Cam Morphology in the Human Hip

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ABSTRACT

A growing interest exists in the diagnosis and treatment of femoroacetabular impingement. Although cam morphology of the proximal femur may conceptually appear to be a relatively simple topographical aberrancy, it is actually positioned amid a complex developmental, kinematic, and biomechanical region of the human body. The authors introduce a new classification scheme and review the historical and anthropological considerations, biomechanics, and genetic factors involved in cam morphology.

In the past decade, femoroacetabular impingement has been the subject of a rapidly increasing volume of orthope-
Cam morphology | Ng & Ellis

is the consequence of an aspherical as the tilt and pistol-grip deformity, respectively. An original description of this asphericity can be traced back to Charles and Trinkaus as a marked extension of the articular surface of the femoral head onto the anterosuperior surface of the neck. Poirier and Charpy and Kostick further described the “facet,” and Odgers documented the prevalence of an “eminencia articularis colli femoris” in male (70% to 88%) and female (29% to 30%) young adult skeletons in 1931. The implications of impingement against the acetabular margin during squatting motions in early humans were explored by multiple early investigators. The effects of local soft tissue tension, such as the zona orbicularis, the iliofemoral ligament, and the iliopsoas and rectus femoris muscles, have been proposed as potential causes.

ANTHROPOLOGY AND DEVELOPMENT

The evolution and comparative anatomy of this region have been meticulously described and debated for more than a century by anthropologists because it plays a pivotal role in the emergence of human bipedalism. Readers here are referred to discussions by Lovejoy and others. Of particular interest is the developmental pathway of the proximal femur in humans and other mammals. The bony femur arises from a cartilaginous anlage through a combination of endochondral and intramembranous ossification. At the center of the diaphysis, the primary center of ossification forms and advances toward the end of the bone. Likewise, secondary centers of ossification appear and expand radially within the chondroepiphyses (Figure 1). Although shear stress of chondrocytes promotes proliferation followed by hypertrophy and ossification, intermittent hydrostatic pressure preserves the cartilage state, stabilizing the ossification growth front and defining the thickness of articular cartilage. The growth plate, or physis, is formed first at the leading edge of the primary ossification center, then becomes a stratified layer of cartilage interposed between the primary and secondary ossification centers.

Serrat et al analyzed 2 patterns of proximal femoral ossification encompassing a majority of extant species. In many, particularly the cursorial types, the secondary ossification center for the greater trochanter and the femoral head arise separately within the chondroepiphysis but coalesce later, similar to the proximal humerus. Coalescence of the ossification centers within the chondroepiphysis leads to a straighter femoral head–neck interface, termed coxa recta (Figure 2). In others, including humans, they arise and remain separate throughout development (Figure 3).

Lovejoy aptly reported that although the inferior femoral neck is simply the medial femoral metaphysis, in some ways the superior portion is conceptu-
Histomorphometric analysis in
Prior demonstrated
provides mechanical support. At the proximal femur, these structures differ from other locations, and together with the interepiphyseal area were named the perichondrial fibrocartilaginous complex by Chung et al. Between 6 to 13 years, the perichondrial complex decreases in size and mechanical support until it comprises a rim of articular cartilage at the periphery of the physeal–metaphyseal junction of the femoral head. Histomorphometric analysis in rats has demonstrated RNA expression involved with morphologic changes in these specific regions.

Starting in early childhood and continuing until adolescence, biologically induced structural modifications of the physis to withstand shear stress occur. These changes coincide with the development of familiar trabecular patterns in the metaphysis and similar findings in the trochanteric physeal morphology. Mammillar processes and undulations in the physis allow for interdigitation with the metaphysis. Peripheral lappets, or extensions of the epiphysis and articular surface over the femoral neck, become evident in areas of shear stress. Ogden reported that an osseous extension, analogous to the groove of Ranvier, occurs at the junction of the capital and interepiphyseal physes. Similarly, Siebenrock et al demonstrated that anterosuperior extension of the epiphysis and capital physeal scar contributes to a convex head–neck junction as opposed to the typical concave curvature.

The susceptibility of the physis to intense and varied loading and the ability of the physis to affect subsequent morphology have been described. Prior to skeletal maturity, the protein nature of the physis manifests in numerous ways. After angulated healing of diaphyseal fractures, the asymmetric growth of the physis enables remarkably rapid realignment of adjacent articular surfaces. It has been postulated that eccentric physeal or periphyseal growth is responsible for cartilage-capped sessile and pedunculated exostoses known as osteochondromas.

**BIOMECHANICS**

An ubiquitous and indispensable focal point of any discussion on the biomechanics of the hip is Wolff’s law. Combined with the principle of functional adaptation as a self-organizing process introduced by Roux, the mathematical optimization of bony architecture has been used to explain the structure of many osseous locales, most notably the proximal femur. The exact nature of Wolff’s law for bone remodeling has been disputed in multiple regards, such as the necessity of perpendicularly intersecting trabeculae correlating to lines of stress and the emphasis on mathematical laws of maximal strength and minimal weight guiding bone formation. Nevertheless, the general paradigm intertwining mechanical loading and biologic adaptation with structure and morphology is convincing.

Multiple aspects, gleaned from interdisciplinary work, are potentially germane to cam morphology and deserve particular attention because they expand on the rudiments of orthopedic learning. Although little debate exists that the principal compressive group of trabeculae aligning with the inferomedial neck and calcar is predominantly under compression, the commonly named principal tensile group has been long recognized as a possible misnomer. The trabecular bone structure along the inferior femoral neck is significantly more anisotropic and superoinferiorly oriented than the superior femoral neck.

