were all activities that the Neolithic agriculturalists were engaged in while they were building their sedentary homesteads, which have been well documented in the archaeological record. In females, the change in tools used to grind grains seemed to effect entheses; the female Natufians who used two-handed saddle grinders had greater deltoid entheseal change scores than the Neolithic agricultural females who used pestles. In the Neolithic, females had greater entheseal changes in the elbow, which was tied to basketry, spinning, and weaving, than their male counterparts; yet these sex differences in the elbow are not statistically significant and sample sizes were small. Often when reverse or unexpected sex differences are found, we see that these differences are not statistically significant and thus should not be reported as differences. Nevertheless, many anthropologists continue to report nonsignificant findings in ways that suggest that the results are important (see Weiss et al., 2012). In all fairness, the lack of significant findings is in part due to small sample sizes that are inevitable in our field; in the past, I too have reported marginally or nonsignificant findings and was encouraged to do so by reviewers for this reason.

In another Middle East study, Peterson (1998) looked at Jordanian and Palestinian sites dating between 12,500 and 10,500 years ago to try to understand the evolution of hunting tool use. The question that arises is whether these final hunter-gatherers—the Natufians—had the bow yet. Evidence from the archaeological record to answer this question is lacking; thus, Peterson looked at entheseal changes instead. Consequently, this study is unique because it tests the predictive validity of entheseal changes. Peterson worked out that with a spear or atlatl, the supinator, anconeus, triceps brachii, and pronator teres are used, whereas with a bow and arrow, one would expect to see entheseal changes at the trapezius, latissimus dorsi, biceps brachii, right teres major, and left triceps brachii. The asymmetry from the bow and arrow comes from using the arms in two different ways. From the data, Peterson was able to suggest that the high triceps brachii and anconeus entheseal changes indicated the use of a spear or atlatl but not the bow and arrow. In one of the first entheseal change studies to look at weaponry, Olivier Dutour (1986) also examined hunting technology. Looking at a small sample of Neolithic Saharans, Dutour determined that enthesophytes, which he termed "osteophytes," were the result of javelin throwing, archery, and woodcutting. Hence, in his study Dutour implied that throwing and archery overlap and cannot necessarily be separated.

Although many studies are conducted in Europe and the Middle East, African sites have yielded some interesting patterns too, as noted by the Dutour (1986) study. More recently, Sarah Schrader (2012) found that wealthy individuals had lower entheseal changes than others in Egyptian Empire–ruled Nubia (dated between 1500 BC and 1069 BC and in modern day Sudan), which is a result also found in the Moravia European study (Havelková et al., 2011). Overall, however, entheseal changes were less prominent in the Nubian sample compared to previously studied populations that used the same Hawkey and Merbs (1995) methods, which may be activity-related or population differences dependent on genes and body forms.

Looking at multiple sites, Steven Churchill and Alan Morris (1998) employed entheseal changes to determine the microenvironment effects on bones and activities (in a similar way to other studies that followed their example, mentioned earlier, e.g., al-Oumaoui et al., 2004). They found in South Africa that when comparing forest to **fynbos** (a biologically diverse environment on the South African coast) to savanna grassland populations, female differences did not arise. But the males differed in all three environments. Forest males have the greatest entheseal changes, which the authors connect to hunting, followed by the males of the fynbos, which may be attributed to shell fishing. The authors suggest that these differences may relate to the intensity of the required activities in the different **biomes** (a term for the total complex biological community that is characteristic of a particular zone); in other words, the savanna grassland activities were less labor intensive than the forest or fynbos activities. The grasslands are the least biologically rich of the environments; thus, hunters may have employed less labor-intensive methods to increase their catches without increasing energy use. For example, they may have used nets and traps for animal catches. It should be noted, however, that Africa has a great deal of morphological variation and the greatest genetic diversity in the world; hence, these differences may reflect population differences based on biology and not activities. For instance, savanna peoples, such as the Turkana, are tall and slender whereas the forest-dwelling pygmy population is short; these differences may be the result of evolutionary selection for successful survival in different biomes.

Evidence from Known Occupation Samples

Since few clinical studies on entheses have been conducted, nonanthropological evidence of activity-related entheseal changes has been lacking. Entheseal changes, for the most part, are asymptomatic and thus have not been extensively examined in clinical research. The exceptions to this are fibrocartilaginous sites that result in enthesophytes, such as the heel and the elbow, as mentioned earlier. But since much entheseal change research in anthropology is on fibrous entheses, this fibrocartilaginous research is of limited help to anthropologists.

Animal studies have sometimes been used as evidence that entheseal changes are a result of activity patterns (Schlecht, 2012). For example, rat studies have shown that bony spurs can develop in the endochondral ossification sites of fibrocartilaginous entheses without inflammation or tears (Benjamin et al., 2000). The studies by Savio Ly Woo and colleagues (1981) and A. Chamay and P. Tschantz (1972) have been cited as evidence of activity-related entheseal change formation, but these studies do not look directly at entheses.

Research by anthropologists on known occupation skeletal samples has also been used to cement the connection between entheseal changes and activity patterns. For example, Villotte and his colleagues (2010a) examined whether occupations correlated with entheseal changes using binary entheseal change scores and controlling for age; they found that entheseal change did correlate with a categorical occupation variable. Other studies have had difficulty replicating these results; for instance, Marco Milella and colleagues (2012) looked at a twentieth-century sample

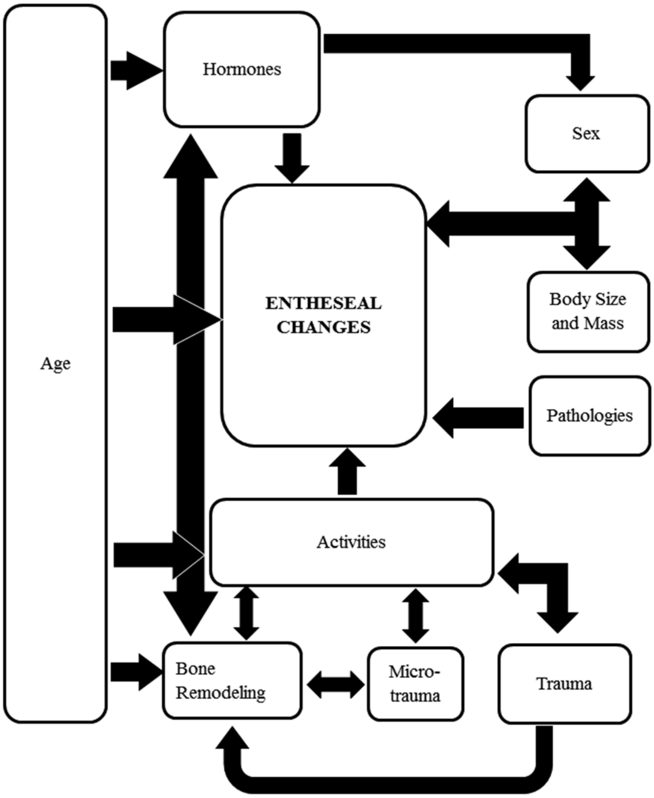

Figure 3.3. Entheseal change etiology. This chart summarizes different ways in which different factors may affect entheseal changes based on clinical and anthropological research. Modified from E. Weiss, 2015. The surface of bones: methods of recording entheseal changes. Surface Topography: Metrology and Properties, special issue Exposing the Past (3:034003). DOI: 10.1088/2051–672X/3/3/034003 © IOP Publishing. Reproduced with permission. All rights reserved.

with nearly 500 individuals and found that robusticity was higher in light workers, such as painters and shoemakers, compared to hard workers, such as farmers and miners. Milella and colleagues suggested that the lack of correlation may be due to an overly vague occupation variable. In a Portuguese sample of more than 100, Alves Cardoso and Henderson (2010) also found no correlation between occupation type and entheseal changes. Only at one enthesis site did manual laborers have more enthesophytes than skilled workers. But these inconclusive results on occupation and entheseal changes have not deterred anthropological researchers from using entheseal changes to reconstruct past activity patterns. The lack of occupation correlations with entheseal change scores may be the result of the multifactorial etiology of entheses; Figure 3.3 illustrates the complex etiology of entheseal changes.

Confounding Factors in Entheseal Change Formation

Regardless of the strength of their findings, anthropologists have been reluctant to attribute all entheseal changes to activity patterns. Most (if not all) anthropologists acknowledge that confounding factors exist and that these factors cannot be entirely controlled (e.g., Havelková et al., 2011; Lieverse et al., 2013; Schrader, 2012; Villotte et al., 2010b). Confounding factors, in statistics, are variables related to the variables defined in a study (e.g., the study variables) that can mask an actual association or falsely demonstrate an apparent association between the study variables where no real association between them exists. If confounding factors are not measured and considered, bias may result in the conclusion of the study. Due to confounds and multifactorial etiology, some anthropologists are warier of activity pattern reconstruction claims than others (e.g., Schlecht, 2012; Weiss, 2014a, 2015b).

Age Effects

Age is the number one predictor for entheseal changes. Age has been repeatedly found to affect entheseal change scores (e.g., Chapman, 1997; Cunha and Umbelino, 1995; Milella et al., 2012; Robb, 1998; Weiss, 2003b, 2014a). Although many of the early publications on age correlations with entheseal changes were from studies of archaeological samples with estimated ages (e.g., Chapman, 1997; Weiss, 2003b), more recent studies on known age samples have corroborated age's effect on entheses (e.g., Alves Cardoso and Henderson, 2010; Milella et al., 2012, Niinimäki, 2011). Older individuals have greater entheseal changes than younger individuals. Pere Ibáñez-Gimeno and colleagues (2013) also found that entheseal changes only emerge in adulthood. Hakwey and Merbs (1995) realized early on that research by Donald Enlow published in the prestigious *Yearbook of Physical Anthropology* in 1976 would have implications for entheseal change research; they pointed out that Enlow found and wrote that muscle insertion sites on children are not affected by localized mechanical loads; actually, these insertion sites in children are only a result of the muscle–bone attachment forming. Muscle insertion sites in juveniles are due to the onset of the anchoring muscles into bones. Entheseal changes do not form until long-bone growth stops. Sirpa Niinimäki (2011) found age correlations with entheseal changes of the radius and further noted that once long-bone growth stops, entheseal changes start to correlate with age.

The cause of the age effect continues to be debated. Milella and colleagues (2012) pointed out that age's effect may be due to the effect of mechanical stresses over time. Others who have looked at known occupation and age skeletal samples, such as Alves Cardoso and Henderson (2010), found no occupation correlations with entheseal changes, but they found age correlations with entheseal change scores did occur.

In the clinical literature, Pascal Claudepierre and M. C. Voison (2005) noted that enthesopathies increase with age, which may be attributed to repetitive strains, but other causes may also be underlying this pattern; for example, diabetes has been reported to increase enthesopathies, and diabetes risk also increases with age. Other medical researchers have noted that entheseal changes may be part of the natural aging process (Abreu et al., 2003). Benjamin and colleagues (2000) stated that enthesopathies are usually age related and peak at around age 60.

Stephen Schlecht (2012) noted that the periosteal fibrous entheses become bony as the periosteum disintegrates over time. Consequently, the rugosity of muscle insertion sites is not likely to be due to the accumulation of activity-related stresses and bone remodeling, but is likely due to the accumulation of periosteal disintegration. Interestingly, Villotte and Knüsel (2013) mentioned that fibrocartilaginous entheses, which show fewer robusticity changes, are less affected by age.

Regardless of the reasons for age correlations with entheseal changes, most researchers control for age in the anthropological studies. They may do this by excluding certain age groups (e.g., Villotte et al., 2010b), by examining results by age groups (e.g., Molnar, 2010), or by statistically controlling for age (e.g., Weiss et al., 2012). Yet archaeological samples often have only age estimates, so these controls are imperfect. Forensic anthropologists have suggested that entheseal changes may actually be useful in age determination of adults who are notoriously difficult to age (e.g., Listi, 2016).

Body Size Effects

In addition to the age effects on entheseal changes, many anthropologists find a body size or body mass effect (e.g., Lieverse et al., 2009; Myszka and Piontek, 2011; Weiss, 2003b). Most research on entheseal changes and size correlations has occurred on populations with unknown weights. Yet Kathrin Godde and Rebecca Taylor (2011) examined an autopsy collection (a skeletal collection that is composed of individuals with known ages and sexes because the remains were procured or donated after an autopsy) with known body weights. They found that in a sample of 102 white males, body weight was positively associated with thirteen entheseal change sites whereas only two entheseal change sites were associated with stress from known activities. Larger individuals have more pronounced entheseal changes than smaller individuals; the implications for sex differences are addressed below. These correlations are especially prominent in fibrous entheses and in the lower limbs (Weiss, 2014a). Zumwalt and colleagues (2000) found that body size was more strongly correlated with entheseal changes than locomotor type in nonhuman primates.

Body mass or measures of the joint surfaces, such as the humeral head, correlate to entheseal changes, whereas bone length does not correlate with entheseal changes (Myszka and Piontek, 2011). This correlation also interacts with population differences since some populations have long limbs and small articular surfaces while others have broad short limbs and large articular surfaces; it appears that shorter, broader populations, such as the Aleut and Eskimos, have greater entheseal changes than long, slender populations, such as Europeans and Nubians. These body shape differences are usually associated with natural selection, with differences having arisen for different climates (as mentioned in chapter 2). Cold-climate body types conserve heat through broad body types (that also usually have robust entheseal changes), while hot-climate body types are usually evolved to dissipate heat (and also tend to have fewer entheseal changes).

Body Size, Hormones, and Sex Confounds

The body size and mass effect, which is only sometimes controlled for, can create problems when comparing sex differences since males tend to be larger than females. Although sex differences are often attributed to activity pattern differences (e.g., Eshed et al., 2004; Molnar, 2006; Schrader, 2012), they may also relate to body size differences. The body size and sex confound may explain some reverse sex difference patterns (i.e., when females have greater entheseal change scores than males). A possibility is that when reverse sex differences occur, they occur in bones that are not likely to preserve in the average female. For example, reverse sex differences are often seen in the scapula (shoulder blade), which is a fragile bone. The average female scapula is unlikely to preserve, but the largest females are more likely to have preserved scapulae. On the other hand, the average male would have preserved scapula in the same environment (Weiss et al., 2012). Thus, in the end, the data collected are from large females and most males.

When controlling for body size or mass through covariance or ranking, the sex differences still tend to favor greater entheseal changes in male remains (Weiss et al., 2012). Consequently, these controls may be insufficient. This may be because sex differences are likely to be in part hormonal. Some anthropologists have suggested that sex differences are related to estrogen (Milella et al., 2012). Benjamin and colleagues (2002) discussed research on myostatin-deficient mice that may shed light on entheseal changes and sex differences. Myostatin protein regulates skeletal muscle and is more prominent in females. Myostatin-deficient mice increased their muscle bulk and the likelihood of a third femoral trochanter (a fibrocartilaginous enthesis). This increase in entheses was likely due to muscle size rather than muscle use.

Furthermore, entheseal changes seem to be controlled, at least in part, by other hormones, such as the parathyroid hormone, which also regulates osteoclast activity, as mentioned in chapter 2. Hence, the sex difference is likely more complicated than the body size confound suggests.

Diseases and Entheseal Changes

Another factor that may affect anthropologists' ability to use entheseal changes in activity reconstruction is the correlation of fibrocartilaginous entheses with diseases. Henderson (2008) found that many diseases, especially rheumatic and **autoimmune diseases** (diseases in which the body produces antibodies that attack its own tissue), may mimic effects of entheseal changes from activities. Fibrocartilaginous entheses are more greatly affected by diseases than fibrous entheses, but fibrous entheses have been linked to **calcified tendinitis**, which causes cortical erosion from calcium deposits (Henderson, 2008, 2013). Diseases that mimic activity-related entheseal changes include **fluorosis** (which, unlike the other diseases mentioned here, is environmental; it is a condition caused by the ingestion of excess amounts of fluoride that can lead to osteoporosis or osteopetrosis) and DISH, as mentioned earlier.

DISH, which affects the spinal ligaments and causes fusion of the vertebrae, is usually looked for in samples; individuals suspected of having DISH are excluded from entheseal change research (e.g., al-Oumaoui et al., 2004; Havelková et al., 2011). However, Henderson (2008) pointed out that this action is still not enough, and she suggested that entheseal changes are overdiagnosed and that non-activity-related diseases are underreported. Some of these diseases, such as DISH, are more common in males than females and may explain some of the trend of higher entheseal scores in males. Most of these diseases are genetic and therefore the formation of entheseal changes at fibrocartilaginous sites may also be in large part controlled by genes, especially if anthropologists are misdiagnosing diseases as mere entheseal changes.

Summary

Anthropologists have gotten better at collecting data on entheseal changes; methods have improved, but what information entheseal changes reveal is still unknown. Niinimäki (2012), for example, found that entheseal changes did not correlate with cross-sectional robusticity in the humeri. And Ksenija Djukic and colleagues (2015) used recent biologically compatible methods from Villotte and from Alves Cardoso and Henderson to compare entheseal changes with microarchitectural changes in bone but found no correlation between microarchitectural changes and entheseal changes. The authors suggested that entheses are structurally designed to meet the muscular tensile demands that the entheses are exposed to. This sentiment is expressed repeatedly in the clinical literature (e.g., Benjamin et al., 2000, 2002; Schlecht, 2012; Shaw and Benjamin, 2007). Some researchers have suggested that enthesophyte development is genetically determined. Juliet Rogers and colleagues (1997) studied skeletal samples and found that, although bony spurs increase with age, both enthesophytes and osteophytes (not related to entheses) are strongly correlated throughout an individual's body. Thus, some people may be inclined to excess bone formation.

With all the biological noise, it is difficult to determine what predictive value entheseal changes can have when archaeological evidence is excluded (see Schlecht, 2012). Over time, anthropologists have learned that age is the best predictor of entheseal changes, but even with controls for age, other confounds exist. The genetic effects on entheseal changes are very poorly understood, and even in utero baselines have not been established (Schlecht, 2012). Clinicians are aware of how hormones such as estrogens and testosterone affect bone cells, but how these hormones influence entheses is still not understood (Schlecht, 2012).

Furthermore, the entheses associated with our most powerful muscles are also the entheses least explored by clinical researchers (Benjamin et al., 2002; Schlecht, 2012). The lack of good research on entheseal changes is not solely the fault of researchers, whether clinical or anthropological researchers. Claudepierre and Voison (2005) pointed out that entheseal tissue is difficult to collect. And anthropologists are left with only bone; no tendons or even periosteal tissues are preserved. Perhaps nothing highlights this difficulty in understanding entheses more than the lack of understanding even the most basic concepts, such as Sharpey's fiber definitions and the division between fibrous and fibrocartilaginous insertions (Shaw and Benjamin, 2007).

Before anthropologists continue in their endeavors to reconstruct activity patterns through the use of entheseal changes, perhaps a greater understanding of entheseal changes is needed from other fields of study. And if the suspicion that entheseal changes are simply part of the natural aging process can be verified, then clearly all bets are off.

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OSTEOARTHRITIS

Osteoarthritis is the most commonly identified skeletal pathology in the bioarchaeological record (Weiss and Jurmain, 2007). Osteoarthritis is also the most common form of arthritis in living peoples; it occurs in seven out of 10 people over 65 years old (Guilak, 2011). The ubiquity of osteoarthritis in the skeletal record has led to a rich anthropological literature on the pathology. Osteoarthritis more so than any other skeletal indicator has been incorporated into site reports and studies on past populations' quality of life. The assumption is that osteoarthritis is a result of wear and tear on joints caused by activity patterns. Yet clinical research on osteoarthritis is abundant, and conclusions drawn by this research indicate strong biological (and perhaps genetic) components to who gets osteoarthritis and how severe the osteoarthritis becomes. Yet much remains to be understood in regards to osteoarthritis diagnoses and etiology.

Erosive Joint Disease

Arthritis is any disease that affects joints. Most forms of arthritis are erosive; in other words, the pathology results in bone loss at the joints. Erosive arthritis, such as rheumatoid and juvenile arthritis, are less frequent than osteoarthritis both in living peoples and in the skeletal record. Furthermore, erosive arthritis forms—and a few proliferative forms, such as diffuse idiopathic skeletal hyperostosis (which is mentioned in the previous chapter)—are likely the result of genetics. Their etiologies have been understood to exclude environmental factors. Many erosive forms of arthritis are actually autoimmune related and afflict females more than males. Although anthropologists have written about erosive arthritis, these studies are few and are mainly case studies to understand the skeletal features found in erosive arthritis cases. For example, Juliet Rogers and colleagues (1991) examined a skeleton from London that was dated between the late fourteenth century and the early sixteenth century that had evidence of rheumatoid arthritis. In a 2010 publication, Julie Bukowski noted that although many cases of osteoarthritis were present in the prehistoric Illinois sample examined, just one individual with rheumatoid arthritis was found. Rheumatoid arthritis accounts for less than 5% of all arthritis cases, and yet it is the second most common form of arthritis (Rogers et al., 1991). Another example of erosive arthritis was published by Diane Hawkey (1998), who described a skeleton from prehistoric New Mexico with a rare form of juvenile arthritis.

Another form of rare arthritis is gout-related arthritis. **Gout** is a disease caused by excessive uric acid retention in joints, especially hand and foot joints. Gout is usually found in overweight or obese individuals; thus, it is not surprising that evidence of gout is rare in the bioarchaeological record. Koji Inoue and colleagues (1998) found perhaps the oldest case of gout in a 4,500- to 3,500-year-old skeleton from Asia. All these case studies are of interest to anthropologists but not for those interested in activity-pattern reconstructions.

Osteoarthritis Basics

In both anthropological research (e.g., Bridges, 1992) and clinical research (e.g., Guilak, 2011), osteoarthritis has been defined as a proliferative arthritis that results from wear and tear of the joint. This definition should make osteoarthritis ideal for activity reconstructions. Yet the abundance of research on osteoarthritis from multiple disciplines suggests that the etiology is far more complex than just wear and tear.

Osteoarthritis Terminology

Before discussing osteoarthritis in more depth, I would like to explain osteoarthritis terminology. Some anthropologists prefer the terms "degenerative joint disease" or "osteoarthrosis." The emphasis of degenerative joint disease seems to be on the breakdown of cartilage. My preference is to use a term that includes bone (i.e., osteo) in the word since anthropologists actually examine only the bone rather than the entire joint; thus, my predilection is to use either "osteoarthrosis" or "osteoarthritis." Osteoarthrosis is sometimes favored by European anthropologists, and it has been preferred by anthropologists and clinicians who suggest that since the suffix "-itis" refers to inflammation, osteoarthritis should only be used when inflammation is present (see Weiss and Jurmain, 2007). Recent research has revealed that osteoarthritis is an inflammatory disease (Guilak, 2011; Sandell and Aigner, 2001), so I think it reasonable to use osteoarthritis. Osteoarthritis is my preferred term and is used throughout this chapter.

Diarthrodial Joint Anatomy

Osteoarthritis is the only form of joint disease that has been linked to activity reconstruction. The frequency of osteoarthritis coupled with the ease of seeing osteoarthritis on bones has led bioarchaeologists to use osteoarthritis patterns to answer questions regarding differences in activities based on class (e.g., Knüsel et al., 1997; Palmer et al., 2016), sex differences in labor in past populations (e.g., Nicholas, 2007; Sofaer Derevenski, 2000), activity level changes in relation to subsistence patterns (e.g., Eshed et al., 2010; Larsen, 1995), and what specific activities past peoples engaged in (e.g., Bridges, 1994; Garvie-Lok, 2010). To understand how anthropologists come to their conclusions, one needs to understand how osteoarthritis changes joint morphology.

Osteoarthritis occurs in diarthrodial joints, also known as synovial joints. Diarthrodial joints are the most moveable joints; these include **apophyseal joints** in the vertebral column, temporal-mandibular joints (i.e., joints between the cranium and the mandible that moves the jaw), hips, knees, elbows, shoulders, wrists, ankles, and the digits in the hands and feet. Most activities involve diarthrodial joint use; hence, it is easy to understand why anthropologists would consider osteoarthritis useful for activity reconstruction research.

As illustrated earlier in Figure 1.2 (see chapter 1), diarthrodial joint anatomy involves a subchondral bone and a **synovial capsule** that is a closed cavity filled with fluid and is formed by smooth, articular cartilage (also known as **hyaline cartilage**) that covers the articular surface of the bones and surrounds the joint capsule. The cartilage ranges in thickness throughout the joints, between joints, and between individuals (Mow et al., 1984). Cartilage tends to be the focal point of osteoarthritis studies in clinical research. The articular cartilage consists of chondrocytes (cells that secrete immature cartilage), liquid (which is nearly all water), and solids such as type II collagen, proteoglycans, and other proteins (Mow et al., 1984). Articular cartilage consists of a porous fibril network of collagen and solid components in the joints that are swollen with water (Mow et al., 1984).

Cartilage functions, with synovial fluid (also known as extracellular matrix), to reduce friction between the bones. For example, in a diarthrodial joint like the knee, the cartilage with the synovial fluid will make the motion between the distal femur and proximal tibia smooth. Cartilage erodes but repairs itself throughout life.

Cartilage Remodeling, Repair, and Osteoarthritis Formation

Normal cartilage is constantly in a state of slow turnover (Guilak, 2011; Sandell and Aigner, 2001). This turnover results in a homeostatic balance between **catabolic** (i.e., destructive action) and **anabolic** (i.e., synthesis of simple matter to more complex matter) events of chondrocytes to form the highly complex matrix of cartilage (Guilak, 2011). Throughout life, chondrocytes and subchondral bone cells perceive stresses and react (Lories and Luyten, 2011). In balance, this results in a healthy joint. Normal loading helps to maintain the cartilage's remodeling and repair balance (Guilak, 2011). Conversely, excessive loads can damage the **collagen fibril network** (the porous matrix of articular cartilage) and result in cracks and fissures that are too big to repair (Guilak, 2011). When this occurs, osteoarthritis arises.

Exactly how and why cartilage becomes damaged beyond repair is not well understood (Arokoski et al., 2000). It appears that one of the first indicators of osteoarthritis is an increase and then a decrease in proteoglycans (Arokoski et al., 2000; Sandell and Aigner, 2001). When the collagen matrix is damaged, there is a loss of collagen and proteoglycan, and in response chondrocytes first proliferate and synthesize collagen and proteoglycan (Lories and Luyten, 2011). This effect, however, is temporary. The cartilage then becomes soft, perhaps as a result of excess water drawn to the joint by synovial fluid ions, and begins to tear more. This results in production of inflammatory cytokines by the synovial fluid and the chondrocytes.

Osteoarthritis is a condition of the entire joint (Goldring, 2012; Lories and Luyten, 2011; Sandell and Aigner, 2001); it involves articular cartilage degeneration, synovial fluid and capsule inflammation, subchondral bone thickening, degenerative changes of ligaments, and osteophyte formation. The degenerative changes to cartilage occur when damage outpaces repair (Sandell and Aigner, 2001), but the bony changes are of greatest interest for anthropologists since these are the only visible changes left on skeletal remains. The connection between cartilage and subchondral bone is not completely understood, but researchers have determined that subchondral bone has an interlocking structure similar to that of the tooth-and-socket morphology seen the jaws, between cartilage and skeletal bone (Hoemann et al., 2012). There is cross-talk between the bone and cartilage, which likely is partially responsible for the bony changes seen in osteoarthritis (Suri and Walsh, 2012). It is unknown whether osteoarthritis changes begin at the surface of the joint, which would be at the synovial capsule, or at the deep subchondral bone of the joint (Goldring, 2012; Nukavarapu and Dorcemus, 2013).

The changes that occur as a result of osteoarthritis include the fact that the articular cartilage has a proliferation of chondrocytes and an increase in extracellular matrix, which in turn increases the production of inflammatory cytokines (Lories and Luyten, 2011). The inflammatory cytokines and other destructive enzymes, which are proteins that speed up the rate of chemical reactions, create a rapid loss of normal tissue and thinning of cartilage (Lories and Luyten, 2011). The cartilage, on the other hand, can also thicken in osteoarthritis (Hoemann et al., 2012). In either case, the cartilage becomes mineralized and less flexible, which results in tears and an increase in vascularization that allows for nonchondrocyte invasion into the cartilage (Suri and Walsh, 2012). In either change, the cartilage matrix is weakened and erosion occurs, which results in the cartilage's loss of elasticity, decreased compressive resistance, and a lack of tensile strength (Goldring, 2012; Grodzinsky et al., 2000).

In the bone, osteoarthritis results in an increase in bone remodeling as well as a thickening and hardening of the subchondral plate, which is the tidemark between bone and cartilage (Lories and Luyten, 2011). There may also be modification of the trabecular architecture and bone attrition (Lories and Luyten, 2011).

Osteoarthritis Features

The changes mentioned above result in physical manifestations of joint space narrowing, hardening of cartilage and osteophytes. **Osteophytes** are bony spurs at joint surfaces. These bony spurs can be covered with cartilage (Sandell and Aigner, 2001).

Osteophytes, which are also known as secondary cartilage formation, are a consistent osteoarthritis feature in both natural and lab settings (Sandell and Aigner, 2001; see Fig. 4.1). They seem to arise at the chondrosynovial junction (Lories and Luyten, 2011; Sandell and Aigner, 2001). But the function of these bony spurs remains an enigma (Sandell and Aigner, 2001).

Although clinical studies and active practice in clinical settings use a variety of traits and symptoms to diagnose osteoarthritis, many of these features are not available to bioarchaeologists. Clinicians, for example, use osteophytes, joint space narrowing, cartilage changes, and pain surveys (e.g., Jones et al., 2000; Kalichman et al., 2005; Weiss, 2014b). The anatomical changes of osteoarthritis are determined by radiographs and magnetic resonance imaging in clinical settings (e.g., Weiss, 2014b; Zhai et al., 2004). Anthropologists, on the other hand, most often just use their eyes to examine joint surface for evidence of osteophytes, eburnation (see below), and porosity (e.g., Cope et al., 2005; Garvie-Lok, 2010; Watkins, 2012). Some anthropologists have also included changes in bone shape (e.g., Hodges, 1991; Waldron and Rogers, 1991). However, Kimberly Plomp and colleagues (2015b) examined articular change with a three-dimensional scanner and found that three-dimensional morphometrics of articular surfaces were not useful in determining the presence of osteoarthritis. Osteophytes are the easiest to identify and are also the most common feature of osteoarthritis (Weiss and Jurmain, 2007, see Fig. 4.1). They appear as excess bone growths on or near joint surfaces.

Eburnation, which is the degeneration of bone into a hard, shiny, and ivory-like mass, has been recognized as a pathogenic (i.e., disease-causing) trait of osteoarthritis. Eburnation is sometimes referred to as a bony polish. It appears that eburnation results from bone-on-bone rubbing where cartilage has been eroded away. A good example of eburnation can be seen in Figure 4.2. Eburnation, which is less frequent than osteophyte formation, has been linked to osteoarthritis progression (Rando and Waldron, 2012). Eburnation is sometimes the only feature used to identify osteoarthritis by bioarchaeologists since it is a known pathogenic trait, but since clinical researchers of osteoarthritis have found osteoarthritis without eburnation, using eburnation as the only an indicator of osteoarthritis presence will likely cause bioarchaeologists to underreport the frequency

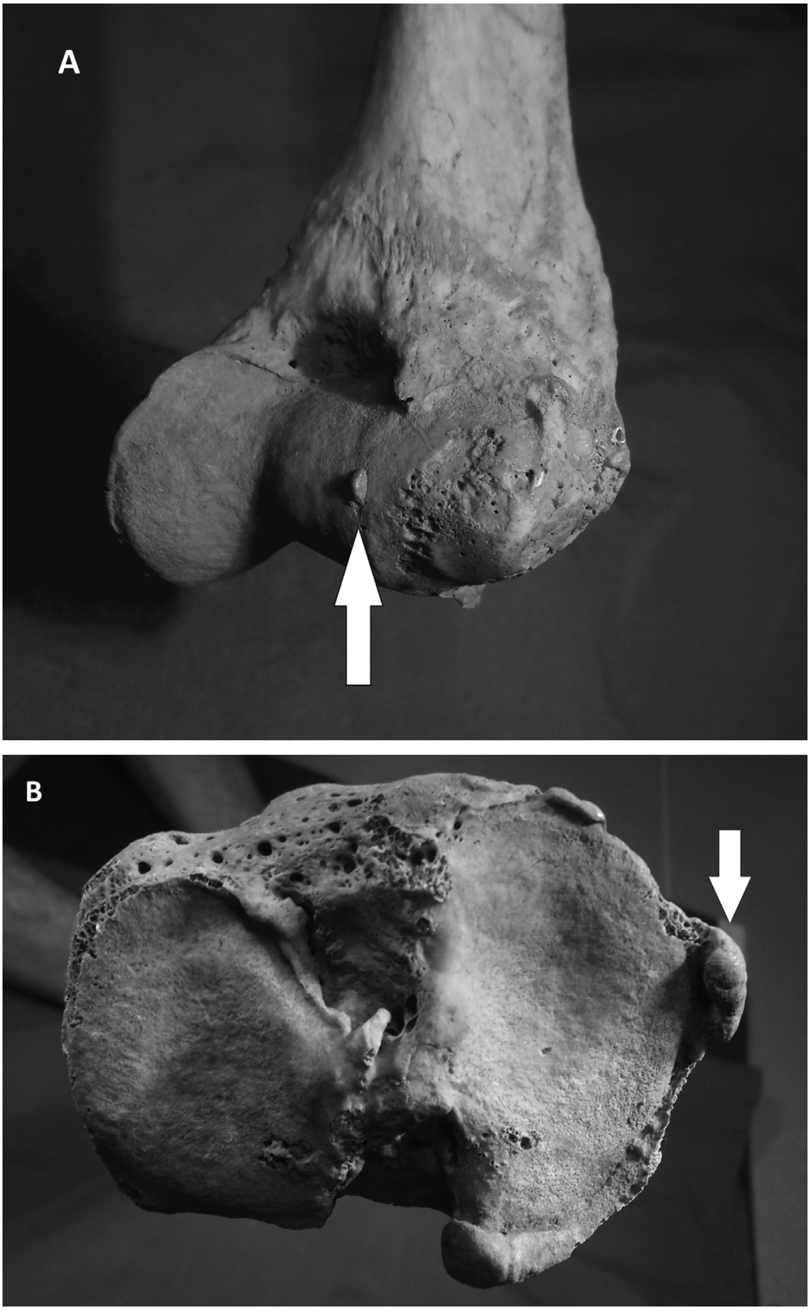

Figure 4.1. Osteoarthritis: osteophyte. Two examples of osteophytes: (*a*) on the distal humerus; (*b*) on the proximal tibia.

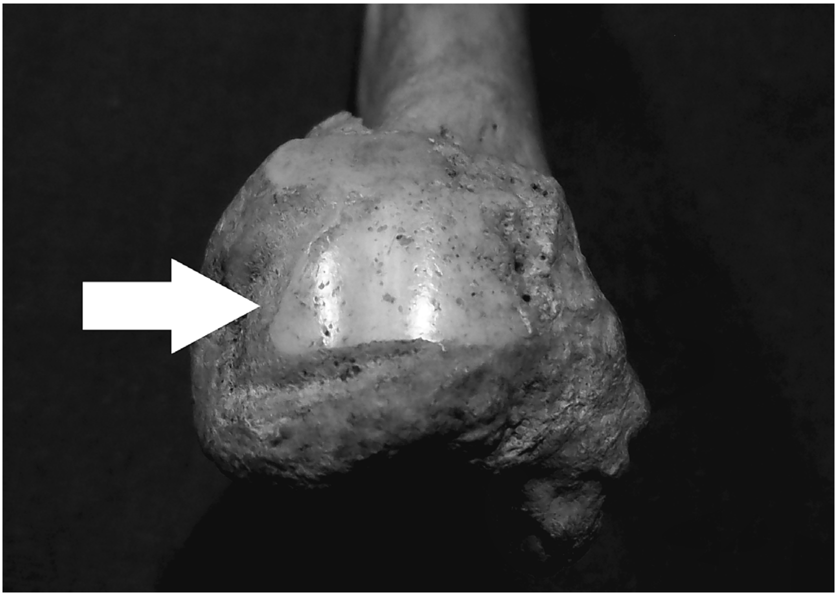

Figure 4.2. Osteoarthritis: eburnation. An example of eburnation on a distal ulna.

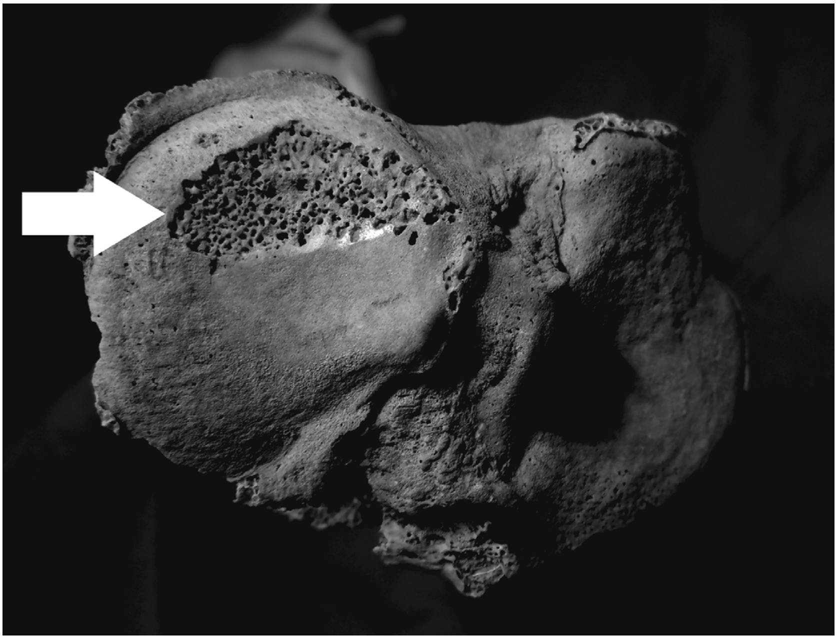

Figure 4.3. Osteoarthritis: porosity. An example of osteoarthritis of the proximal tibia; porosity is the most prominent joint change featured. However, this joint also has evidence of eburnation and osteophytic lipping.

of osteoarthritis. Thus, eburnation is better viewed as a severity indicator rather than the sole indicator of presence or absence of osteoarthritis.

Porosity, which is a trait that describes small but still macroscopic holes on the articular surface, can also be detected on joints; Figure 4.3 has an excellent example of porosity with a small degree of eburnation and some osteophytic **lipping** (the formation of a bony ring around the articular surface) on a proximal tibia. Porosity can be similar in appearance to blood vessel holes called nutrient foramen, and the porosity may also look like entheseal changes stress lesions, but both of these types of holes are not on the articular surfaces of bones. Since porosity is not used in clinical research or in medical practice as a diagnostic feature, understanding its relation to osteoarthritis has been difficult. Some researchers, such as Tony Waldron (1992a), only include porosity when it is in conjunction with other osteoarthritis traits, as in Figure 4.3 where porosity is coupled with the other two osteoarthritis traits (i.e., eburnation and lipping). Still, others are even more skeptical of using porosity as an indicator of osteoarthritis. Bruce Rothschild (1997) noted that not only is porosity not included in medical radiology for joint disease diagnoses but porosity cannot even be recognized in X-rays. In his study, Rothschild (1997) examined skeletons from an autopsy collection of known ages and sexes called the Hamann-Todd autopsy collection to investigate porosity's relationship to other osteoarthritis indicators. The Hamann-Todd collection was started in Cleveland, Ohio, in 1911; by 1938 the collection contained 3,600 individuals of known sex, age, height, and weight. Rothschild found that nearly 30% of individuals examined had osteoarthritis, but 82% who had the osteoarthritis traits of osteophytes and eburnation had no porosity. Furthermore, 70% of individuals with porosity had no other osteoarthritis traits. So, although some anthropologists have suggested that porosity is the result of bone **sclerosis** (or hardening) coupled with a loss of vascularity or the intrusion of synovial fluid into exposed subchondral bone, no clinical evidence exists to link porosity to eburnation or osteophytes. And although there is a scarcity of clinical research into other skeletal traits, such as entheseal changes, this is often complicated by the fact that these activity indicators do not result in pain and, thus, the traits have not received attention from the medical community. The opposite is true of osteoarthritis; it is a leading cause of joint pain and disability and, hence, has received ample attention from medical researchers.

Although the traits examined for osteoarthritis determination are few, diagnoses are not standardized in anthropology (see Waldron, 1992a; Bridges, 1993) or medicine (see Cicuttini et al., 1996). The lack of standardization makes comparing studies difficult; Patricia Bridges (1993) noted that two researchers studying the same sample could come up with very different results in presence and severity of osteoarthritis. This lack of standardization in data collection is also found in the entheseal change literature. Furthermore, Waldron and Rogers (1991) noted that even when using the same methods, different observers disagreed about whether lipping and porosity were present, and observers disagreed about the severity of the traits. Researchers most often agreed on eburnation scores; that is, the lowest interobserver error rates were found in the eburnation traits compared to lipping and porosity. But eburnation is also the least common osteoarthritis trait. The interobserver error rates problem is also found in entheseal change scores; one may suggest that more training in data collection is needed, but, surprisingly, experience made little difference in error rates. Even experienced researchers disagreed with other experienced researchers, which may mean that different results reflect researchers' opinions and perceptions on what is normal variation compared to pathological variation in joints. In short, beyond determining which features to use, anthropologists need to focus on lowering error rates.

Activity-Pattern Reconstructions

Evidence for Activity Induced Osteoarthritis

Anthropologists looking at these bony changes most often do so in an attempt to reconstruct activity patterns. Both clinicians (e.g., Gabay et al., 2008; Goldring, 2012; Grodzinsky et al., 2000) and anthropologists (e.g., Baetsen et al., 1997; Bridges, 1992; Waldron, 1995; Walker and Hollimon, 1989) have written on the importance of mechanical stresses in osteoarthritis formation, but they also underscore that osteoarthritis etiology is multifactorial. In vitro research has illustrated that excessive loads have deleterious effects on joints, which include cell death, disruption, inflammation, and damage to collagen (see Guilak, 2011). In lab studies, mechanical stresses have been successfully applied to produce osteophytes (see Sandell and Aigner, 2001). Both chondrocytes and subchondral bone are subject to static and dynamic loads that stimulate maintenance of the joint; thus, chondrocytes and subchondral bone sense and respond to mechanical stimuli (Grodzinsky et al., 2000). And, like bone remodeling, response depends on duration, frequency, and amplitude of the stresses; overloads can result in damaged tissue and osteoarthritis (Grodzinsky et al., 2000). Clinical researchers have reported that abnormal mechanical stresses do induce catabolic and inflammatory-related occurrences throughout the joint.

Anthropologists have pointed out nonarchaeological evidence of osteoarthritis and activities linked to support their claim that osteoarthritis is at least in part activity induced (see Weiss and Jurmain, 2007). Elizabeth Weiss and Robert Jurmain (2007) reviewed the sports literature in connection to osteoarthritis in their oft-cited review article that was actually an update of Jurmain's (1991) trailblazing article that examined the link between osteoarthritis and sports. They reported on osteoarthritis studies on ballet dancers, tennis players, and other athletes that have found links between the activities and osteoarthritis. On the other hand, some researchers have found these sport-based findings unconvincing due to their lack of rigor (Baetsen et al., 1997).

Perhaps one of the strongest arguments for linking osteoarthritis to activity comes from occupational research. Previous studies have linked osteoarthritis to welding, cow milking, and farming (see Thelin et al., 2004; Weiss and Jurmain, 2007). Anthropologists have incorporated occupation research into their analyses of past populations; for example, Ann Stirland and Waldron (1997) included a review of the research on miners and vertebral osteoarthritis in their study of mariners from the 1545 shipwrecked *Mary Rose*. Yet Simon Mays (2012) did not find hip osteoarthritis correlated with occupations when he used a well-documented large London skeletal sample dating from eighteenth to nineteenth century. One reason for Mays' lack of results may have been that he did not have information on nonoccupation activity patterns. Often occupations or sports are examined to understand the effects of activity on osteoarthritis, but some research has combined occupational and recreational activities to further our understanding of osteoarthritis's link to mechanical stresses. For example, Anders Thelin and colleagues (2004) used a sample of more than 300 farmers to understand osteoarthritis in relation to farming activities and found some unexpected correlations with osteoarthritis. Farmers who engaged in sports were more likely to have hip osteoarthritis than nonathletic farmers. It is thought-provoking to question whether osteoarthritis and sports may be activity related in a nontraumatic sense or whether the osteoarthritis relates to injuries. Sports injuries have been suggested to cause bone remodeling, entheseal changes, and osteoarthritis (see Bertram and Swartz, 1991)

Secondary osteoarthritis, which is the term used for osteoarthritis that has been caused by something other than normal joint usage, rather than **primary osteoarthritis** that assumes no additional etiology beyond normal joint wear and tear, occurs when trauma has caused the osteoarthritis. Joint injuries often lead to osteoarthritis later in life (Goldring, 2012). Neanderthals, who were often in contact with large animals as a result of hunting large game, had injuries that frequently led to osteoarthritis (Dawson and Trinkaus, 1997). Christopher Knüsel and colleagues (1995) also found evidence of secondary osteoarthritis in a unique case study published in the *International Journal of Osteoarchaeology*; the burial examined was of a medieval British male who showed evidence of knee osteoarthritis and a **comminuted fracture** (a fracture in which the bone is crushed or splintered) of the tibial condyle that may even have received surgical intervention. Other injury-related osteoarthritis can be found in the early 1900s Washington, DC, almshouse (which were poorhouses and now would likely be referred to as homeless shelters) sample examined by Rachel Watkins (2012). This almshouse sample from a predominantly African American population had higher levels of osteoarthritis than a comparison sample of African Americans from the same time period; the almshouse sample also had higher rates of fractures.

Additionally, Thelin and colleagues (2004) found that farmers with barn animals had higher rates of osteoarthritis, which may be due to the labor involved in caring for and using these animals or due to infectious agents. If osteoarthritis is caused by an infection, such as a bacterial contagion, then it is still considered secondary osteoarthritis. Nevertheless, with evidence from sports, occupation, and clinical research linking osteoarthritis to activities, anthropologists have undertaken activity reconstruction using osteoarthritis.

Bioarchaeological Activity Reconstructions

In anthropological studies, bioarchaeologists have used osteoarthritis patterns in a variety of ways to reconstruct past populations' lifestyles. Some commonly examined questions addressed with osteoarthritis include determining specific activities (e.g., Bridges, 1994; Garvie-Lok, 2010; Walker and Hollimon, 1989), examining class differences (e.g., Knüsel et al., 1997; Palmer et al., 2016; Schrader, 2012), looking at sexual division of labor (Nicholas, 2007; Sofaer Derevenski, 2000; Walker et al., 2004), and assessing the effects of occupations (e.g., Mays, 2012; Owsley et al., 1987; Stevens and Leader, 2006). Anthropologists have also used osteoarthritis frequencies and severities to assess general levels of activity or how hard various populations had to work (e.g., Dabbs, 2011; Eshed et al., 2010; Suzuki, 1998; Woo and Pak, 2013). Yet many of these topics overlap, and, consequently, many studies also have overlapping hypotheses in which sex differences, for example, are assessed with subsistence patterns and activity levels (e.g., Walker and Hollimon, 1989). Furthermore, bioarchaeologists employ a wealth of additional information, such as artifacts and ethnographies, to come to activity reconstruction conclusions.

For simplicity's sake, I will review some research on osteoarthritis by the joints the authors examined. Some studies that view osteoarthritis throughout the body to examine general trends are reviewed at the end of this section.

Although some anthropologists have warned against using osteoarthritis to reconstruct specific activities (see Weiss and Jurmain, 2007), other anthropologists have felt that osteoarthritis patterns coupled with additional nonskeletal materials, such as artifacts, can help to determine who did what specific activities in the past. For example, in a 1994 study by Nancy Lovell, skeletal remains from 4,000- to 5,000-year-old Pakistani Indians were examined for vertebral osteoarthritis. Using an ordinal scale, Lovell concluded that the fairly high levels of cervical (or neck) vertebrae osteoarthritis related to carrying loads on the head. Lovell, who found no sex differences, noted that ethnographic data provided evidence of carrying loads on the head in this region, but this was usually done by females. Lovell argued that the lack of sex differences may be due to the low number of remains that could be accurately sexed. Another possibility is that both sexes engaged in activities that stressed the cervical vertebrae, but that these activities may, nonetheless, differ between the sexes. Finally, it is possible that perhaps sexual divisions of activities were different in the past than in current populations.

Another study that focused on vertebral osteoarthritis in relation to activity patterns came from Eun Jin Woo and Sunyoung Pak (2014).

Woo and Pak examined osteoarthritis of the spine in mid-fifteenth- to twentieth-century Korean remains. Although the authors acknowledged that there is conflicting evidence of the usefulness of vertebral osteoarthritis in reconstructing activity patterns (more of which will be addressed below), Woo and Pak suggested that the vertebral body osteoarthritis may not be useful, but the apophyseal joints (those located on the posterior side of the vertebrae) are more similar to other diarthrodial joints and can be used in activity reconstructions. In their South Korean sample, Woo and Pak found cervical osteoarthritis, which they did not attribute to weight carrying; rather, Woo and Pak suggested this osteoarthritis may have arisen from reading posture. In addition to the activity connection, they acknowledged that the osteoarthritis data strongly correlated with age. Age and osteoarthritis are tightly correlated in many studies, as you will see later in this chapter.

Also examining the apophyseal joints of vertebrae, Claudia Rojas-Sepúlveda and colleagues (2008) looked at pitting, lipping, and eburnation of Colombian skeletal remains from AD 700 to AD 1600. They concluded that the increasingly high levels of vertebral osteoarthritis were linked to the port's salt trade. The salt trade, they suggested, resulted in many individuals carrying heavy loads of salt on a regular basis.

Load-carrying effects in vertebral osteoarthritis are not limited to the cervical vertebrae; Joanna Sofaer Derevenski (2000) tied lumbar osteoarthritis in females from AD 1500 to the late nineteenth century from Ensay Island in the United Kingdom to carrying huge loads in creel backpacks, which were made of wicker and used mainly for carrying fish.

In a 1994 study, Bridges, too, linked vertebral osteoarthritis to load carrying but in a northwest Alabama Amerind sample. Yet Bridges acknowledged that figurines and depictions of tumplines, which are straps worn across the head to secure heavy back loads, showed females only, but the skeletal evidence revealed osteoarthritis in the backs of both sexes.

Humans are not the only animals affected by osteoarthritis; some animals who carry loads may be afflicted with vertebral osteoarthritis as a result of their loads. Gustavo Flensborg and Cristian Kaufman (2012), in an unusual study to further our understanding of the effects of load carrying, examined domestic and wild llamas to determine health differences, which included investigating osteoarthritis patterns. They found that although 20% of the llamas had osteoarthritis, the osteoarthritis could not be attributed to load carrying—rather, llama osteoarthritis was likely related to normal aging; the same may be true for humans, and this may explain the incongruity with osteoarthritis results and the ethnographic or archaeological data mentioned for the Native Alabamans and the Pakistani Indians.

While vertebral osteoarthritis is likely the most commonly studied pathology in the skeletal record (Myszka et al., 2014), nonvertebral joints have also been of interest to anthropologists when reconstructing activity patterns. The possibility of examining upper-limb osteoarthritis to understand weaponry has been undertaken in several studies. For instance, in *Latin American Antiquity*, a geographically oriented archaeology journal, Karen Wise and colleagues (1994) studied a nearly 5,000-year-old Peruvian skeleton with osteoarthritis of the elbow; the authors considered weapon use causes but rejected throwing as the cause of the osteoarthritis since it occurred on both arms. Thus, Wise and colleagues suggested that the osteoarthritis could have been a result of fishing activities, such as pulling in nets. In a far more rigorous study, Graeme Pretty and Morrie Kricun (1989) examined upper-limb osteoarthritis in relation to weapons in a sample of 216 prehistoric Australian Aboriginal human remains from 10,000 to 5,000 years ago and found that the elbow joint was more often affected with osteoarthritis in their Australian Aboriginal sample than in European comparison samples. Pretty and Kricun linked this difference to spear and boomerang throwing, which was supported by archaeological evidence of weaponry, in the Australian Aboriginal population. Nonetheless, they also acknowledged that some of the elbow osteoarthritis may be secondary as a result of injuries; in the Australian Aboriginal limb bones, evidence of ulnar (i.e., related to the forearm bone on the little finger side) fractures was present and likely indicative of hand-to-hand fighting.

In an early cross-cultural study of weaponry that helped define how elbow osteoarthritis is determined, Donald Ortner (1968) examined forearm bones of 165 Eskimos and 485 Peruvians to consider whether differences occurred as a result of spear throwing compared to bow and arrow use. Ortner's results suggested that localized stresses and, therefore, specific activities affect osteoarthritis patterns. One difference between the populations was that the Alaskan Eskimos had a higher rate of humeral capitular degeneration than the Peruvians. Furthermore, the Eskimos had more than three times the rate of humeral osteoarthritis compared to the Peruvians. Thus, although there may be numerous other factors at play, such as genes and climate, it appeared to Ortner that the Peruvian bows and arrows were less strenuous to use than the Alaskan spears. This assumption about the ease of using bows and arrows compared to spear throwing was also made in studies that examined other activity indicators, such as entheseal changes.

Other upper-limb (including hand, arm, and shoulder joints) studies have linked osteoarthritis to specific activities when combined with artifacts, such as heavy lifting in Icelandic peoples (e.g., Walker et al., 2004), making fishnets in the Bronze Age Arabian Peninsula (e.g., Cope et al., 2005), and harvesting grains with sickles among Greeks in the sixth century AD (e.g., Garvie-Lok, 2010). For example, Phillip Walker and colleagues (2004) found in a Viking sample that the males had elbow and wrist osteoarthritis likely linked to lifting during agriculture and maritime activities. Douglas Owsley and colleagues (1987) also found high levels of upper-limb osteoarthritis in males; in their study of an eighteenth-century New Orleans sample, the authors discovered that males had shoulder osteoarthritis frequently, which they linked to work at the Louisiana docks—which was a male work environment—due to the lack of females affected by shoulder osteoarthritis.

Knee osteoarthritis is extremely common in living peoples, occurring currently in a quarter of all U.S. adults (Waldron, 1995; Weiss, 2014b), but in the past other lower-limb osteoarthritis was also present frequently. Waldron's (1995) meticulous research on osteoarthritis patterns over time has revealed some curious trends. Hip osteoarthritis has decreased over time, which may relate to activity differences since the change occurred quickly, suggesting genetics might not be the cause of this trend. Waldron argued that natural selection changes to hip osteoarthritis rates would take longer to occur than cultural factors that could happen within a single generation. In his large skeletal sample of 1,198 from a variety of sites in England, Waldron noted the decrease in hip osteoarthritis from AD 1200 to AD 1850 to contemporary times. The quick change in frequency documented by Waldron is likely linked to activity changes. Currently, hip osteoarthritis is usually bilateral and occurs mainly as a result of obesity. William Stevens and Jonathan Leader (2006) used osteoarthritis coupled with rich archival materials to understand skeletal remains from Confederate sailors. They also attributed hip osteoarthritis to activities; in a small sample of 40 South Carolina Confederate soldiers and marines from 1861, the authors found that acetabular osteoarthritis, which relates to the hip socket located on the pelvis, was frequent and corresponded to activities of lifting and shoveling coal.

Not all studies have been able to tie hip osteoarthritis to activities. Acetabular osteoarthritis differences have been examined in eighteenth- and nineteenth-century London individuals of known ages and occupations by Mays. Mays (2012) found that occupation differences in acetabular osteoarthritis were not present, as mentioned earlier.

Specific activity reconstructions using osteoarthritis have been criticized, but most anthropologists have supported the theory that osteoarthritis can be used as a general indicator of activity levels (see Boyd, 1996; Bridges, 1992; Weiss and Jurmain, 2007). Nevertheless, sometimes even general patterns of activity levels are not as expected. Looking at activity levels, Knüsel and colleagues (1997) examined skeletal remains from medieval U.K. monks compared to laypersons and found no osteoarthritic differences between the populations, which was unexpected since monks were thought to have labored less than the laypersons.

One group of people who consistently have high levels of osteoarthritis are the Aleut and Eskimos. Gretchen Dabbs (2011) found, for example, that the Aleut and Eskimo populations of both the Ipiutak (dating from 100 BC to 500 BC) and the Tiagarra (dating from AD 1200 to AD 1700) had higher levels of osteoarthritis than non-arctic populations, which Dabbs related to the high levels of activity required of the northern peoples, who hunted caribou and whale. Yet, as you will see later in this chapter, cold weather in and of itself may be a causative factor of osteoarthritis. Some of the earliest and most thorough studies of Alaskan samples compared to other populations on osteoarthritis and activity patterns included work from Jurmain (1977a,b, 1980). Jurmain found that Eskimos had greater osteoarthritis than Pecos Southwestern Amerinds, and American blacks and whites from the Terry collection (an autopsy collection that contains individuals from the 1900s).

Looking at general osteoarthritis patterns, Takao Suzuki (1998) found osteoarthritis was more frequent in a population of Japanese **Jomon** dating from 10,000 to 3,000 years ago than in contemporary Japanese samples, which Suzuki attributed to a decrease in activity levels over time. Yet the Jomon had relatively light osteoarthritis levels compared to other prehistoric samples.

Perhaps the most significant event in human history occurred with the transition from various hunting and gathering subsistence traditions to agricultural subsistence. Anthropologists have examined whether this transition increased osteoarthritis and, therefore, agriculture was perhaps actually more labor intensive than hunting and gathering; or did osteoarthritis decrease, which would indicate that agriculture provided a less labor intensive way to obtain food? Interestingly, modern farmers have some of the highest osteoarthritis levels found today (Weiss and Jurmain, 2007). Vered Eshed and colleagues (2010) examined skeletal remains from late hunter-gatherer Natufians and Neolithic agriculturalists from the Levant and found that, at this early agricultural site, osteoarthritis did not increase with the shift in subsistence patterns. Alan Goodman and colleagues (1984), however, found the opposite trend, as did Clark Spencer Larsen in his 1995 review of the effects of the agricultural transition in the New World. Sometimes osteoarthritis patterns change due to other subsistence pattern shifts. For example, Phillip Walker and S. E. Hollimon (1989), using a sample of nearly 1,000, noted that osteoarthritis in Channel Island, California, Amerinds fluctuated depending on the fishing technology, which was determined by the artifacts found with the skeletal remains.

Non-Activity-Related Osteoarthritis Etiology

Even though many anthropologists use osteoarthritis as an activity indicator, nearly all (if not all) anthropologists are aware of the multifactorial etiology of osteoarthritis. Nonmechanical factors include climate, genes, hormones, anatomy, and aging. Even early studies such as Ortner (1968) and Jurmain (1977a,b) noted that factors beyond activity were involved in osteoarthritis presence and severity. The question anthropologists must answer is whether the nonactivity factors outweigh the activity factors in osteoarthritis formation. If the main causes of osteoarthritis are not mechanical stresses, then perhaps not enough variation due to activity remains to use osteoarthritis in activity-pattern reconstructions.

Age

The main nonactivity etiology is age. The age correlation in osteoarthritis is also seen in nonhuman animals (e.g., Flensborg and Kaufman, 2012). The age effect is so strong that some researchers have suggested that osteoarthritis is a normal part of aging (Jurmain, 1977a,b). Readers will recall that the same point regarding normal aging processes was brought up in the previous chapter in relation to entheseal changes. Many anthropologists acknowledge that age plays a key role in osteoarthritis formation (e.g., Molnar et al., 2011; Novak et al., 2012; Palmer et al., 2016; Schrader, 2012; Stewart, 1958). Some anthropologists have put forth that the age correlation with osteoarthritis may be the result of wear and tear over time (e.g., Bridges, 1992). Others are unsure of the reasons behind the age and osteoarthritis correlation (e.g., Myszka et al., 2014). Nevertheless, some anthropologists concede that their osteoarthritis pattern differences, which they have attributed to activity-pattern differences, may actually be attributable to age differences (e.g., Stirland and Waldron, 1997; Watkins, 2012; Woo and Pak, 2013, 2014). For example, Watkins (2012) looked at an African American almshouse sample that included many individuals who engaged in heavy labor and, as you may recall, had high fracture rates. She found that the almshouse individuals had far greater osteoarthritis in the upper limbs than a general comparative population, but the almshouse sample mean age was also older than the comparative sample mean age.

Since the age correlation has been found in many studies and is present in the clinical research, anthropologists have tried to control for age. This is sometimes accomplished by excluding young individuals (e.g., Hodges, 1991; Woo and Pak, 2014) or attempting to look at population differences within age groups (e.g., Klaus et al., 2009). Yet Jack Baker and Osbjorn Pearson (2006) have stated that age adjustments have not been done well in part because determining age in adults accurately is difficult. Aurore Schmitt and colleagues (2007) have pointed out that advanced age cannot be estimated with accuracy or precision since skeletal indicators of age and chronological age do not have a linear relationship. Some forensic anthropologists have suggested using osteoarthritis as a method for determining age (e.g., Lundy, 1986; Snodgrass, 2004). In a classic 1958 study on vertebral osteoarthritis, T. D. Stewart examined the possibility that vertebral osteophytes could be used in age estimation. Stewart, using white American males from the Terry Collection and from Korean War soldiers, concluded that severe vertebral lipping likely indicated the individual was 40 years old or over. Thus, Stewart concluded that although age does correlate with vertebral osteoarthritis and can be used in addition to other age estimation techniques, using vertebral osteoarthritis for precise age estimation is not possible. Snodgrass (2004) has reattempted to estimate age using vertebral osteophytosis and has suggested that one can use these bony changes to estimate age when sexes are separated.

Even though age confounds are a consistent issue in osteoarthritis and activity-pattern research, understanding some age patterns may be able to strengthen the research on activity patterns. According to Weiss and Jurmain (2007), osteophytes are more strongly correlated with age than eburnation or porosity. Osteophytes are also the most common osteoarthritis trait in skeletal remains (Rogers et al., 1997), especially on the vertebral column (Myszka et al., 2014). But eburnation is not free of age effects (Molnar et al., 2011; Rogers et al., 2004). In some studies, age correlates with osteoarthritis severity but not with frequency (Palmer et al., 2016). Consequently, presence or absence of osteoarthritis coupled with evidence of more than just osteophytes may be a way to avoid the strongest age effects.

Climate

One of the less well-understood factors in osteoarthritis etiology is climate. Colder and wetter climates seem to increase osteoarthritis frequency and severity (e.g., Kalichman et al., 2011; Laborde et al., 1986; McAlindon et al., 2007). For instance, Leonid Kalichman and colleagues (2011) looked at X-rays from more than 2,000 Russians in nine geographic locations and found that in this single ethnic group, colder, wetter, and darker climate increased hand osteoarthritis. Clinical research has also found that an increase in humidity and a lack of sunshine were correlated with osteoarthritis even in individuals who did not themselves link their osteoarthritis with climate (Laborde et al., 1986). Kenji Tokumori and coresearchers (2011) even reported that joint pain decreases with sun exposure. Other studies have failed to find climate and osteoarthritis links, but perhaps this lack of a correlation was due to an absence of climate extremes in the research (Wilder et al., 2003).

These climatic studies may help to explain the high levels of osteoarthritis found in northern populations, such as the Eskimos and Aleut. However, in prehistory, these individuals also likely led very arduous lives, which may have contributed to their osteoarthritis. Vitamin D deficiency may be related to the higher levels of osteoarthritis in cold, dark, and wet environments. Vitamin D is a hormone that resides in your skin and is activated by sunlight's ultraviolet rays. Although not fully understood, vitamin D plays an important role in synthesis of proteoglycan by mature articular chondrocytes (McAlindon et al., 1996). If the cause of osteoarthritis in cold, dark, and wet climates relates to vitamin D, then perhaps the osteoarthritis in past peoples was not influenced by the climate since these individuals likely spent a great deal of time outside and were not likely vitamin D deficient. That said, the sun's rays do not have the intensity in arctic regions, and the arctic winter lasts six months.

Although the climate effect on osteoarthritis may only play a small role in osteoarthritis frequency or severity other confounding factors—besides age—seem to play larger roles in osteoarthritis pathogenesis.

Anatomical Variants

Some of the additional non-activity-related osteoarthritis etiological factors still support the mechanical use connection with osteoarthritis. For instance, anatomical variants that have been linked to increased osteoarthritis are said to increase the stresses on the affected joints. Long tibiae have been reported to increase knee osteoarthritis (see Weiss and Jurmain, 2007). It appears that increasing tibial length results in more torsion stress at the knee, and it creates a less stable joint that is more prone to injury. For example, in a large clinical study, David Hunter and colleagues (2005) used a sample of 2,506 and found that knee osteoarthritis in females was twice as frequent as in males, which they were able in part to attribute to knee height, and the subsequent increases in torsion stresses, and muscle strength differences between the sexes. Yet David Felson and colleagues (2002) found that anatomical variation between Caucasians and Chinese could not explain the knee osteoarthritis differences in females. The bowing of the legs, however, did affect the male osteoarthritis pattern. Others have suggested that sex difference in knee osteoarthritis is also linked to cartilage volume; males, it appears, have thicker cartilage than females (Jones et al., 2000). Thus, even with the same mechanical forces, females would get osteoarthritis more often and sooner. A shallow acetabulum can also affect osteoarthritis; shallow acetabula increase the risk of hip **dysplasia** (dislocation) and thereby also increase secondary hip osteoarthritis (Weiss and Jurmain, 2007). All of the factors are in large part controlled by genes; limb length, although affected by nutrition, is strongly heritable. Cartilage thickness too is likely controlled by genes.

Inflammation

Perhaps one of the strongest arguments for mechanical factors influencing osteoarthritis is the strong correlation of osteoarthritis with obesity. Although past populations likely had very few obese individuals, understanding the effect of body weight on osteoarthritis can help anthropologists determine osteoarthritis etiology. In an exception to the lack of obesity in the past, an eighteenth- to nineteenth-century Lithuanian mummy who was obese was found to have knee osteoarthritis (Piombino-Mascali et al., 2014).

In weight-bearing joints, obesity and even a general increase in body mass index has repeatedly been found to increase osteoarthritis frequency and severity (e.g., Cicuttini et al., 1996; Guilak, 2011; Hunter et al., 2005; Weiss, 2014b). For example, Flavia Cicuttini and colleagues (1996) looked at twin females and found that the heavier twin had more knee osteoarthritis than the lighter twin. The argument has been that the excess weight places excessive loads on the joints and, thus, results in osteoarthritis.

However, not all researchers (e.g., Gabay et al., 2008) attribute mechanical factors to obesity's impact on joints. According to experimental research, a joint can normally withstand millions of cycles of loading with up to 10 times an individual's body weight (Guilak, 2011; Hamrick, 1999). Some evidence that weight's effect may be more complex than simple loading comes from studies that have linked obesity to hand osteoarthritis (Berenbaum and Sellam, 2008; Kalichman et al., 2005). For instance, Kalichman and colleagues (2005) found that body mass index correlated with hand osteoarthritis in a huge sample of 12,000 individuals.

Additionally, osteoarthritis has been suggested to be a **systemic disease** (a disease that effects the entire body) caused by inflammation. Multiple joints are often affected in a single individual (e.g., Cushingham and Dieppe, 1991; Ding et al., 2003; Maillefert et al., 2003). Females seem more often affected by systemic osteoarthritis than males; J. F. Maillefert and colleagues (2003), for instance, found that when examining hip osteoarthritis in a sample of 508, females were also likely to have osteoarthritis in other joints that were completely unrelated to the lower limb.

If it is not weight's mechanical stresses causing osteoarthritis in obese individuals, then it may be inflammation. **Adipose tissue** (i.e., the loose connective tissue in which fat cells accumulate) is a source of inflammation since inflammatory cytokines can be produced in fat (Guilak, 2011).

Females tend to have more adipose than males, which may help to explain the link to systemic osteoarthritis sex differences too. Furthermore, leptin, a protein found in adipose tissue, has the capacity to stimulate bone formation, which may be why one of the features of osteoarthritis is osteophyte formation (Grabiner, 2004). Leptin has been linked to osteoarthritis formation in animal clinical research (Dumond et al., 2003).

Yet, by all accounts, obesity is a recent medical problem and therefore not likely to explain osteoarthritis in past populations. It may be that the inflammatory causes of osteoarthritis in past populations were unrelated to leptin but rather inflammation may have occurred as a result of overuse. **Mechanoreceptors** (sense organs that respond to mechanical stimulus) can stimulate cytokines too (Berenbaum and Sellam, 2008). Moderate exercise seems to be good for joint maintenance; yet the extracellular matrix is very sensitive to loading signals; thus, excessive exercise is actually bad for joints. Additionally, inflammation of the extracellular matrix (or synovium) occurs after injuries even when injuries are minor. For example, with **meniscus** tears, inflammation and collagen loss occurs quickly (Goldring, 2012). Abnormal loads can also induce catabolic and inflammatory-related responses. Thus, perhaps the main causes of osteoarthritis in past populations differ from causes of osteoarthritis in modern populations (Vanna, 2007).

Other inflammatory-response-related events such as diseases may also be linked to osteoarthritis. R. L. Blakely and B. Detweiler-Blakely (1989) have reported that **rubella** (a contagious virus also known as German measles), for example, can cause secondary osteoarthritis in small joints. Infectious diseases were likely prevalent in many prehistoric and, indeed, historic populations.

Genes

Genetic factors may also play a role in osteoarthritis etiology. Genes can influence osteoarthritis in numerous ways. Guangju Zhai and colleagues (2004), for instance, found high heritability in muscle strength, cartilage volume, and bone size. These factors influence knee osteoarthritis even when controlling for age, sex, weight, and height. About 60% of knee osteoarthritis etiology can be attributed to genetic factors. Tim Spector and Alex MacGregor (2004) reviewed the literature on monozygotic (or identical) and dizygotic (or fraternal) twins and concluded that heritability of osteoarthritis varies by the joint affected. **Heritability** is the proportion of observed variation in a trait that can be attributed to inherited genetic factors rather than environmental factors. The knee and vertebral column joints have greater heritability than upper-limb joints. For example, knee heritability runs at around 65% whereas the heritability of hand osteoarthritis is 39%. Weiss and Jurmain (2007) advised against using vertebral bones to examine activity patterns due to the high heritability of spinal osteoarthritis. Remarkably, knee osteoarthritis is common in modern populations whereas it was less prevalent in past populations (Waldron, 1995). And joints that have low heritability, such as the elbow, have higher rates in past populations, which again suggests that the main causes of osteoarthritis in past populations may differ from the main causes in modern populations. Females, it appears, have higher heritability rates than males, which may be related to epigenetic effects of estrogen and adipose tissue (see Weiss and Jurmain, 2007).

Recent research has suggested that **polymorphisms** (the existence of genes in several allelic forms) in some **pleiotropic** genes (in reference to single genes that code for more than one trait) may be related to osteoarthritis (see Weiss and Jurmain, 2007; Spector and MacGregor, 2004). Josine Min and colleagues (2005), for example, looked at G-allele of R32HG and found one variant was associated with multijoint osteoarthritis. **Single nucleotide polymorphisms** are variations (also referred to as alleles) on genes in which one nucleotide base is changed. The first evidence of genetic variation caused osteoarthritis occurred in the type II collagen gene, which is named COL2A1 (Holderbaum et al., 1999). This gene was linked to early-onset systemic osteoarthritis in a Michigan family; since this discovery, other families with the same gene variant have been found, and they too have early-onset systemic osteoarthritis. The gene variant also affects spinal dislocation. In this allele, arginine-519 has been replaced with cytosine on the twelfth chromosome (Holderbaum et al., 1999). Other similar genetic mutations have also been linked to osteoarthritis. For example, the genetic mutation that causes **Stickler syndrome**, which has symptoms that include eye problems, deafness, and flat facial features, also causes early-onset osteoarthritis. There are 13 COL2A1 mutations that have been found to result in osteoarthritis. Other chromosomal loci that may affect osteoarthritis are those involved in vitamin D receptors.

Still, some researchers question whether the osteoarthritis seen in people with these genetic mutations is actually osteoarthritis or rather another joint disorder, especially since the diseases associated with some of the mutations are rare and yet osteoarthritis is so common (Spector and MacGregor, 2004).

Summary

Osteoarthritis has been extensively studied. In the anthropological literature, osteoarthritis has been found going as far back as 1.76 million years ago on the foot of OH8, an early hominid who was likely a robust australopithecine (Weiss, 2012b). It has been assumed that osteoarthritis is related to wear and tear, but osteoarthritis etiology is truly multifactorial. Since osteoarthritis etiology is multifactorial, determining how much of the physical manifestations of osteoarthritis on bones relates to activity is difficult. There are many non-activity-related etiological factors, and joints can withstand a great deal of stress. However, clinical research is often conducted on samples who led vastly different lives than past peoples. Velissaria Vanna (2007) has suggested that biological effects override cultural or activity effects in modern samples, but the same cannot be concluded about past populations, who likely worked early in their lives and harder throughout their lives. Trends in osteoarthritis suggest that joints now uncommonly affected were commonly affected in past populations; these joints, perhaps not coincidentally, have lower heritability rates and are less frequently associated with systemic osteoarthritis and body mass index. However, the osteoarthritis seen in skeletal remains may not always be related to overuse; trauma may have affected many individuals. And, like in entheseal changes, diseases such as DISH could hide or be mistaken for osteoarthritis (Maat et al., 1995).

The omnipresence of osteoarthritis has led to the question of whether osteoarthritis is truly a disease or simply a normal part of aging (Weiss, 2013). Perhaps osteoarthritis has an adaptive purpose; research into the inverse relationship between osteoarthritis and osteoporosis has led to an evolutionary explanation of why osteoarthritis is so common. Osteoporosis is one of the most common afflictions in elderly individuals, and yet a broken bone can result in death. The evolutionary theory, on the other hand, fails since osteoporosis occurs in postreproductive individuals and thus does not affect the ability to pass on one's genes. Plus, David Burr and colleagues (1983) discovered that osteoarthritis severity was actually higher in osteoporotic females in Alaskan Eskimos; they concluded that although osteoarthritis severity is high in males with high bone mineral content, osteoarthritis and osteoporosis are not inversely related in females. Both diseases are related to aging.

Thus, with osteoarthritis's multifactorial etiology, it is not a perfect activity indicator, but with age controls and considering joints less likely to be affected by nonactivity factors such as heritability, osteoarthritis can still be used to draw conclusions about levels of activity rather than specific activities. To enhance osteoarthritis research, anthropologists may wish to avoid including spinal osteoarthritis in their analyses on activity even though vertebral osteoarthritis is one of the most commonly studied skeletal indicators of activity. Standardization of diagnoses should be attempted; eburnation-only research methods fail to catch all osteoarthritis cases, and eburnation is more tightly linked to severity of osteoarthritis than to presence or absence of osteoarthritis. Porosity alone should also be excluded since it is not solely linked to osteoarthritis. Finally, osteophytes are good indicators of osteoarthritis presence, but they are also strongly correlated with age; thus, age controls (which will never be ideal) must be attempted.

5

STRESS FRACTURES

Stress fractures, which are also known as fatigue fractures, are fractures of bones that result from microcracks caused by repetitive forces that accumulate, leading to a larger crack and likely a complete break. However, sometimes stress fractures can be linked to an acute traumatic event, an injury that resulted from carrying heavy loads (sometimes caused by inexperience in the workforce), or even an accident. Additionally, some stress fractures tend to have specific cross-cultural patterns that suggest that biological factors are at play in stress fracture etiology; in other words, activity alone cannot explain all stress fracture occurrences.

Most stress fractures occur in the vertebrae or lower limbs. For example, in runners and soldiers, stress fractures often occur in the distal tibia and fibula (the thin lateral lower leg bone) (Czarnecki et al., 1988; Tam et al., 2014). Runners may also experience sacral (related to the bone that sits between the two pelvic bones) stress fractures, which could relate to asymmetry in the long bones (Czarnecki et al., 1988). Foot bone stress fractures have been around even before *Homo sapiens* evolved. Laura Martin-Francés and colleagues (2015) found a stress fracture in the fourth metatarsal (a bone of the foot) of a 780,000-year-old *Homo antecessor*, which the authors attributed to extensive walking. Even dinosaurs have been found to have experienced stress fractures in their feet (Rothschild and Tanke, 1992).

Upper-limb stress fractures have also been reported on. For example, Luigi Capasso and colleagues (1999) have written about a hand fracture at the first metacarpal (a bone of the palm) that has been linked to grasping saddle horns; it has been named the "cowboy thumb fracture." Margaret Judd (2008) outlined how to identify the differences between a **parry fracture** (a fracture that occurs when trying to defend oneself from a blow to the head) and a stress fracture in the ulna. She noted that ulnar fractures are common in rowers, tennis players, and bowlers. Field-gun runners carrying heavy guns either for sport or as a military duty have been found to have bilateral fractures of the radius (Farquharson-Roberts and Fulford, 1980). And clavicular fractures may also be fatigue-related (Abbot and Hannafin, 2001). Yet nearly all stress fractures studied in the bioarchaeological record that have been thoroughly examined in regards to reconstructing activity patterns and looking at non-activity-related etiologies involve vertebrae. Thus, the rest of this chapter is on vertebral stress fractures since these fractures can be most useful in examining whether the fractures were a result of genes or environment.

Vertebral Stress Fractures

In the previous chapter we learned that vertebral osteoarthritis may not be useful in reconstructing activity patterns; therefore, anthropologists may wonder whether other vertebral variances may be used to determine past activities. There are three main types of vertebral stress fractures that bioarchaeologists commonly examine to reconstruct activities: **spondylolysis**, **Schmorl's nodes**, and **clay-shoveler's fractures**. Although spondylolysis and clay-shoveler's fractures are true fractures, Schmorl's nodes are better understood as hernias.

Methods of Identification

In nearly all stress fracture and Schmorl's node research on skeletal remains, the features are identifiable through macroscopic examinations (e.g., Jordana et al., 2006; Mays, 2007; Šlaus et al., 2004). Judd's (2008) seminal article on identifying parry fractures has helped bioarchaeologists diagnose stress fractures too. The fractures are easily spotted, especially since many of them do not heal completely, which has been assumed to be because of the repetitive stresses caused by movement that keep the bones apart (Masharawi et al., 2007). Stress fractures, unlike many other fractures, perimortem injuries, and postmortem breaks, tend to have smooth margins and sometimes pseudarthroses (Judd, 2008). **Pseudarthroses** occurs when cartilage forms over the fracture elements and a fake joint develops; this abnormal union is formed by a fibrous tissue between the parts of bone that have been fractured. Stress fractures often have perfect alignment because the break occurs in the direction of the repeated stresses (Judd, 2008).

Most studies employ binary absent or present coding with stress fractures, but some studies use three categories for Schmorl's nodes—absent, present, and severe (e.g., Plomp et al., 2012). The severity is measured by the size and depth of the hernia. Additionally, for many studies, which vertebrae are affected, whether healing is present, and the location and symmetry of the fracture are noted.

Ironically, although stress fractures are easily identified in skeletons, seeing them in living people, such as patients in a clinical setting, can be difficult (Cancelmo, 1972; Fibiger and Knüsel, 2005; Merbs, 1996a). Often the two parts of the bone are held together by ligaments and muscles and thus cannot be detected with simple X-rays (Yamaguchi et al., 2012). Hence, medical doctors may use magnetic resonance imaging and other advanced imaging techniques to help find, diagnose, and suggest treatment for stress fractures (Western and Bekvalac, 2015; Williams et al., 2007; Wilms et al., 2012). But looking for specific features on an X-ray can also help doctors. For instance, a "double" spinous process (the bony projection off the posterior of each vertebrae) shadow in an X-ray may reveal a clay-shoveler's fracture (Cancelmo, 1972). Additionally, X-rays taken at multiple planes can improve diagnostics (Cancelmo, 1972).

Linda Fibiger and Christopher Knüsel (2005), in their highly regarded study of spondylolysis stress fractures, have noted some issues with comparing stress fracture rates. Unlike what we have seen for entheseal changes and osteoarthritis, stress fracture identification interobserver and intraobserver error rates are low among bioarchaeologists (Fibiger and Knüsel, 2005). Nevertheless, comparing rates of stress fractures from one population to another can be difficult since anthropologists determine the rates differently. For instance, some may count the number of individuals afflicted while others may count the number of vertebrae with stress fractures (Fibiger and Knüsel, 2005). Even counting methods that are similar, such as counting individuals with entire vertebral columns compared to counting individuals with partially preserved columns, may result in very different population rates (Fibiger and Knüsel, 2005).

Despite these complications, anthropologists have undertaken many research studies of vertebral stress fractures to understand activity patterns and other possible causes of stress fractures in past populations.

Spondylolysis

The most common stress fracture in the archaeological record is spondylolysis (Merbs, 1996a). Figure 5.1 illustrates an example of spondylolysis. It is also the most common overuse injury among athletes (Stasinopoulos, 2004). “Spondylo-” refers to “back” in Latin whereas “-lysis” means dissolution (Merbs, 1996a). Spondylolysis is a descriptive term rather than an etiological one (Merbs, 1996a). The fracture occurs when the vertebral arch, which is the back part of the vertebra, separates from the round anterior part of the vertebra called the body.

Figure 5.1. Spondylolysis. This is an example of a complete bilateral separation of the neural arch from the vertebral body. In a living individual, the two separated parts of the vertebra would be held together by soft tissue.

There are multiple types of spondylolysis. Spondylolysis can be atypical, which means it comes from trauma or a pathology or is congenital. On the other hand, spondylolysis can be typical, which means it results from stress. Anthropologists who examine spondylolysis tend to focus on typical spondylolysis to reconstruct activity patterns.

Spondylolysis occurs mainly in the lumbar (or lower) vertebrae; specifically, it is most commonly found in the fifth lumbar followed by the fourth lumbar (Merbs, 1996a). However, it can also be found in other lumbar vertebrae and in the sacrum (e.g., Merbs, 1996b).

It has been assumed that spondylolysis is a process rather than an event or condition, and at the end of the process there may be complete bilateral separation of the isthmus (or pars interarticularis) from the vertebral body (Merbs, 2002). The **isthmus** is a part of the vertebral arch that consists of a thin segment of bone that connects the lateral joints of the spine. Consequently, most spondylolysis is symmetrical when identified by clinicians (e.g., El-Rassi et al., 2005; Leone et al., 2011). Unilateral (also known as asymmetrical) spondylolysis may reflect that the process has not yet been completed or that healing has occurred (Leone et al., 2011; Merbs, 2002).

Activity-Related Etiology

In examining spondylolysis, many anthropologists have relied on clinical research to determine what activities may cause spondylolysis. Clinicians have found that spondylolysis is frequent in participants of soccer (Stasinopoulos, 2004), rugby or American football (Sakai et al., 2010), judo (Sasa et al., 2009), and sports that require hyperextension (extension beyond the normal range of motion) of the hip, such as gymnastics, and torsion of the hip, such as baseball (Stasinopoulos, 2004). Weight lifting and doing squats have also been linked to spondylolysis (Lessa, 2011).

In the sports literature, adolescent athletes are reported as being at greater risk for spondylolysis than adult athletes (Álvarez-Díaz et al., 2011). Dimitrios Stasinopoulos (2004), in his thorough review of the sports literature, found that by some estimates, up to 47% of adolescent athletes may experience spondylolysis. Clinical researchers are not in total agreement when it comes to the cause of spondylolysis. Although some clinical researchers surmise that spondylolysis results from stress over time even in adult athletes (e.g., Reitman et al., 2002; Leone et al., 2011), others suggest that spondylolysis can be caused by one acute trauma (van der Heijden et al., 2007).

Research reported in sports literature, however, is not the only type of research linking spondylolysis with activities. Experimental tests on lumbar bones have also revealed that spondylolysis fractures can be created with torsion and flexion stresses (see Merbs, 1996a). Other experimental studies, highlighted by Charles Merbs (1996a), done on cadavers have illustrated that spondylolysis can result from hyperextension. These studies suggest spondylolysis etiology is in large part activity related.

Division of Labor in the Past

Armed with the experimental and sports literature, anthropologists have used spondylolysis to reconstruct activity patterns in past populations. Examples of activities in the archaeological record that have been linked to spondylolysis include carrying heavy loads among Cambodians from 400 BC to 200 BC (e.g., Pietrusewsky and Ikehara-Quebral, 2007), California Amerinds hunting with harpoons (Pilloud and Canzonieri, 2014), stooping posture among Northeastern Nebraskan Natives (Reinhard et al., 1994), and spear throwing in prehistoric coastal Brazilian peoples (Lessa, 2011). Perhaps one of the most iconic activities linked to spondylolysis in the bioarchaeological record is T. D. Stewart's (1953) linkage of spondylolysis to the Eskimo habit of bending at the hip. In an even earlier study, E. Barclay-Smith (1911) suggests that a female's skeleton from Egypt's Ptolemaic period (also known as the Hellenistic period) dating between 600 BC and 500 BC received spondylolysis as a result of being a contortionist; this young female had a slew of vertebral anomalies that could have occurred as a result of being a contortionist, or these anomalies could have enabled her to bend her body in ways that someone without these anomalies could not do. At the end of the article, Barclay-Smith notes that this skeleton reminds him of artwork that depicted female acrobats carved in a nearby tomb.

In addition to specific activities, trends in sex differences and temporal differences have frequently been addressed (e.g., Arriaza, 1997; Jiménez-Brobeil et al., 2010; Sakai et al., 2010). For example, Bernardo Arriaza (1997) found high rates of spondylolysis in a Guam population from AD 1200 to AD 1521; eight of the 38 spines examined had evidence of spondylolysis. Males were two times more likely to have spondylolysis than females, but this sex difference was not statistically significant due to the small sample size. Arriaza attributes the high male spondylolysis rate to the activity of erecting fourteen-ton stone pillars that supported the wood houses. Arriaza acknowledges that since moving the pillars would not have been a daily task, acute trauma may have caused some of the spondylolysis fractures. Michael Pietrusewsky and colleagues (1997) also support that sex differences may be related to sexual division of labor in the Guam Mariana Island sample of indigenous Chamorro peoples.

Other studies that link high spondylolysis rates in males compared to females also suggest this difference is likely due to activity pattern differences. For instance, Andrea Lessa (2011) found high spondylolysis rates in males compared to females in a pre-Columbian Brazilian coastal hunter-gather-fisher population. Lessa suggests that the spondylolysis in males may have resulted from harpooning or spear throwing. Plus, Merbs' (1996b) examination of sacral spondylolysis among Canadian and Alaska Inuit links sex differences to weight lifting, kayak paddling, and harpooning; evidence of these activities exists in both the archaeological record and from ethnographic accounts of Inuit culture. S. A. Jiménez-Brobeil and colleagues (2010) looked at a sample of more than 100 individuals from Bronze Age Spain and link the three cases of male spondylolysis to harder labor than females would have experienced, which they support with entheseal change sex differences too. One may also wonder to what extent males' larger body size would accommodate harder labor; in other words, is it really a sex difference if males and females do different levels of labor but in proportion to their body builds?

The sex differences do not always reflect higher rates of spondylolysis in males compared to females. In a 200 BC to AD 400 Cambodian sample, for example, spondylolysis was only found in female lumbar vertebrae, which the authors attributed to carrying heavy loads (Pietrusewsky and Ikehara-Quebral, 2007). Amanda Agnew and Hedy Justus (2014) found spondylolysis in medieval Poland equally in both sexes, which they ascribed to heavy lifting.

In addition to relating sex differences to sexual division of labor, some anthropologists have used spondylolysis rates over time to assess effects of cultural changes, such as subsistence patterns and contact with Europeans. In a study of Omaha Native American fur traders, Karl Reinhard and colleagues (1994) and Kari Sandness and Reinhard (1992) noted that after contact with Europeans, physical labor likely increased, as seen in high spondylolysis and osteoarthritis rates. Heavy lifting and stooped posture were associated with these stress fractures.

In a study that looked at spondylolysis in the United Kingdom over time, H. A. Waldron (1991), who has excelled at determining rates of skeletal indicators over long periods of time, found that spondylolysis rates decreased from 5.08% in medieval times to 1.42% in the eighteenth and nineteenth centuries. The medieval rate was similar to earlier periods; Waldron suggests that physical labor was lowest in the most recent sample, and this decrease in labor accounts for the lower stress fracture rates. Fibiger and Knüsel (2005) also found a decrease in spondylolysis in the United Kingdom from the thirteenth century to the nineteenth century, but they acknowledge that comparisons can be difficult since spondylolysis is easily missed in X-rays, and even within skeletal samples there are multiple ways to calculate the percentage of the sample afflicted. Still, Fibiger and Knüsel agreed with Waldron (1991) in that U.K. bioarchaeological rates—even if they are underestimated—are low compared to other bioarchaeological samples.

Cross-Cultural Patterns

Although cultural variation in spondylolysis frequency exists with some populations exhibiting rates of less than 5% (e.g., Waldron, 1991) and other populations exhibiting rates of up to 50% (see Merbs, 1996a), there are cross-cultural similarities. For instance, as mentioned before, the fifth lumbar is most commonly affected; the next most-often affected vertebrae is the fourth lumbar (Merbs, 1996a). Merbs, who has published extensively on spondylolysis, has suggested that these cross-cultural patterns are a result of bipedality and work to increase flexibility in the lower back. Yet, as Merbs noted, he was not the first to link spondylolysis with walking on two legs instead of four. As early as 1911, Paul Poirier associated spondylolysis with bipedality; since then, research has shown that spondylolysis has not been found in nonwalking adults, in nonhuman primates, or in individuals too young to walk. Merbs' article in the prestigious *Yearbook of Physical Anthropology* in 1996 could be said to have rebooted bioarchaeologists' interest in spondylolysis from both activity-related perspectives and investigation into other etiologies. Several key patterns of typical spondylolysis have led researchers to suggest that spondylolysis relates to bipedalism:

The 5th lumbar is most frequently affected.
Complete bilateral separation is most common.
It occurs in individuals of walking age.
It is associated with bipedality.
It is more frequent in males compared to females.

Although sex differences have been attributed to activity patterns, in most cultures males have higher rates of spondylolysis than females (Merbs, 1996a). This sex difference may relate to anatomical variation in the pelvis.

Additionally, in both bioarchaeological and clinical samples, bilateral spondylolysis seems to be more frequent. For instance, Tony Waldron (1992b) noted that unilateral spondylolysis was rare. Efstratia Syrmou and colleagues (2010) also found unilateral spondylolysis to be rare in their clinical research, but they acknowledged that spondylolysis is usually diagnosed late in comparison to when it first starts to form. And, as mentioned previously, Merbs (1996a) has suggested that spondylolysis starts on one side and progresses to bilateral separation.

Unlike osteoarthritis, spondylolysis seems not to be degenerative (Brooks et al., 2010; Mays, 2006; Suzuki, 1998), but the onset seems to be linked to adolescence. Not all researchers agree, and in a Copenhagen sample of 29- to 93-year-olds, Stig Sonne-Holm and colleagues (2007) found an increase in spondylolysis with age. Patricia Bridges (1989b), too, found more spondylolysis in older individuals in her archaic Southeastern Amerindian sample. One reason for the lack of consistency may be that some spondylolysis fractures may heal as one stops engaging in the activity that caused the stress. Another possibility is that osteoporotic bone loss increases spondylolysis risk, and the later onset in females is in part related to hormonal changes at menopause (Bridges, 1989b). Even though variation in spondylolysis between cultures exists, there are enough cross-cultural patterns noted by researchers that factors other than activity need to be considered in spondylolysis etiology.

Non-Activity-Related Etiologies

Some rare forms of diseases seem to increase spondylolysis risk; for instance, **pycnodysostosis**, which is an inherited form of skeletal dysplasia, has been found to increase spondylolysis risk (Ornetti et al., 2008). This disease and others like it usually result in dense, sclerotic bones that are

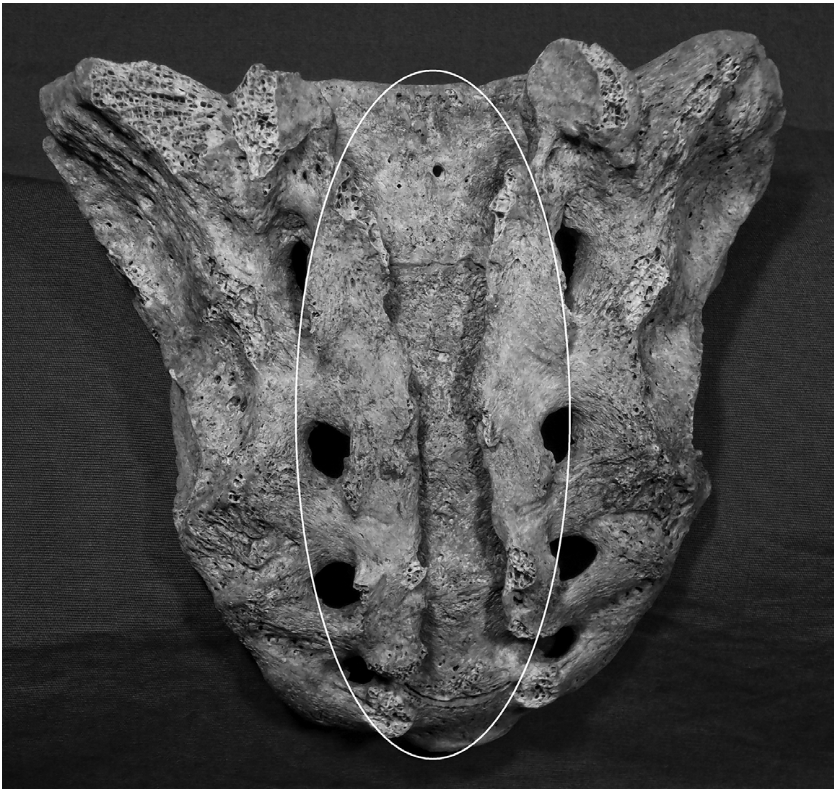

Figure 5.2. Spina bifida occulta. This minor form of spina bifida, a congenital lack of fusion of the sacrum, has been associated with spondylolysis.

brittle and likely to fracture. Toshinori Sakai and colleagues (2010) noted that 70% of osteopetrosis individuals have spondylolysis. Yet the rarity of these diseases makes it highly improbable that the spondylolysis found in the bioarchaeological record resulted from diseases that induce brittle bones.

Other studies have looked to more common diseases or anomalies to understand spondylolysis etiology. A commonly found disorder in the bioarchaeological record is spina bifida occulta. **Spina bifida** is a congenital (birth) defect in which there is a failure of the vertebral arches to fuse at the spinous processes, and the spinal cord is exposed; it can be a result of inbreeding or a maternal deficiency in folate (vitamin B12). This nutritional deficiency in mothers-to-be has been linked to causing epigenetic changes in growth and development of the fetus. Although spina bifida can be severe enough to cause fetal death and therefore is not often found in the bioarchaeological record, less severe forms of spina bifida are common. **Spina bifida occulta**, which is an open sacral spinal column, may or may not result in symptoms (see Figure 5.2). Due to its high prevalence in the archaeological record, spina bifida occulta has been studied for its relationship to spondylolysis. Sakai and colleagues (2010) found that spina bifida occulta increases the risk of spondylolysis by 3.7 times. S. Eisenstein (1978) examined the Raymond Dart autopsy collection from South Africa's University of Witwatersrand for a spina bifida and spondylolysis correlation. He found that, in this sample of 485 individuals who were collected between 1920 and 1958, 11.8% of individuals with spina bifida occulta had spondylolysis, whereas less than 2% of those without spina bifida occulta had spondylolysis. The fact that spina bifida occulta increases the risk of spondylolysis implies that other vertebral variants may explain spondylolysis rates.

Transitional lumbar and sacral vertebral anatomical variation has also been examined in relation to spondylolysis; Figure 5.3 displays an example of this variation. **Sacralization** (in which the last lumbar is morphologically similar to the sacrum) and **lumbarization** (in which the first sacral segment is similar to the lumbar vertebrae) are two developmental variants commonly found in skeletal samples. They are not likely to cause pain, but they can increase or decrease flexibility. Transitional vertebrae are likely inherited and related to growth genes. Elizabeth Weiss (2009b) found that males in a California hunter-gatherer population with lumbarization were more likely to have spondylolysis than other males. Merbs (1983) noted that the increase in pre-sacral length was tied to spondylolysis risk likely because of the extra stresses experienced by these more flexible lower backs. Thus, the anatomical variation, which is genetically determined, increases mechanical loading and increases spondylolysis risk. This environment and gene interaction is similar to the one that I mention in chapter 4 in relation to interplay of tibial length, torsion, and knee osteoarthritis.

More subtle anatomical variation may also increase spondylolysis risk (e.g., Masharawi et al., 2007; Sonne-Holm et al., 2007; Ward et al., 2010; Ward and Latimer, 2005). Anatomical correlates with spondylolysis have been discovered in clinical (e.g., Sonne-Holm et al., 2007) and skeletal samples (e.g., Mays, 2006; Ward et al., 2010). For instance, **lordosis**, which is pronounced lower back curvature, also known as swayback, has been

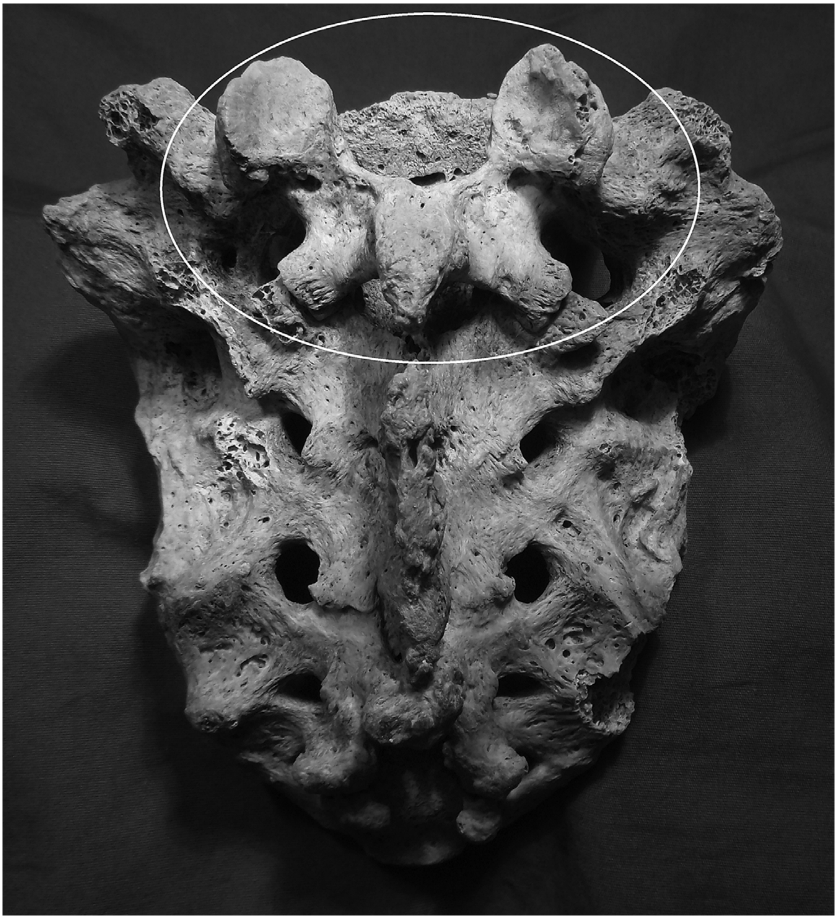

Figure 5.3. Sacral anatomical variation. Transitional vertebrae, such as the case of lumbarization shown here, have been associated with spondylolysis.

found to increase spondylolysis in a clinical sample from Copenhagen (Sonne-Holm et al., 2007).

Both articular facet spacing and orientation seem to affect spondylolysis risk. In the Hamann-Todd collection, spacing between vertical articular facets in the form of narrow lumbar vertebral bones increased spondylolysis risk (Ward et al., 2010). Carol Ward and colleagues noted that adults with an insufficient caudal increase in mediolateral spacing between the right and left vertebral articular facets on the fifth lumbar and first sacral segment had an increased risk of spondylolysis. And, Youssef Masharawi and colleagues (2007) discovered that the orientation of the lumbar facets could affect spondylolysis risk by altering compressive stresses. They observed that individuals with more frontally oriented facets were more likely to have spondylolysis. Furthermore, Masharawi and colleagues found that asymmetry in facets was also linked to spondylolysis. Another stress-related finding in anatomy comes from Navkirat Bajwa and colleagues (2012), who found that pedicle length increased spondylolysis risk, which they attribute to an increase in shear forces at the isthmus.

Sacral angle orientation varies naturally and affects the distance between facets along with the connectivity of the pelvis. Mays (2006) found that when the **sacral table** (the top part of the sacrum that articulates with the last lumbar vertebra) inclines and affects the sacrum's connections with the pelvis, spondylolysis risk in both the Wharram Percy medieval U.K. sample and in clinical samples was increased. In a similar study using a large sample of more than 2,000 individuals from the Hamann-Todd collection, Smadar Peleg and colleagues (2009) found that a higher risk of spondylolysis was associated with a horizontally oriented sacral table. It appears that this smaller angle can cause a pinching effect on the vertebral arch.

Research has found family patterns of spondylolysis that strongly imply spondylolysis risk is inherited. For example, Antonio Maria Leone and colleagues (2011) found that within family heritability rates near 70%. Yet what is being inherited is difficult to assess (Merbs, 1996a). As mentioned previously, anatomical variants are very likely inherited, so although the variants may affect mechanical loading, the root cause of the spondylolysis is connected to genes.

A common interpretation of the reason for increased spondylolysis risk in these myriad anatomical variations is that stress on the lower back is increased. Stress caused by activity patterns may have the same effects on vertebrae. As has been suggested for osteoarthritis, it is possible that past population spondylolysis was more likely activity related due to the intensity of the activities than spondylolysis in modern populations, except that of young athletes. Sports among adolescents have become more intense and competitive over the last five decades, which has resulted in a dramatic increase in stress fractures and injuries in young people (see Weiss, 2014c, for a discussion of this issue).

Although spondylolysis may in large part be activity related, one must still be cautious about attributing spondylolysis to specific activities since torsion, flexion, compression, extension, and shearing have all been found to be associated with spondylolysis. Many anthropologists are well aware of this issue and, accordingly, use spondylolysis and other stress fractures as general physical activity indicators (e.g., Cybulski, 1988; Meyer et al., 2013; Stevens and Leader, 2006; Suzuki, 1998; Waldron, 1991) rather than linking to specific activities. When specific activities are reconstructed, archaeological and historical information helps bioarchaeologists narrow down the possible specific causes (e.g., Arriaza, 1997; Lessa, 2011).

Schmorl's Nodes

Another indicator of general stress that is often combined with spondylolysis rates is Schmorl's node frequency. Schmorl's nodes are round to oval depressions on the inferior or superior surface of the vertebral body that are caused by a **herniation** (an abnormal protrusion of a body structure) of the **nucleus pulpous** (or intervertebral disk) past the thin cortical bone layer and into the trabecular bone of the vertebral body. Photos in Figure 5.4 show a variety of Schmorl's nodes. These vertical herniations occur most often in the lower thoracic (middle back) and upper lumbar bones (Kyere et al., 2012; Plomp et al., 2015a). Schmorl's nodes have been found in skeletal remains from 7,000 years before present to the twentieth century (Faccia and Williams, 2008).

Activity Levels in Past Populations

The etiology of these Schmorl's nodes, which were named after their discoverer, Georg Schmorl, in 1927, remains elusive (Plomp et al., 2015a). It appears that, like spondylolysis, Schmorl's node etiology is multifactorial with physical strain included as a possible cause, but developmental problems, genetic predisposition, and vertebral disk composition have also been implicated in Schmorl's node formation (Plomp et al., 2015a).

Military research has found high rates of Schmorl's nodes, with 74% of individuals affected compared to a civilian rate of 19% (Burke, 2012). Kelly Burke suggested that this high rate of Schmorl's nodes found in the Central Identification lab sample of military personnel reflects trauma experienced by those serving in the armed forces. Kwaku Kyere and colleagues (2012) also tied Schmorl's nodes to trauma; in a review of gymnasts compared to nongymnast controls, Kyere and colleagues noted that

Figure 5.4. Schmorl's nodes. These photographs illustrate the variation in Schmorl's nodes that can be found in skeletal samples.

71% of the gymnasts had Schmorl's nodes whereas 44% of the controls did. The high rate among gymnasts was suggested to be a result of microtrauma. It is interesting to note the high rate of Schmorl's nodes in the control sample; one question that arises with Schmorl's nodes and spondylolysis is whether these features cause pain. In young athletes, they are often found due to pain the individuals experience, but high rates of Schmorl's nodes in nonpained individuals are prevalent in some studies too (e.g., Stasinopoulos, 2004; see Weiss, 2014c, discussion on back pains). Plus, conservative treatment of rest seems to be preferred by most clinicians for both types of stress fractures, which implies that the pain may be muscle related rather than a result of the fractures or hernias themselves (e.g., Álvarez-Díaz et al., 2011).

As mentioned earlier, anthropologists have most frequently combined Schmorl's node data with other activity indicators to write about overall activity levels in past populations. For instance, Jerome Cybulski (1988) noted that a Quebec prisoner-of-war sample dated between AD 1746 and AD 1747 had high rates of spondylolysis at 18.5%, and nearly three out of four individuals had Schmorl's nodes. Cybulski related these findings to the heavy activity during the war, and agricultural duties prior to these military duties would also have been labor-intensive. Sandness and Reinhard (1992) found that strenuous activities of postcontact Nebraskans led to an increase in activity indications, including spondylolysis, osteoarthritis, and Schmorl's nodes. In the precontact population, 16.7% of individuals had Schmorl's nodes; once Europeans had engaged with the Nebraskan Amerinds, strenuous activities such as an increase in trade and horseback riding led to a Schmorl's node rate of 42.8%. Rachel Wentz and Nancy De Grummond (2009) also linked horseback riding to Schmorl's nodes formation in Black Sea Scythaian nomads of the fourth and fifth century.

Some researchers have, however, focused solely on Schmorl's nodes to reconstruct activity patterns. For instance, Mario Šlaus and colleagues (2004), Mario Novak and colleagues (2009) and Novak (2011) examined skeletal remains from eighteenth- and nineteenth-century Croatia and linked higher male rates of Schmorl's nodes compared to female rates to sexual division of labor. Furthermore, Novak and colleagues (2009) concluded that the lower degree of sex differences in an urban sample was related to the less physically demanding city lifestyle compared to the rural population. Yet some anthropologists allow that anatomy, size, and hormonal differences may impact sex differences in Schmorl's nodes expression.

Non-Activity-Related Etiologies

As in spondylolysis research, a number of anthropologists, such as Anja Meyer and colleagues (2013) and Plomp and colleagues (2015a), have suggested that high Schmorl's nodes rates may be in part related to non-activity factors, such as a lack of calcium or anatomical variation. As with spondylolysis, examinations of vertebral anatomy have also been undertaken to determine whether factors other than activities may explain Schmorl's node formation. Plomp and colleagues (2012), looking at a medieval United Kingdom population, found that Schmorl's nodes are correlated with vertebral shape; with a 91% accuracy rate, the authors used shape to predict whether skeletal individuals would have a Schmorl's node. Large circular vertebral bodies were most likely to be affected by one of these hernias. They suggest that the reason for large vertebral bodies to be predisposed to Schmorl's nodes lies in **Laplace's law**, which states that the ability for a fluid-filled tube to resist tension is decreased with an increased radius. Thus, the intervertebral disk, which is like a fluid-filled tube, will be stronger in smaller vertebrae if tension forces are applied.

Another anatomical variant that has been linked to an increase in Schmorl's node risk is short **pedicle length**, which is the length of the segment between the transverse process and the vertebral body. It appears that short pedicles may not adequately buttress the vertebrae from stresses when the vertebral body is large (Plomp et al., 2015a). This combination of short pedicles and large circular vertebral bodies as a risk factor for Schmorl's nodes has been reported in both clinical and skeletal studies (see Plomp et al., 2015a).

Developmental abnormalities have also been suggested to affect Schmorl's node rates; for instance, flawed notochord regression may weaken the vertebral cortical bone (Saluja et al., 1986). The **notochord** is a long flexible rod of cells that forms the support axis of the body in higher vertebrates (animals with backbones). The notochord is almost reduced to nothing in adults as the bony vertebral column develops. Schmorl's nodes may form at the center of the endplate and arise because of incomplete notochord regression. **Endplates** are the superior and inferior portions of the vertebral bodies that abut the intervertebral disks. Furthermore, juvenile **kyphosis** (or hunched back), which is sometimes called **Scheuermann's disease** has been linked to Schmorl's nodes, but researchers are unsure whether Schmorl's nodes cause the kyphosis or whether the kyphosis causes Schmorl's nodes (Faccia and Williams, 2008; Saluja et al., 1986).

Although most Schmorl's nodes are considered **idiopathic** (or of unknown etiology), perhaps the most convincing evidence that Schmorl's nodes are not activity related but rather due to genes comes from twins. Looking at female monozygotic twins and dizygotic twins in a classic twin study design, Frances Williams and colleagues (2007) found that 30% of the females had Schmorl's nodes and that Schmorl's node heritability was 80%. Williams and colleagues went on to state that Schmorl's nodes are associated with juvenile kyphosis and **chondrodysplasias**, which are inherited diseases that affect cartilage development, result in dwarfism, and cause premature disk degeneration.

Clay-Shoveler's Fracture

The last of the stress fractures to be discussed is called a clay-shoveler's fracture. The **clay-shoveler's fracture** is when the spinal tip breaks off of a cervical or thoracic vertebrae. It most often occurs in the seventh cervical vertebra or the first thoracic vertebra (Knüsel et al., 1996). These fractures are **avulsions**, which means that the break occurs on a growth plate. They can occur during youth or adulthood. It is important to note that spinous process fusions occur between 17 to 25 years of age, so most clay-shoveler's fracture avulsions would occur after adult labor has begun but the individual's bones would not be fully fused, especially in past populations (Upex and Knüsel, 2009). Some researchers have suggested that youth fractures are more often associated with a single traumatic episode or disease (Knüsel et al., 1996).

While clay-shoveler's fractures have been tentatively linked to diseases, such as osteochondritis, **necrosis** (death of living tissue) of bones, and certain growth disorders, most clinicians accept that a clay-shoveler's fracture is mainly activity related (e.g., Cancelmo, 1972; Goldberg et al., 1989; Yamaguchi et al., 2012). **Osteochondritis** is a painful joint condition in which bone underneath the cartilage dies due to a lack of blood supply; osteochondritis can be genetic or related to trauma. Kent Yamaguchi and colleagues (2012), for example, note that manual laborers sometimes experience these fractures due to the forceful contraction of the powerful trapezius and rhomboid muscles of the back on the fairly fragile spinous process. Activity and trauma that result in hyperextension of the neck, such as car accidents (Goldberg et al., 1989), golf swings (Kang and Lee, 2009; Kim et al., 2012), and rock climbing (Kaloostian et al., 2013), have been linked to clay-shoveler's fractures. Interestingly, both researchers who found golfers with clay-shoveler's fractures note that these were fatigue fractures rather than a result of acute trauma. The rock climbing example did not come from an individual with a rock climbing accident but rather someone who felt pain after reaching behind, which also suggests that the fracture was the result of fatigue that accumulated into a fracture (Kaloostian et al., 2013).

Although many clinical cases include acute trauma, clay-shoveler's fractures can also result from repetitive stresses (Resnick and Niwayama, 1981). In a case study coupled with a review of clay-shoveler's fractures in a chiropractic journal, Victor Feldman and Frank Astri (2001) reviewed the three types of clay-shoveler's fractures that can occur: direct fractures that result from an acute trauma; indirect fractures, which are true avulsions that can occur when growth has not ceased; and stress-related fractures. The different types of clay-shoveler's fractures, as noted by clinicians, are based on etiology; thus, bioarchaeologists would not necessarily be able to determine the type of clay-shoveler's fracture present in skeletal remains.

Most commonly, clay-shoveler's fractures have been tied to metal dipping and shoveling hard substances (Meyer et al., 2011). By one measure, 97% of clay-shoveler's fractures are related to shoveling (see Knüsel et al., 1996). Dating back to the 1930s, researchers have linked these fractures to clay-shoveling in Western Australia (Feldman and Astri, 2001).

Bioarchaeological Case Studies

Bioarchaeological studies on clay-shoveler's fractures tend to be in the form of case studies since their occurrence is rarer than the previously discussed stress fractures. For instance, Knüsel and colleagues (1996) and Gillian Stroud and Richard Kemp (1993) note that there were perhaps half a dozen discovered cases of clay-shoveler's fractures in the United Kingdom between the first and sixteenth centuries. Activity may not have been the only factor that caused the fractures in some of these individuals since the remains reported by Stroud and Kemp (1993) and Knüsel and colleagues (1996) were all male. In the three first- to fifth-century AD Romano-British skeletons, the males were all tall and may have had long and slender spines. Yet Knüsel and colleagues (1996) note that the remains were males from lay worker cemeteries.

Other cases of clay-shoveler's fractures in the bioarchaeological record include two cases in Arizona and Inuit Amerinds (Merbs, 1983). One may assume these two individuals led very different lives and, thus, clay-shoveler's fractures may not be activity related. Yet both the Arizona Amerind and the Inuit resided in environments where the earth is hard, resources are scarce, and intense physical labor was likely a daily part of life.

Xavier Jordana and colleagues (2006) reported on a single male from first- to third-century AD Spain who had a clay-shoveler's fracture with pseudarthrosis. This 30- to 40-year-old male had poorly developed entheseal changes, which suggested to the authors that he may have experienced the fracture from engaging in new labor or in an infrequent activity. Others have noted that untrained laborers may be susceptible to clay-shoveler's fractures too (Meyer et al., 2011). But there may be age confounds since fusion of the vertebral spinous process occurs at around the time strenuous labor may begin in one's life. Unfortunately, the rarity of clay-shoveler's fractures makes determining etiology difficult.

Summary

Looking at stress fractures may help anthropologists determine overall physical strains that people may have experienced. But the skeletal system is complex, and multiple etiologies are a persistent theme. In stress fractures, perhaps anatomical variation plays the greatest role in determining who gets a stress fracture and who does not. Genes likely set these anatomical variations, so more research on heritability rates is needed. Where twin studies have been conducted, heritability was found to be as high as 80%. Without further information, it is hard to draw definitive conclusions regarding activity patterns using these easily identifiable skeletal markers.

6

ACTIVITY INDICATOR FACETS

The last of the skeletal features that are reviewed are **activity indicator facets**, which can take the form of **accessory facets**, **extended facets**, or **pressure facets**. Accessory and extended facets are modifications in articular surfaces whereas pressure facets are nonarticular indentations or grooves. Anthropologists have assumed that the primary etiology of these activity indicator facets are the joint reactions caused by forces that include weight, momentum, and muscle contractions coupled with the elasticity of the connective tissues on the bone (Trinkaus, 1975). Yet, even with this explanation, understanding the mechanics of these facets has been lacking, which may be one reason why activity indicator facet research has not gained as much popularity in the anthropological literature as other activity indicators. However, activity indicator facets are still a mainstay for student research, research pertaining to case studies, and particular site description research. Additionally, some forensic anthropologists have suggested that activity facet indicators can be used to identify tribal aboriginal persons since some of the activities indicated, such as squatting, would not be engaged in by an individual of nonaboriginal descent (Byard and Simpson, 2005). Thus, although activity indicator facets are currently infrequently used in testing hypotheses regarding changes through time, population differences, division of labor by sex, and other questions frequently addressed using the other activity indicators, activity indicator facets are still commonly employed to understand activities and are assumed to be made by activity pressures. Yet these facets may be a part of normal genetic variation. This means that incorrect conclusions about activity are being drawn. Again, a fundamental rethink about what these skeletal features can and cannot tell us may be appropriate.

Methods of Identification

Accessory facets and facet extensions can be easily seen on skeletons; they, like entheseal changes, osteoarthritis, and stress fractures, are examined macroscopically, and no tools are needed to collect the data. An accessory facet is when, in addition to the usual articular locations, extra facets can be seen. These extra facets differ from the surrounding bone by having a smooth and compact appearance and a feel that mimics the features of articular bone surfaces (Boulle, 2001b; Trinkaus, 1975).

Extended facets, which occur mainly in the lower limb, the pelvis, the shoulder complex, and in the vertebral column, are visible elongations or extensions of nearby articular surfaces. Again, these extensions—like accessory facets—are similar in appearance and feel to usual articulation surfaces (Trinkaus, 1975).

In perhaps the most famous study of squatting facets, Erik Trinkaus (1975), a renowned researcher of Neanderthals, mentioned that these activity indicator facets are reaction areas that appear as dense, smooth areas of cortical bone overlying trabecular bone. The facets, consequently, are easily distinguishable from surrounding nonfacet areas. However, according to Eveline Boulle (2001b), pressure facets do not have this distinction. Pressure facets are more difficult to assess since they tend to be shallow grooves or dents in bones that are easily mistaken for normal—nonactivity and nonpathological—variation (Boulle, 2001b).

While the activity indicator facet areas may be fairly easily identified, the facets are not well defined; for instance, both **Poirier's facets** (anterior extensions of the articular surface of the femoral head) and **Allen's facets or fossae** (also known as anterior cervical imprints due to their location on the anterior of the femoral neck) are defined as imprints or indents on the anterior femoral neck that have been said to be indicators of kneeling or squatting. Nico Radi and colleagues (2013), who specifically examined the femoral neck, have developed a more refined data collection method that may help to standardize accessory facet data collection. Sebastien Villotte and Christopher Knüsel (2009), who have pioneered new methods of entheseal change research by encouraging anthropologists to employ recent clinical research to develop biologically valid data collection methods, state that to improve facet data, collection measures should be formulated based on clinical research. However, although anthropologists easily identify the facets by studying skeletal remains, clinical comparisons are hard to come by since the articular changes are difficult to spot in X-rays (Boulle, 2001b; Martus et al., 2008), and the lack of pain associated with these changes means that clinical research into activity indicator facets has been lacking. Some of these issues are present with other activity indicators covered in previous chapters; for example, the entheseal changes that have been most thoroughly studied by clinical researchers are those that may cause pain through the formation of enthesophytes, such as the fibrocartilaginous entheses at the calcaneus. One exception to the pain-free association of activity indicator facets has been found; Hisateru Niki and colleagues (2015) noted that accessory anterolateral talar facets are associated with pain in flat-footed teens who engage in athletic endeavors. In reference to the difficulty of spotting activity indicator facets on X-rays, it should be noted that if one looks closely, activity indicator facets can be seen on X-rays. In X-rays activity indicator facets that are articular appear as dense bone whereas pressure facets are indistinguishable from surrounding areas (Baykara and Yilmaz, 2007; Boulle, 2001b). Stress fractures can also be difficult to spot on X-rays; thus, like with stress fracture identification in clinical settings, close examination of X-rays is needed to find accessory facets.

Once researchers decide on their method of identification, activity indicator facets are recorded as present or absent. The binomial method of coding these activity indicators reduces observer error, but, as noted earlier, it also does not allow for many complex and powerful statistical analyses.

Activity Associations

Luigi Capasso and colleagues (1999) summarized the main types of activity indicator facets found in the bioarchaeological research, coupled with their likely activity links (see Table 6.1). In total, 19 facets are described; 15 of these occur in the lower limb. Out of these 19 facets, 16 have been tied to squatting behavior. However, Trinkaus (1975) has suggested that the actual number of squatting facets are far fewer than 16. Besides squatting, changes in articular surfaces have been linked to kneeling, sitting cross-legged, prolonged walking, running downhill, tumpline carrying, weight bearing, and fruit picking. Many of the facets have been linked to multiple behaviors. One example of these includes the extension of the distal articulation on metatarsals onto the superior surface, which has been tied to

Table 6.1. Accessory facets, facet extensions, and pressure facets

Activity indicators	Anatomical location	Activity	Alternative activity
Facies lunata enlargement	Acetabulum of the pelvis	Squatting	Sitting with crossed legs
Accessory sacral facet	Pelvis and sacrum	Carrying loads	
Poirier's facet	Anterior femoral head	Squatting	
Peritrochlear groove	Anterior distal femur	Squatting	Prolonged standing and walking
Posterior cervical imprint	Femoral neck	Squatting	Prolonged standing and walking
Charles' facet	Medial epicondyle of the femur	Squatting	
Tibial imprint	Distal medial femur	Squatting	
Martin's facet	Lateral distal femur	Squatting	
Supratrochlear facet	Anterior distal femur	Squatting	
Osteochondritic imprint	Posterior lateral distal femur	Squatting	
Posterior cruciate groove	Posterior distal femur	Squatting	
Anterior cervical imprint / Allen's fossa	Anterior femoral neck	Squatting	Walking or running downhill
Ankle flexion facet	Distal anterior tibia	Squatting	Kneeling
Trochlear extension	Medial or lateral talus	Squatting	
Squatting facets of talus	Superior lateral talus	Squatting	Walking
Facies externa accessoria corpora	Sulcus of the talus	Squatting	
Executive's foot	Distal metatarsals	Squatting	Kneeling, sitting on seat's edge
Articular extension and wedging	Proximal foot phalanges	Kneeling	
Cervical fusion and faceting	Atlas fused to occipital; cervical vertebrae 3 and 4	Tumpline use	Carrying
Baastrup's syndrome	Lumbar vertebral spines	Posture	Gymnastics
Supraglenoid articular facet	Scapular glenoid articulation	Fruit picking	

Source: Compiled from Capasso et al., 1999.

kneeling and squatting. **Baastrup's facet** (also known as kissing spines), a condition in which the spinous processes of the vertebrae touch one another and form a facet between them, has been suggested to have different etiologies based on age. And the anterior cervical imprint on the femur has been linked to squatting or walking and running downhill.

In the following pages, I review these activity indicators by their main activity. Thus, carrying, kneeling, and squatting sections follow.

Carrying

Among the early studies, Mildred Trotter (1964) examined accessory facets of the sacroiliac joint (the joint that connects the sacrum to the pelvis) to examine load carrying in East Africans. As early as 1938, T. D. Stewart linked these pelvic accessory facets to stresses and strains involved in weight bearing. Stewart (1938) examined nonhuman primate sacroiliac accessory facets compared to human sacroiliac accessory facets and found that accessory facets were common in gorillas, but these facets were in a slightly different location than in humans. Chimpanzees and orangutans, too, had accessory facets, but these were more similar in location and morphology to humans than those found in gorillas. Hylobates, the lesser apes also known as gibbons and siamangs, had no accessory facets. Stewart (1938) concluded that the facets were a combination of evolutionarily determined pelvis shape and weight bearing, with gorillas having the greatest frequency of accessory facets due to their high bodyweights. Other early studies reviewed by Trotter (1964) showed that accessory facets of the sacroiliac connection increased with age, and the facets are more often found in males compared to females. This sex difference may relate to larger male size or pelvic differences related to childbirth. It seems unlikely that these sex differences are only related to activity patterns; yet some cultures have the reverse sex difference (in which females have sacroiliac accessory facets more often than males), which does help support anthropologists' perspective that these facets may actually relate to activity patterns and not biology.

In Trotter's (1964) sample of East Africans from an autopsy collection, the accessory facets increased with age, but females were more likely to have accessory sacroiliac facets than males, which Trotter linked to female load carrying on the back. This activity is rarely seen in males in East Africa. The backload carrying often starts at a young age and includes carrying offspring, which is a female task in East Africa. Thus, Trotter put forth that the accessory sacroiliac facets are, indeed, related to activity patterns and similar conclusions could be drawn for past populations.

Ping Lai and Nancy Lovell (1992), looking at fur traders dated between 1799 and 1875 in Alberta, Canada, found accessory sacral facets that they associated with weight bearing. Fur traders carried between 40 kg and 45 kg fur bundles on their backs and with tumplines. Lovell and Aaron Dublenko (1999) found similar results in fur traders. However, both Lai and Lovell (1992) and Lovell and Dublenko (1999) argue that caution must be exercised in coming to conclusions about activity patterns and skeletal variation, especially with small sample sizes. With both studies combined, the number of individuals total 18. Yet, for these sites, artifacts and historical documents provided much information that enabled the anthropologists to draw realistic conclusions about activity patterns. But, as we have seen in previous chapters, sometimes it is the richness of archaeological material that can lead to circular reasoning and conclusion-led studies that would not arise with blind studies.

Besides sacroiliac accessory facets, cervical fusion with faceting can also be associated with carrying. Use of tumplines and carrying loads on the head have been correlated with facet changes in the occipital (the bone of the cranium that is posterior and inferior and connects with the first cervical vertebra) and the first cervical vertebra (also known as the atlas) (Capasso et al., 1999). Sometimes changes in facets can also be found in the second cervical vertebra (or axis) and third cervical vertebra (Capasso et al., 1999).

Kneeling

The two most common activities linked to facet morphology are kneeling and squatting. Kneeling facets have been found in many populations, including Ecuadorian agriculturalists (Ubelaker, 1979), Canadian fur traders (Lai and Lovell, 1992; Lovell and Dublenko, 1999), seventeenth-century Chesapeake colonialists (King and Ubelaker, 1996), and Neolithic Middle Easterners (Molleson 1989, 2007). Distal articular changes in metatarsals and phalanges have been tied to kneeling (Capasso et al., 1999; Ubelaker, 1979). The facet extensions on the metatarsals onto the superior surface have also been tied to squatting and sitting on the edge of one's seat, which is why these are sometimes referred to as Executive's Foot (Capasso et al., 1999). Articular extensions of the foot phalanges coupled with wedging is more closely linked to just kneeling (Capasso et al., 1999).

In 1979 Douglas Ubelaker published an especially rigorous article on kneeling facets over time in Ecuadorian populations in the *American Journal of Physical Anthropology* that likely influenced many young researchers. By examining both the metatarsals and foot phalanges, Ubelaker found that later populations dating between AD 1200 and AD 1550 had more than twice the rate of kneeling facets than did the earlier AD 700 population. The most frequently affected joints were that of metatarsals one through three and the first phalanx. Ubelaker attributes these facets to resting on one's toes during kneeling while grinding grains. Ubelaker failed to find these facets in the Terry collection, a twentieth-century autopsy collection, and he found few examples of kneeling facets in cold climate populations.

Theya Molleson (1989, 2007) notes that in Central Turkey and Syria, grain preparation was a female job and was associated with kneeling facets. In an 8,000-year-old Neolithic sample, Molleson (1989) found foot phalanges with articular surface extensions and wedging; interestingly, the changes, especially the wedging, were most often seen on the fifth phalanx. The wedging, facet extensions, and impressions were assumed to be associated with dorsiflexion at the ankle and toes, which is found to be common in kneeling when the toes are curled under the foot. Kneeling in this sample was likely done while using a saddle **quern** (a simple hand mill for grinding grains) to process food; ethnographic data has revealed that saddle querns are often used in a kneeling position. Molleson (1989) also notes that entheseal changes support grinding seeds as the activity that was linked to kneeling; the humeral deltoid and radial tuberosity were well developed and these entheses are associated with muscles that are employed in the grinding movement. Charles Merbs and Robert Euler (1985) also found kneeling facets related to grinding; in an Arizona sample, tibial facets were tied to kneeling before querns (or, as they are sometimes called in New World archaeology, **metates)** to grind corn. In cases that date prior to metate use, the same facets may be used to reconstruct the activity as squatting rather than kneeling (Merbs and Euler, 1985). Thus, to determine whether kneeling or squatting was the activity that caused the facets, artifacts are needed—in this case, querns or metates. Without the archaeological information, the specific activities cannot be determined; age and sex differences may also hinder specific activity reconstructions (Radi et al., 2013).

Not all kneeling facets are linked to grinding; Lai and Lovell (1992) found kneeling facets in three individuals' metatarsals and first proximal phalanges in their Canadian fur traders, which they link to habitual kneeling while canoeing. Once again the specific activity was narrowed down through the use of nonskeletal information; in this case, archaeological information coupled with historic documents helped the authors suggest canoe kneeling rather than squatting or kneeling on land was the activity that created the facets.

In some studies, a lack of kneeling facets has been cited as evidence of cultural variation; for instance, Molleson (2006) examined a Kurdish sample dated between 10,500 to 8,400 years ago and noted that the lack of kneeling facets on the first metatarsal is evidence that a saddle quern was not likely used to grind grain and that kneeling did not likely occur in this population. Yet, drawing conclusions based on an absence of data is usually frowned upon since it may be that the evidence has just not been found yet. There are two common adages for scientists that researchers should remember: the absence of evidence is not evidence of absence, and you cannot prove a negative.

Squatting

Although some kneeling facets and squatting facets overlap, the assumption has been that habitual kneeling is a relatively new activity that starts with agriculture and the grinding of foods, while squatting is a normal pose that has no technological links, except that chairs prevent squatting (e.g., Merbs and Euler, 1985; Molleson, 2006, 2007). Infants adopt squatting, and although chair-raised adults may find it difficult to squat, individuals in non-Western cultures find it comfortable (Molleson, 2007). Squatting (and kneeling) occur in the passive arch and, thus, thigh muscles flex the tibia to 120 degrees but then have no effective **moment arm**, which is the perpendicular distance from an axis to the line of action of a force that determines torque quality (Freeman and Pinskerova, 2003). **Torque**, a rotational force, enables movement at joints. Thus, having no effective moment arm will mean that rotational forces are not being used and the body will be stable without having to use muscles to stay in that position. Squatting is a resting postural complex that involves hyperflexion of the hip and knee and hyperdorsiflexion at the ankle and subtalus joints (Ari et al., 2003). In this position, the medial side of the femoral condyle rolls up and back into the posterior horn of the meniscus (Freeman and Pinskerova, 2003).

Squatting indicators are the most often discussed activity indicator facet in the anthropological literature. As early as 1889, Arthur Thomson linked facets to squatting (see Ari et al., 2003). Squatting facets have been found in many different skeletal samples, such as East Indians (Kumar and Koranne, 1983; Sethi et al., 2014), South African stone age foragers (Dlamini and Morris, 2005), an ancient Belize family from AD 1450 to AD 1500 (White et al., 2010), Pacific Islanders (Pietrusewsky, 1989), and even Neanderthals (Trinkaus, 1975).

Although Capasso and colleagues (1999) listed 16 types of squatting indicators, Trinkaus (1975) suggested that only facets on the posterior-superior femoral condyles and grooves on the femoral intercondylar line from the posterior cruciate ligament are definite squatting indicators. In 1963 E. L. Kostick examined a large sample of Nigerian femora and found that the distal femur is more often affected with facets than other parts of the femur, and that the femoral neck changes often associated with posture are likely normal variation. Arunachalam Kumar and S. P. Koranne (1983) note that the reason the distal end of the femur may be indicative of squatting is due to the abutting of the medial tibial condyle against the popliteal surface of the femur. Facets other than these at the distal end of the femur that have also been called squatting facets may actually indicate other activities. For example, some other so-called squatting facets can be from walking or running (Trinkaus, 1975). Consequently, traits like Poirier's facet, which, as mentioned earlier, is an anterior extension of the articular surface of the femoral head, would not be considered a squatting facet by Trinkaus (1975), but it has been used to identify squatting early on by R. H. Charles (1893). In a modern American sample based on a skeletal collection from the twentieth century, 70% of males and half of the females had Poirier's facets; it has therefore been suggested that normal movement may be the cause of these articular extensions (Capasso et al., 1999). And although ankle flexion facets, which occur on the anterior distal tibia presumably from pressure occurring as a result of the

Figure 6.1. Squatting facet. An example of an ankle flexion facet, which is also sometimes called a squatting facet, although other activities have been linked to these distal tibiae facets.

talus placement during dorsiflexion at the ankle (see Fig. 6.1) are actually called "squatting facets," they may also be from kneeling and are found in metate-using populations (Capasso et al., 1999).

Osteochondritic imprints, also known as facets of the femoral condyles, and the posterior cruciate groove are most securely linked to squatting as opposed to other activities. But the posterior cruciate groove, which seems to be a result of the tension on the posterior cruciate ligament when the knee is hyperflexed, can be difficult to distinguish from the intercondylar line, which is a normal anatomical feature (Capasso et al., 1999; Trinkaus, 1975).

With these factors in mind, I review how anthropologists have used skeletal remains to determine squatting behaviors. Some of the most interesting studies have been those looking at facets occurring early in human evolution. For instance, Qian Wang and colleagues (2008) found that a 120,000-year-old femur (which likely came from an early *Homo sapiens*) from South Africa's Blind River Site had a squatting facet. This femur, which was initially described in 1935, has a 13 mm deep groove on the anterior distal end of the femur. C. P. Martin (1932) suggests that patellar grooves can arise from the sliding back and forth of the patella from squatting and rising. When one examines the ratio of the groove depth to femoral length, the nonsquatting ratio is about 1:60, whereas the squatting ratios are 1:45 or higher. The Blind River specimen has a groove to femoral length of 1.26:45. Additionally, Wang and colleagues (2008) mentioned that the trochlear surface of the lateral condyle extended by 35 mm. A similar conclusion was drawn from three adult skeletons from Klaises River, South Africa; metatarsals of three adults dating between 100,000 and 90,000 years ago had extended articular surfaces that G. Philip Rightmire and colleagues (2006) conclude are the result of hyperdorsiflexion of the toes while squatting. Kneeling was ruled out as the activity since no evidence of grinding foods has been found that far back in human history. Yet this assumes that people did not kneel for other activities, which is unknowable. In a nearly 200,000-year-old Omo, Ethiopian tibia, Osbjorn Pearson and colleagues (2008) noted a shallow pit at the distal end, which they suggest is likely related to squatting. These examples suggest that more than 100,000 years ago humans already exhibited habitual squatting postures.

Going even farther back, squatting facets have been found in the distal tibia of an *Australopithecus africanus*, which is an early hominin dating between two and three million years ago from South Africa. Lee Berger and Phillip Tobias (1996) noted that specimen Stw514b had a slight anterior extension of the articular surface that they attribute to squatting. And, in a 1.89-million-year-old East African hominin from Koobi Fora, Kenya, the distal tibia has a similar facet (DeSilva and Papakyrikos, 2011). Yet these remains are not anatomically modern humans, so we are not comparing like with like. Hence, the facets may relate to other activities or be a normal anatomical feature. Plus, while many anthropologists such as W. Quarry Wood (1920), Capasso and colleagues (1999), Nonhlanhla Dlamini and Alan G. Morris (2005), and Christine White and colleagues (2010) link this extension of articular surface on the distal tibia to squatting, others—notably Trinkaus (1975)—have suggested that this feature is not solely caused by squatting. But, in fact, this articular extension at the distal tibia was one of the first linked to squatting. And although Wood (1920) notes that this feature may also be linked to kneeling, some argue that it is unlikely that these early hominins were kneeling habitually for the same reason given for the early humans. Grinding foods, it has been argued, was not yet likely an evolved activity, but there may have been other reasons for kneeling.

Perhaps the early hominins that have most intrigued people are the Neanderthals. Determining the extent of their similarity with modern humans has been an ongoing quest in human evolutionary studies. One of the most famous researchers of Neanderthals, Trinkaus, has looked thoroughly at postural habits of Neanderthals. In a 1975 study, Trinkaus determined which facets he thought were most likely linked to squatting; his use of comparative data helps illustrate that some squatting facets are actually found in nonsquatting populations, such as Eskimo populations. Additionally, Trinkaus found that truer squatting facets are linked to metatarsal changes nearly 80% of the time. Trinkaus acknowledges that many extensions can be just normal variation or related to normal movement. After determining which facets to examine, Trinkaus found that Neanderthals from Western European sites had a high frequency of anterior femoral condyle facets and a high frequency of extensions at the knee, ankle, and subtalar joints. Although some of these extensions may relate to activities other than squatting, the extension of facets in the anterior condylar region of the distal femur helped Trinkaus conclude that Neanderthals, like many human populations, probably engaged in habitual squatting. He was not the first to suggest this; Charles (1893) was likely the first to suggest Neanderthals squatted. In 2008 Trinkaus and colleagues reported on a large facet on the distal tibia of a Crimean Neanderthal, which they attribute to squatting (even though it was not among the indicators that Trinkaus had stated in his earlier work are definite squatting indicators). Their decision to state that this facet is the result of squatting was likely due to the previous discovery that Neanderthals squatted and, thus, the evidence on the distal tibia was assumed to be enough to support that this Neanderthal squatted.

Squatting activity has been examined extensively in more modern samples too. Many of the studies, like in the human evolutionary studies, are simply case studies of single individuals (e.g., Mant, 2014; Weisler et al., 2000) or extremely limited sample sizes (e.g., Pearson et al., 1971;

Walimbe and Mushrif, 1998/1999). For example, Marshall Weisler and colleagues (2000) mentioned squatting facets on the medial talus and distal tibia of a single adult male from Marshall Island, which is located in the North Pacific Ocean northeast from Australia, dating to the third century AD. And White and coresearchers (2010) observed squatting facets on an AD 1450 to 1500 male's tibia; the male came from a group of skeletons that included one male, one female, and an infant. The adults of this collection have been nicknamed the "loving couple." The authors supported their conclusion of squatting posture use with entheseal changes. The entheses of the lateral gluteal maximus, the quadriceps femoris, and the soleus were well developed; these muscles are used when rising from a squatting position. M. Gaultier and colleagues (2005) found three Omani individuals dated to around 5000 BC who displayed squatting indicators; one had a left tibial squatting facet and two had Allen's fossae. Allen's fossae, as mentioned before, are impressions on the anterior portion of the femoral neck, and these fossae have also been linked to walking and running (Capasso et al., 1999).

Other studies on ancient peoples have looked at larger samples to draw conclusions about population differences (e.g., Ari et al., 2003), temporal trends (e.g., Boulle, 2001a), and sex differences (e.g., Ari et al., 2003; Baykara et al., 2010). For instance, Ilknur Ari and colleagues (2003) looked at thirteenth-century-male Byzantine remains from Turkey and, using the 1959 Singh classification (which looks at presence or absence of a multitude of facet extensions on both the tibiae and tali), they found that nearly half of the individuals were affected by squatting indicators compared to 7% in European samples and more than 80% in East Indian samples. Some research has reported higher rates of squatting indicators in females compared to males, but this study illustrates a highly affected male sample (Ari et al., 2003).

Interestingly, Indian samples from bioarchaeological remains and autopsy collections have been found to have high rates of squatting indicators (see Kumar and Koranne, 1983; Sethi et al., 2014; Shishirkumar et al., 2014; Singh, 1959). Yet there is variation in these samples; for example, S. N. Shishirkumar and colleagues (2014) found that Southwest Coast Indians had lower rates of squatting indicators on tali and tibiae than Northern Indians. Southwest Coast Indians have squatting indicator rates between 30% and 50%, whereas Northern Indian rates are nearly always over 80%. Indian populations are not the only populations with extremely high squatting indicator rates; Australian aborigines, for instance, have been reported to have rates between 79% and 81% (Ari et al., 2003).

Sex difference research has also been conducted; for instance, Molleson (2007) examined both squatting and kneeling facets on Neolithic Syrian agriculturalists and found that although males are more often found to have patellar notches and squatting facets compared to females, the females have more variation in the facets, which may be because the females engaged in a wider range of activities, especially when including food preparation. Yet in East Anatolia from the tenth to the thirteenth century AD, wider facet variation existed in males, which Ismail Baykara and colleagues (2010) suggests may have been due to greater activity ranges for males compared to females. This East Anatolia population lived in a very harsh mountainous environment where agriculture was not a viable food source option; thus, the population depended greatly on livestock. Baykara and coresearchers surmise that some of the other activities that may have caused squatting facets could include crouching during milking and knitting. Michele Toomay Douglas and colleagues (1997), in yet another look at sex differences, examined over 150 tibiae and tali of a Guam sample dating between AD 1000 and AD 1520 and found both males and females are equally affected with squatting indicators. They also note that over half of the individuals had sacroiliac accessory facets that may have been a result of carrying stone pillars.

Temporal variation in facet frequency has also been used to understand past cultures. For instance, Dlamini and Morris (2005) report that although no squatting indicators were found in an autopsy collection, farmers from the Iron Age in South Africa have more squatting indicators than Later Stone Age foragers. This pattern may be because some squatting facets actually are indicators of kneeling, which is a common posture to process grains. Boulle (2001a) looked at 543 French skeletons from the first to eighth centuries AD and compared them to the twentieth-century American Hamann-Todd collection and found that squatting indicators decrease through time, which is attributed to a change in interior design, especially the use of chairs.

Although most of the above-mentioned studies link facets to activities, some researchers have allowed for other possibilities. Some anthropologists suggest that the difference in squatting indicator frequency is a result of methods used to record the data (Javia et al., 2014). For instance, the use of tibiae and tali extensions may cause an overcounting; tali are often used in Indian studies (e.g., Iqbal et al., 2012; Singh, 1959) and Turkish studies (e.g., Baykara et al., 2010).

Some studies have also suggested that there is a genetic component to squatting indicators (e.g., Boulle, 2001a,b; Jeyasingh et al., 1979). Support for the genetic contribution to squatting facets comes from fetal research; C. H. Barnett (1954) found squatting facets in European fetal remains. Remarkably, Inderbir Singh (1959) notes that although Indian adults have tali with squatting indicators more often than European adults, the reverse is true in fetuses. As a result, Singh suggests that the Indian squatting indicators are acquired and distinct from the European tali facets, which may relate to fetal position only. Boulle (2001b) states that D. Mitrovic (1973) suggests that facets are genetically determined, but their development depends on movement and posture. Therefore, if an individual is born with a squatting facet and if the individual does not squat, then the squatting facet is not maintained.

According to Boulle (2001b), Mitrovic (1973) further suggests that individuals who did not have squatting facets when they were fetuses cannot develop articular squatting facets in life since articular joints cannot develop after the cartilage model has begun to undergo necrosis and permanent joint formation has started. Individuals without fetal squatting facets who squat develop nonarticular pressure facets, according to Mitrovic (1973) (see Boulle, 2001b).

More research on the genetics of squatting facets and other activity indicator facets is needed. Some anthropologists, nonetheless, have used activity indicator facets as a way to look at biological distance between populations. For instance, Deborah E. Blom and colleagues (1998) include facets in the nonmetric trait list to determine biological distance in South American populations during the Tiwanaku colonization that dated from AD 500 to AD 1000. Until more is understood about activity indicator facets, it may be just as reasonable (or even more reasonable) to use these traits to understand biological distance as to understand activities.

Summary

In short, many anthropologists accept that accessory facets, facet extensions, and nonarticular facets are the result of activity patterns. Yet some anthropologists argue that one needs to be cautious in activity-pattern reconstructions since sample sizes are often small and there is a lack of good clinical comparative data (e.g., Blau, 1996; Lai and Lovell, 1992; Lovell and Dublenko, 1999). But other anthropologists are quick to point out that genes (e.g., Baykara et al., 2010; Boulle, 2001a,b; Oygucu et al., 1998) and recording methods (e.g., Villotte and Knüsel, 2009) may play a role in facet expression and frequency. Unfortunately, no clinical studies are available to determine if the activity indicator facets are associated with sports that may involve activities similar to those one may expect to see in past populations. And although some populations that are well known for squatting have high rates of squatting indicators and some archaeological populations with evidence of food grinding with saddle querns have high rates of kneeling facets, there are anomalies too. For instance, the Aleut, who are not known to squat, have squatting facets. In order to use these activity indicators successfully, anthropologists should agree upon standardization of data collection methods, test for genetic variation, undertake experimental tests (perhaps in nonhuman samples), and continue to gain a better understanding of bone and cartilage biology. As other skeletal features are now being referred to with neutral terms, we may wish to consider a new term for activity indicator facets. The term "activity indicator facets" is a loaded term that could bias researchers and may not be justified.

7

CONCLUSIONS

Nature versus Nurture

Perhaps the most important theme running through scientific research is the question of how much influence the environment has on a feature versus how much genes determined the variation. The environment versus genes question is asked by anthropologists, psychologists, medical researchers, and many others. In psychology, the question has been phrased as nature versus nurture. Once, many behavioral traits were thought to be based on environmental influences, but research over the last three decades has shown that many behavioral traits actually have a genetic component (see Plomin et al., 2013). Furthermore, the behavioral traits are affected by evolutionary forces, such as natural and sexual selection (e.g., Ellis et al., 2012). In medicine, researchers are discovering more genetic predispositions in diseases that were once thought to be the result of lifestyle decisions; for example, cholesterol levels are now known to be almost completely determined by genes rather than diet, and many high cholesterol foods, such as eggs and shrimp, are no longer considered to put individuals at risk of high cholesterol (e.g., Fernandez, 2012). In anthropology, research on head shape by Franz Boas (1912) was once used to illustrate the plasticity of the skeleton and the importance of the environment, but recent analyses of crania have revealed that cranial morphology is after all more determined by ethnicity (and, thus, genes) than by the environment (see Sparks and Jantz, 2003).

Yet there is good evidence that the environment, whether it is the air we breathe, the activities we engage in, the food we eat, or the microorganisms we are exposed to, influences our health and lives. For instance, even with the evidence of the genetic propensity toward certain behaviors, there is evidence that environmental factors mediate those behaviors too. One example that may have had a wide range of effects is the deleading of gas, paint, and dishes, which is suggested to have had positive effects on intelligence and crime rates (e.g., Chen et al., 2007; Stretesky and Lynch, 2004). Lead, a heavy metal, is known to have detrimental effects on growing individuals' neurons, so taking lead out of the environment has led to a decrease in these negative effects. Perhaps the most obvious example of the nature or nurture question is body weight; some people are more likely to gain weight but without excessive calorie consumption (for that individual), one will not become overweight or obese (see Choquet and Meyre, 2011).

The factors discussed in this book, like the subjects in psychology and medicine, are a result of both genes and environment. Cross-sectional geometry has been used to reconstruct activity patterns, especially in terms of the extent of mobility in relation to subsistence patterns. A strong anteroposteriorly oriented femoral cross-section has, for example, been associated with extensive walking. The theory behind linking cross-sectional morphology with activity patterns has been phrased as a part of Wolff's law of bone remodeling. Yet some researchers, such as Osbjorn Pearson and Daniel Lieberman (2004), have questioned whether Wolff's law, which works well in predicting trabecular bone orientation, can actually influence and be used to predict cortical bone morphology. The question of whether muscle use actually places enough force on cortical bone to stimulate bone remodeling in order to prevent the bone from breaking is one that has not been adequately addressed. And some research has demonstrated that body type can affect cross-sectional geometries (see Ruff, 2002; Weiss, 2003a). Body type is in part regulated by the evolutionary trends of Bergmann's rule and Allen's rule that are dependent on the climate for which a population is evolved. **Bergmann's rule** states that larger bodies are selected for in cold northern climates so that heat is conserved; **Allen's rule** states that shorter distal elements are selected for in cold climates to preserve heat. Hence, cold-climate individuals are actually more apt to have thicker cross-sections than warm-adapted individuals. The cross-sectional properties that seem most likely to be affected by these climate-driven evolutionary trends are cortical area and total area, whereas cross-sectional properties that look at shape are less affected (see Lieberman et al., 2004; Weiss, 2005).

Some features that have been addressed throughout these pages have been studied thoroughly by the medical community. Osteoarthritis, for instance, has been the subject of many medical research endeavors. Osteoarthritis, which is a leading cause of disability and pain, has been found to have a strong genetic component. For instance, some studies have found that 70% of the variation of spinal osteoarthritis can be explained through genes (e.g., Spector and MacGregor, 2004). Nevertheless, some joints like the elbow are less affected by genetic variations, and some anthropologists have argued that early-onset osteoarthritis, which is what is seen most often in the bioarchaeological record, may be different from the osteoarthritis in today's elderly individuals (see Spector and MacGregor, 2004; Weiss and Jurmain, 2007).

Elderly individuals, in and of themselves, are a new and perhaps even unnatural development when compared to previous generations of short-lived people. Thus, some supposed morphologies are likely just symptoms of old age and not any genuine pathology. Clearly, this controversial assertion would have massive and profound implications for our understanding of many of the topics covered in this book and would require a paradigm shift in scientific thinking and research in these areas of study.

Activities of the past, furthermore, may have started earlier in life, may have been more labor-intensive, and were likely done more regularly than activities of modern peoples; thus, the osteoarthritis found in past populations may have been more likely to have been the result of the activities rather than genes (see Weiss and Jurmain, 2007).

Although anthropologists have been seeking answers to questions in nonanthropological literature, such as in the fields of aging, sports medicine, and even animal research, to further their understanding of activity indicators, most research on activity indicators that anthropologists use has not focused on genetics. Rather, anthropologists have looked at demographic patterns to help explain whether the features used in activity reconstructions are likely to relate to biological (and, therefore, genetic) reasons. These biological factors, which are sometimes termed biological confounds, include age, sex, and body size.

Biological Confounds: Age, Sex, and Body Size

Since bioarchaeologists using the skeletal features described in this book are mainly interested in reconstructing activity patterns, biological confounds can deter them from coming to conclusions. Or, the researchers can come to potentially false conclusions through ignoring or deemphasizing confounds or even not being aware of them. The effects of age are perhaps the best known and understood out of the biological confounds. Increases in osteoarthritis with age have been well documented in both clinical and bioarchaeological studies. The reasons for age increases in osteoarthritis are multitude and may include wear and tear over long periods of time, microtrauma, or a lack of cartilage repair (see Weiss, 2014c; Weiss and Jurmain, 2007). Age effects are also known on entheseal changes (e.g., Chapman, 1997; Niinimäki, 2011; Villotte et al., 2010a; Weiss, 2003b). Some anthropologists have even suggested that entheseal changes may be better used as age indicators rather than activity indicators (e.g., Milella et al., 2012). The cause of more pronounced entheseal changes with age may also be a result of wear and tear over time, but it has been suggested that age changes in bone remodeling, with more remodeling occurring at the periosteum rather than the endosteum, may affect the appearance of entheses (Ruff and Hayes, 1983; Weiss, 2014c). This difference in bone remodeling also impacts cross-sectional geometries (see Ruff and Hayes, 1983). Age effects should be easy to control for and, consequently, eliminated as a confound when using entheses, cross-sections, or osteoarthritis to reconstruct activity patterns, but since anthropologists estimate age, the controls for age confounds are incomplete (see Mays, 2015; Milner and Boldsen, 2012). Furthermore, the best age estimates are in young individuals, who are less likely to display osteoarthritis and entheseal changes (Milner and Boldsen, 2012). Determining age of an individual who has reached full adulthood is difficult and age ranges tend to be between 10 and 15 years old; hence, this makes controlling for age difficult (Mays, 2015; Milner and Boldsen, 2012).

Sex differences may seem to be better controlled for than age differences since determining sex through the use of the pelvis or the skull can be done fairly easily, and accuracy in determining sex when using either the whole skull or the entire pelvis is often between 80% to 90% (see İşcan and Steyn, 2013); however, since many hypotheses revolve around sexual division of labor, determining which sex differences are biological and which are activity induced may be tricky. Furthermore, some studies use robusticity as a sex indicator and then also use robusticity to determine activity patterns. Janet Cope and colleagues (2005), for example, used hand bone robusticity to determine sex and then also used hand bone robusticity to reconstruct activity patterns; this can result in circular reasoning. Best practice is to use two different skeletal parts (one for sex determination and one for activity pattern determination) and different types of traits to determine sex and activity patterns.

Another confounding feature, especially in relation to entheseal changes, is body size or body mass (e.g., Weiss, 2003b, Nolte and Wilczak, 2013). Some have argued that fibrocartilaginous entheseal changes are not as affected by body size than fibrous entheses; thus, using the correct entheses controls for body size complications (see Villotte et al., 2010a; Weiss, 2015a,b). Yet body size factors into entheseal changes, cross-sectional geometries, and osteoarthritis; moreover, these can then be confounded with sex differences since there is a strong correlation between body size and sex. Thus, controlling for body size sometimes eliminates the sex differences and thereby forces us to accept that sexual division of labor is difficult to determine (see Weiss et al., 2012).

Improving Lifestyle Reconstructions

One may wonder how to get around these biological confounds to determine whether activity patterns can be accurately reconstructed. Although there is no magic formula, there are some basic guidelines one may wish to follow. Controlling for age, sex, and body size variations statistically can help to ensure that what is left over relates to activity patterns, although sometimes this is not possible (e.g., when sex differences in labor is the question of interest). Still, following medical research, controls for as many confounds as possible can leave only the variation of the researchers' interest and allow us to draw better conclusions (e.g., Weiss, 2007, 2014b,c; Weiss et al., 2012).

One method to determine what is biologically determined and what is culturally specific is to look at many studies and search for patterns. If the same pattern occurs regardless of the sample, then the pattern is likely biological. For instance, since in nearly all studies entheseal changes are greater in older individuals compared to younger individuals, then the difference is likely not related to activities but rather to the physiological changes that occur with aging. Additionally, if males in nearly all populations experience greater frequency of spondylolysis, then they are likely biologically (and specifically maybe anatomically) predisposed to these stress fractures. When we see reversal in expected trends, like as in the higher robusticity of female entheses than male entheses (see discussion in Weiss et al., 2012), then the difference is more likely related to culture and, thus, due to activities.

Aggregation is another useful method to improve lifestyle reconstruction; many anthropologists aggregate by looking at multiple traits (see Weiss, 2003b). Aggregation reduces error variance (since error is random) and increases construct validity. However, one must be careful not to aggregate skeletal indicators with the same confound issues without controlling for the confounding factors; for example, one would not want to use both entheseal changes and osteoarthritis without controlling for the effect of age since age greatly influences both these factors.

In addition to aggregation, better methodologies should be employed in bioarcheology. Many studies draw conclusions on small samples or even single individuals, especially when archaeologists are employing activity indicators to increase information on a specific site (e.g., Knüsel et al., 1996; Lovell and Dublenko, 1999; Mant, 2014). Statistical significance needs to be reemphasized in our field and a greater importance placed on hypotheses testing (see discussions in Armelagos and Van Gerven, 2003; Stojanowski and Buikstra, 2005). Those studies that are more site specific and often published in journals that are geographically focused tend to be more descriptive in nature. Data collection also needs to be tested for error rates; entheseal change error rates, for instance, are remarkably high (see discussions in Weiss, 2015b) whereas error rates for stress fractures and accessory facets are quite low. Standard methods of data collection for all activity indicators should be the goal, even though the standards may change over time when a greater understanding of the feature is gained. In addition, standardized or clear information on how population rates for these skeletal traits are calculated is needed. Cross-sectional geometries are well standardized, nonbinary, and often studied in statistically sophisticated manners, whereas osteoarthritis is less standardized, and there is great discussion over which traits should be used and which should be left out (see discussion in Weiss and Jurmain, 2007). Activity indicators are also often recorded as present or absent, or another form of binary coding (e.g., Baykara et al., 2010; Cashmore and Zakrzewski, 2013; Plomp et al., 2015a) and, thus, sometimes just analyzed with nonparametric tests. Binary variables are not necessarily bad; they often have low error rates, but they lend themselves to less powerful statistical methodologies. Sebastien

Villotte and colleagues (2010a) have started to use more powerful methods to analyze binary data from entheses, and these methods could also be used on other skeletal features.

Even after controlling for confounds and using better methodologies, bioarchaeologists still need more information from clinical research regarding the biology of skeletal features. Unfortunately, clinical research usually revolves around topics that relate to pain and disability; as a result, features that are not known to cause pain, such as accessory facets and entheseal changes, are not as well studied or understood as features that are thought to cause pain, such as Schmorl's nodes and osteoarthritis. Nevertheless, these features may not always cause pain, and perhaps there are just as many nonpained individuals with these features, but they are not being represented in the research (see Weiss, 2014c).

Bioarchaeologists should practice good science by avoiding circular reasoning (as mentioned previously) and focusing on predictive validity. A trait has predictive validity when conclusions can be drawn without the use of extra support. Sex determination features of the pelvis in humans can accurately give us information about that individual's sex without other information, such as clothing worn, artifacts found, and chromosomal tests. The question is whether indicators of activity can do the same; can studying kneeling facets actually tell us whether an individual knelt even if we do not have artifacts to suggest food grinding activities? Or can looking at entheseal changes tell us whether males and females engaged in different activities without supporting artifactual evidence? And can cross-sectional analyses truly tell us an individual walked more than another individual if we did not know anything else about these past peoples? The predictive validities for all of the skeletal features discussed in this book are low; we may be able to say general things about activity; for instance, one population has a higher frequency of Schmorl's nodes than another population that may relate to carrying, twisting, or biological differences. The vague statements made can only be narrowed with a slew of other information and many anthropologists acknowledge that skeletal features cannot be used to determine specific activities. Therefore, we must ask whether these features are useful or whether more research needs to be conducted on understanding the features before using them for lifestyle reconstruction.

Final Conclusions

The human skeleton is a fascinating entity that has so much to tell us about the past. The myriad features on the skeleton, such as many of those covered in this book, seem to be inviting the anthropologist to read the skeleton and tell the story of past individuals. We can almost feel their pain and feel the sweat of their brows. However, before creating elaborate stories regarding the lives of past peoples, we need to know what the skeletal features really signify. Their etiologies are complex and multifactorial; determining the major causes for any of the so-called activity indicator features has been difficult but not impossible. We know, for instance, that age is the best predictor of entheseal change. Continuing our research into the factors that result in activity pattern indicators, we may find that the skeleton wants to tell a different story. Perhaps the story is of relatedness or biological sex differences rather than of activities. Thus, more research is needed to understand the skeleton's features, especially in terms of the etiology of the activity indicator features discussed in this book. Regardless of the information we wish to extract from the skeleton, in the end we need to let the data speak for themselves.

GLOSSARY

accessory facets: Articulation facets that are in addition to the usual facets, which may be caused by activities.

activity indicator facets: Areas on bone that are either articular extensions or shallow dents that have been associated with activities.

adipose tissue: Loose connective tissue in which fat cells accumulate.

aggregation: The collecting of units or parts into a mass or whole.

Allen's facets (or fossae): An impression or dent on the anterior neck of the femur that has been suggested to be indicative of squatting or kneeling.

Allen's rule: A rule stating that, in warm-blooded animals, there tends to be a reduction in size of protuberant parts of the body in populations living in cooler climates.

anabolic: The constructive part of metabolism concerned especially with macromolecular synthesis.

anisotropic: Exhibiting properties with different values when measured in different directions.

apophyseal joints: Also known as zygapophyseal, these are the inferior and superior articular hinge-like facets that lie behind the vertebral body that link the vertebrae together.

apoptosis (plural apoptoses): Genetically programmed cell death.

arthritis: Inflammation of joints due to infectious, metabolic, or constitutional causes.

articular cartilage: A smooth, white fibrous and flexible tissue that covers the ends of bones in joints to enable smooth movement.

atlatl: A device for throwing a spear that consists of a rod or board with a projection (as a hook) at the rear end to hold the weapon in place until released.

autoimmune disease: A disease in which the body produces antibodies that attack its own tissues.

avascular: Associated with a lack of blood vessels.

avulsion: An injury occurring when a joint capsule, ligament, tendon, or muscle is pulled from a bone, taking with it a fragment of the bone to which it was attached; usually it occurs along growth lines.

Baastrup's facet: A condition in which spinous processes of vertebrae touch one another, forming a facet between them, which is usually associated with activity patterns; also known as kissing-spines.

basic multicellular unit (BMU): A wandering group of cells that dissolve an area of the bone surface and then fill it with new bone.

bending: Deformation in which compression occurs on one side and tension occurs on the other side.

Bergmann's rule: A rule that among warm-blooded animal species, the body size of animals living in cold climates tends to be larger than in animals of the same species living in warm climates.

bimanual: The act of using both left and right hands and arms for an activity.

biomes: The total complex of biotic communities occupying and characterizing a particular area or zone, such as a desert or deciduous forest.

botulism toxin: A neurotoxin that can occur naturally or be synthesized, and that causes paralysis.

calcified tendinitis: An inflammatory condition that occurs most often in the shoulders and in which calcium builds up in tendons, causing joint stiffness.

calcium: A soft and silvery mineral that is the most abundant mineral in the human body, most of which is stored in bones and teeth.

canaliculus (plural, canaliculi): In bone, a branching tubular passage that radiates from a lacuna to connect to other canaliculi and the Haversian canal.

catabolic: Metabolic breakdown of complex molecules into simpler ones, often resulting in a release of energy.

chondrocyte: A cartilage cell.

chondrodysplasia: An inherited disease that affects the development of cartilage, especially of the limb bones, which results in arrested growth and a type of dwarfism.

clay-shoveler's fracture: A stress fracture in which the spinous process of either the lower cervical vertebrae or upper thoracic vertebrae is broken.

collagen: A fibrous protein constituent of bone, cartilage, tendons, and other connective tissues.

collagen fibril network: A porous matrix in articular cartilage that is damaged in arthritis.

comminuted fracture: A fracture in which the bone is splintered or crushed; the bone is broken into more than two fragments.

compression: An action that tends to shorten or squeeze the bone or body part.

construct validity: The degree to which a variable measures the characteristic being investigated.

cortical bone: Also known as compact bone; it is the compact, noncancellous portion of bone that is organized in the Haversian system.

cortical cross-sectional area (CA): A measurement of the total amount of cortical bone in a cross-section.

cytokine: A protein that is secreted by a cell that carries signals to neighboring cells.

diarthrodial joints: Movable joints.

diffuse idiopathic skeletal hyperostosis (DISH): A form of arthritis, which is inherited, associated with flowing calcification along the sides of the vertebrae of the spine. Also known as Forestier's disease.

dysplasia: In the hip, a socket that does not fully cover the femoral head and increases the risk of hip dislocation.

eburnation: The degeneration of bone into a hard, shiny, ivory-like mass, which occurs at articular surfaces of bones in osteoarthritis. Sometimes referred to as sclerosis.

endocortical bone: Compact bone that lies on the inside of the shaft and lines the medullary cavity.

endplate: In vertebrae, the top and bottom portions of the vertebral bodies that interface with the vertebral disks.

entheseal changes: Changes at muscle attachment sites that consist of ridges, bony spurs, or pitting; usually thought to be associated with muscle use.

enthesis (plural, entheses): A muscle attachment.

enthesopathies: Changes at muscle attachments that are thought to be a result of injury, trauma, or disease.

enthesophyte: A bony spur that relates to a muscle attachment; sometimes referred to as an entheseal osteophyte.

epigenetic: Relating to or arising from nongenetic influences on gene expression; environmental or biological mechanisms that switch genes on or off.

erosive changes: Changes that cause superficial destruction of tissue.

estrogen: Any of a group of steroid hormones that promote the development and maintenance of female characteristics of the body; it also plays a key role in bone maintenance.

etiology: The cause, set of causes, or manner of causation of a disease or condition.

extended facets: Extension of articular surface that is usually associated with activities.

extracellular fluid: All of the body fluid lying outside the cells; related to extracellular fluid is extracellular matrix which is the network of proteins and carbohydrates that lie around cells.

fatigue fracture: See *stress fracture*.

fibroblast: An immature cell in connective tissue that produces collagen and other fibrous tissues.

fibrocartilage: Cartilage that contains fibrous bundles of collagen; for example, intervertebral disks.

fibrocartilaginous enthesis: A muscle attachment in which the muscle is attached to the periosteum of bone via a tendon.

fibrous enthesis: A muscle attachment in which the muscle attaches directly to the periosteum of bone without a tendon.

fluorosis: A condition due to the ingestion of excessive amount of fluoride; it can lead to osteopetrosis or osteoporosis.

force: A push or pull exerted on one object by another object; for example, when a muscle contracts, it forces the limb to move.

fynbos: Unique to southern and southwestern South Africa; a type of environment where the vegetation is characterized by evergreen hard-leaved shrubs and almost no trees.

gout: A disease in which defective metabolism of uric acid causes arthritis (especially in the smaller bones of the feet), deposition of chalkstones, and episodes of acute pain.

Haversian system: The fundamental functional unit of mature cortical bone. Also known as osteons, they are roughly cylindrical structures that are usually several millimeters long and about 0.2 mm in diameter.

heritability: The proportion of observed variation in a trait that can be attributed to inherited genetic factors rather than environmental factors.

herniation: An abnormal protrusion of a body structure through a defect or natural opening in a covering membrane, muscle, or bone.

homeostasis: The state of equilibrium (balance between opposing pressures) in the body with respect to various functions and to the chemical compositions of the fluids and tissues.

hyaline cartilage: See *articular cartilage*.

hypertrophy: Condition characterized by excessive bone robusticity, thickening, or growth.

idiopathic: Denoting a disease or condition of unknown cause.

interobserver error: The differences between interpretations of two or more individuals making observations of the same phenomenon.

interstitial: Pertaining to between cells.

intracortical bone: An osteon; see *Haversian system*.

intraobserver error: The differences between interpretations of an individual making observations of the same phenomenon at different times.

isthmus: A part of the vertebral arch also known as the pars interarticularis. A small, thin segment of bone that connects the facet joints at the back of the spine.

Jomon: Related to an early Mesolithic-type culture in Japan (circa 10,000 BC to 300 BC).

kyphosis: Excessive outward curvature of the spine that causes the hunching of a back.

lacuna (plural, lacunae): A minute cavity in bone occupied by osteocytes (bone cells).

lamella (plural, lamellae): A thin, sheet-like structure that surrounds the Haversian canal in concentric layers.

Laplace's law: States that the tension within the wall of a sphere filled to a particular pressure depends on the thickness of the sphere. Thus, even at a constant pressure, the tension within a filled sphere decreases with an increase of the thickness of the sphere's wall.

Levant: A region on the eastern coast of the Mediterranean Sea north of the Arabian Peninsula and south of Turkey; includes the modern countries of Israel, Jordan, Lebanon, and Syria.

ligament: A short band of tough, flexible, fibrous connective tissue that connects two bones or cartilages or holds together a joint.

lining cells: Cells that have formed from osteoblasts; they are flat in shape and regulate the passage of calcium in and out of bone. They also respond to hormones by making specific proteins that activate osteoclasts.

lipping: The formation of a lip-like structure around the articular end of a bone, usually from osteoarthritis.

lordosis: Excessive inward curvature of the spine.

lumbarization: Transitional vertebral change in which the first sacral vertebra is similar to a lumbar vertebra; the first sacral vertebra is not completely fused to the rest of the sacrum.

mechanical loading: The application of force on a bone or other object.

mechanoreceptor: Any of the sense organs that respond to vibration, stretching, pressure, or other mechanical stimuli.

medieval: Pertaining to the Middle Ages, which is usually from AD 1000 to AD 1500.

medullary cavity: The marrow cavity of bone, located in the center of long bone shafts; sometimes also called the medullary canal.

meniscus: A crescent-shaped piece of cartilage that provides cushion and smooth movement between the femur and the tibia.

Mesolithic: The period after the Paleolithic and before the Neolithic, usually thought to occur near the end of or after the last Ice Age; dated to about 11,600 years ago to 5,000 years ago, but dates vary depending on the geographic region. The Mesolithic lasts longer in Europe than in the Near East.

metate: See *quern*.

microdamage: In bone, damage caused by a variety of normal everyday loads that can result in diffuse damage and microcracks.

microtrauma: A small and insignificant injury, especially one of a series that can lead to major injury.

mobility: The movement from one place to another.

moment arm: The perpendicular distance from an axis to the line of action of a force that determines torque quality.

moments of inertia (*I*): In bone, representing the object's resistance to change in angular velocity; in this case, bending forces.

morphogenetic protein: A member of a superfamily of proteins that promotes the formation of bone and helps mend broken bones.

Natufian: Semisedentary hunter-gatherers living in the Levant region of the Near East between about 12,500 and 10,200 years ago.

necrosis: Death of living tissues or cells.

Neolithic: Relating to the last Stone Age and sometimes called the New Stone Age; dates vary depending on the geographical location; in the Near East, the Neolithic may have started as early as 10,000 years ago, but it starts at least 2,000 years later in Europe and even later in Asia. The Neolithic is sometimes defined by the adoption of agriculture and megalithic structures.

notochord: A longitudinal flexible rod of cells that in embryos of the higher vertebrates forms the supporting axis of the body; it is almost obliterated in adults as vertebrae develop.

nucleus pulpous: An elastic pulpy mass in the center of each intervertebral fibrocartilage disk and regarded as a remnant of the notochord.

ontogeny: The development of an individual organism from embryo to adult.

osteoarthritis: Also known as degenerative joint disease and osteoarthrosis; degeneration of joint cartilage and the underlying bone, most common from middle age onward. It causes joint pain and stiffness.

osteoblast: A cell that deposits bone.

osteochondritis: A painful joint condition in which bone underneath the cartilage of a joint dies due to lack of blood flow; can be caused by injury, but it may have a genetic component.

osteoclast: A cell that absorbs bone tissue.

osteocytes: Cells inside bone that formed from osteoblasts; they have tendrils that sense cracks and that also direct osteoclastic activity.

osteogenic cell: The only bone cell that divides; it differentiates and develops into an osteoblast that, in turn, is responsible for forming new bone.

osteoid: Immature bone that has not undergone calcification.

osteopetrosis: A bone disease that makes bones abnormally dense and prone to fractures.

osteophyte: A bony spur, which can be called an enthesophyte when it occurs at muscle attachments, or secondary cartilage when it occurs at joints.

osteoporosis: A condition in which bone becomes weak and brittle; characterized by loss of bone mass and density.

Paleolithic: The Old Stone Age, which starts around 2.6 million years ago with the first stone tools and ends around 10,000 years ago.

parry fracture: A fracture of the ulna that occurs when trying to defend oneself from a blow to the head.

pedicle length: The length of the segment between the transverse process and the vertebral body.

periosteal bone: Bone formed by osteoblasts of the periosteum; the bone underneath the periosteum, which is a membrane that covers the outer surface of nonarticular bone.

pleiotropic: In relation to genetics, a gene that codes for more than one trait.

Poirier's facets: Anterior extension of the articular surface of the femoral head that has been associated with squatting and kneeling.

polar moment of inertia (J, Zp): A measure of a circular beam's ability to resist torsion forces.

polymorphism: In genetics, existence of a gene in several allelic forms.

porosity: The quality of being porous; macroscopic holes in articular surfaces assumed to be associated with osteoarthritis.

pressure facets: A nonarticular indent or impression on bone that is thought to arise from activities such as kneeling or squatting.

primary osteoarthritis: Osteoarthritis that is assumed to be caused only from wear and tear.

proinflammatory: In cells, tending to cause inflammation, which is usually destructive to tissue health.

proliferative changes: Changes in entheses and joints that involve bony growths.

proteoglycans: Any of a group of polysaccharide-protein conjugates present in connective tissue and cartilage; they form the main substance in the extracellular matrix of connective tissue and also have lubricant and support functions.

pseudarthrosis: Also called a false joint; an abnormal union formed by fibrous tissue between parts of a bone that have fractured.

pycnodysostosis: A rare inherited genetic condition characterized by short stature, fragile bones, shortness of the fingers and toes, failure of the anterior fontanel to close properly, and a receding chin.

quern: A simple hand mill for grinding grain.

regression formula (plural, formulae): An equation that models the dependent relationship of two or more variables; also known as a regression equation.

remodeling: In bone, the process, which occurs even without an injury, where mature bone tissue is removed from the skeleton (in a process called bone resorption) and new bone tissue is formed (in a process called ossification).

repair: In bone, the replacement of destroyed bone by new formations; occurs after a fracture or other injury.

resorption: In bone, the removal of mature bone.

rheumatic diseases: Diseases that affect joints and muscles.

rheumatoid arthritis: Chronic inflammatory disorder that is thought to be inherited; typically affects the small joints in hands and feet.

robusticity: In cross-sectional geometries, the strength of bone to resist mechanical forces; in entheseal changes, features of proliferative changes that include ridges and mounds; also called rugosity.

rubella: Also known as German measles, a contagious virus that causes a body rash and leads to mild fever, headache, runny nose, inflamed eyes, and aching joints (especially in young females).

sacralization: Transitional vertebral morphology in which lumbar vertebrae fuse to the sacrum.

sacral table: The top part of the sacrum that articulates with the last lumbar vertebra.

Scheuermann's disease: An inherited growth condition in which the normal curve in the upper spine is increased, forming a hunched back.

Schmorl's node: An upward or downward protrusion of a spinal disk's fibrous tissue into the bony tissue of the adjacent vertebrae.

sclerosis: Hardening of bone usually associated with osteoarthritis, which manifests itself as eburnation.

secondary osteoarthritis: Osteoarthritis that has a cause beyond wear and tear, such as injury or disease.

Sharpey's fibers: Any of the thread-like processes of the periosteum that penetrate the tissue of the superficial lamellae of bones.

shear: Forces that are unaligned, pushing one part of a bone in one direction, and another part of the bone in the opposite direction.

single nucleotide polymorphism: A variation at a single position in a DNA sequence among individuals.

spina bifida: A type of birth defect called a neural tube defect that occurs when the vertebral do not fuse properly around part of the baby's spinal cord.

spina bifida occulta: The mildest form of spina bifida; it only affects the sacral fusion.

spondylolysis: A stress fracture along the isthmus of the vertebra that can separate the vertebral arch from the vertebral body.

Stickler syndrome: A group of hereditary conditions characterized by a distinctive facial appearance, eye abnormalities, hearing loss, and joint problems; symptoms vary widely among affected individuals.

strain: To cause an external change of form or size by application of force.

stress: Internal forces experienced by bone that can result in deformation.

stress fractures: A bone fracture that is the result of repeated stress as opposed to a single traumatic event.

subchondral bone: Bone directly beneath articular cartilage at joint surfaces.

synovial capsule: The closed cavity that contains synovial fluid and is formed by the smooth cartilage that covers the articular surfaces of the bones and the surrounding joint capsule in freely movable joints.

synovial joint: See *diarthrodial joint*.

systemic disease: A disease that affects the entire body.

tendon: A tough band of fibrous connective tissue that connects muscles to bones.

tension: Force that stretches or elongates an object; a force that pulls away from the object.

testosterone: A steroid hormone that stimulates development of male secondary sexual characteristics produced mainly in the testes but also in the ovaries and adrenal cortex; it also plays a key role in muscle maintenance.

Thule: An Eskimo culture that dates from AD 500 to AD 1400 and extends throughout the Arctic from Greenland to Alaska.

tidemark: A transitional zone that appears as a wavy line and marks the junction between calcified and uncalcified cartilage.

topographically: The relief features or surface configuration of an area.

torque: The ability of a force to cause rotation on a lever; it creates movement in the lever system of bones.

torsion: Twisting force.

total cross-sectional area (TA): In cross-sectional geometries, the measurement of the cortical area plus the medullary area.

trabecular bone: Bone in which the spicules or trabeculae form a three-dimensional latticework (cancellous) with the interstices filled with embryonal connective tissue or bone marrow; it is found in the ends of long bones and in irregular bones. Also known as spongy bone and cancellous bone.

tumpline: A strap or sling passed around the chest or forehead to help support a pack carried on a person's back.

unimanual: The act of using either the left or right hand and arm for an activity.

viscoelasticity: Having viscous and elastic properties so that the application of stress may cause temporary deformation if the stress is removed quickly but permanent deformation if the stress is maintained.

Volkmann's canals: Small channels in bone that transmit blood vessels from the periosteum into the bone and that lie perpendicular to and communicate with the Haversian system.

Wolff's law: The law that every change in the form and the function of a bone, or in the function of the bone alone, will lead to changes in its internal architecture and in its external form.

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