Although the proximal femur loaded in isolation may function similar to the static cranes in Wolff’s trajectory theory, the compressive forces applied by the abductor gluteal muscles specialized in humans likely offset a significant portion of the tensile load on the superior femoral
In addition to the trabecular patterning, the orientation and development of these muscles may explain the relative paucity of the cortical bone in the superior femoral neck in humans relative to chimpanzees. It has been postulated that the arcuate (or tensile) trabecular group functions as a flying buttress to assist in the transfer of compressive load to the cortex of the shaft, similar to the Gothic arches in the internal aspect of diaphyses.

The isotropic nature of trabecular orientation in the region corresponding with the confluence of the compressive and arcuate groups likely reflects varied stress directions and adaptation at that location. Although weight-bearing lamellae appear between 3 to 4 years of age, the epiphyseal plate prevents their proximal extension in childhood and, even in early postadolescence, a well defined but subtle breach in continuity exists at the physeal scar. Three-dimensional analysis demonstrates distinct structural differences in the cancellous structure of the former capital epiphysis and the metaphysis, with the compressive and arcuate groups intersecting at the central third of the epiphyseal scar. Unlike the continuous loads used by many studies supporting the well known Heuter-Volkmann law, the nature of dynamic stress applied to the growth plate during in vivo activity is likely far more complex. Unlike other joints, such as the knee, the hip is subject to forces applied in a variety of directions based on the position of the limb and activity of the patient.

**Classification System**

For clinical and research purposes, cam morphology should be divided into at least 3 broad categories: primary developmental, secondary developmental and postdevelopmental. As recognized previously, sequelae of other conditions, such as slipped capital femoral epiphysis, Legg-Calve-Perthes disease, and surgically treated developmental dysplasia of the hip, can manifest as asphericity of the femoral head, reduced head-neck offset, and secondary developmental cam morphology.

Postdevelopmental cam morphology is often encountered in elderly adults with marginal femoral head osteophytes, loss of femoral head sphericity, and other signs of osteoarthritis (Figure 5). The pathogenesis of the degenerative cam exostoses has multiple proposed explanations, including decreased hydrostatic pressure at the joint margin, direct impaction onto the acetabular rim, obligatory shaping of the head over years of predominantly flexion-extension motion, and late manifestations of primary developmental cam morphology. The often present bump in patients with underlying cam morphology has been hypothesized as a reactive phenomenon, which results in bone deposition.

Primary developmental cam morphology likely represents a growth response to increased stress at the physis and its associated structures (Figure 6). Peripheral lappets, epiphyseal extension, and the perichondral fibrocartilaginous complex are normal structures in most individuals, anterior displacement and external rotation of the femoral neck relative to the capital epiphysis through the physis and resultant callos formation can cause prominence of the anterosuperior head-neck junction and secondary cam morphology.
as determined by basic human skeletal morphology. The interaction between the trochanteric physis, the capital physis, and the interepiphyseal area during growth contributes to the intrinsic biologic component of proximal femoral structure. The mechanobiological hypothesis, described by Carter and Beaupre and Pearson and Lieberman, incorporates the effect of strain and the response of bone in morphology. A certain loading threshold, roughly similar to Frost’s mechanostat hypothesis and trabecular distribution and orientation, is likely necessary to instigate changes associated with a progressive continuum of cam morphology. The basic multicellular unit provides an answer to the questions posed by Wolff’s law on idealized bone design. As stated by Huiskes, “There are no mathematical optimization rules for bone architecture; there is just a biological regulatory process, producing a structure adapted to mechanical demands.” At the cellular level, shear loads may have priority over tension and compressive loads by evoking different biophysical stimuli. Young adolescents subjecting their hips to increased articular hydrostatic pressure and periphsyal shear stress likely induce local cellular responses that result in global alterations in proximal femoral morphology.

Throughout history, the proximal femur has undergone multiple evolutionary iterations. The earliest proximal femurs were relatively flat and hinge-like. Later, a more roller-shaped femoral head and neck enabled the hip increased sagittal freedom of motion in cursorial creatures. For more nimble creatures, rotation and abduction of the hip demanded a more spherical femoral head. Bipedal gait in humans has heralded multiple changes in musculoskeletal anatomy and pathology, and although the spherical femoral head persists in most individuals, primary developmental cam morphology may represent an adaptation to varied modes of increased loading. Despite a general resemblance to an earlier quadruped coalesced hip, it is likely a further refinement of the human hip in response to an altered mechanical environment. Progressive increase in skeletal chondro-osseous complexity has been shown on a taxonomic level to mirror mechanical demands and terrestrial imperatives. Vigorous sports during late childhood, adolescence, and early adulthood have been associated with cam morphology, and attention to the physis and epiphysis in this age group has been made by others.

Future research, finite-element and epidemiological, should be devoted to defining exactly what activities predispose to this phenomenon. Likely, based on our clinical observations, stereotyped loading alone, such as inline running, is not sufficient to lead to primary cam morphology but, rather, lateral movement, pivoting, and other activities that provoke elevated multidirectional shear stress at the level of the physis during hip loading are required. Primary cam morphology is not an isolated hip finding in current and former athletes, but rather 1 of multiple musculoskeletal attributes, such as genu varum and lumbar sacralization, that may be associated with future symptomatology and compromised joint longevity. Alterations in the mechanobiologic milieu may be responsible for the constellation of findings associated with cam morphology, such as a wider neck, larger head, and decreased head–neck ratio.

**GENETICS, EPGENETICS, AND PHENOTYPIC PLASTICITY**

A recent sibling study demonstrated a potential genetic predisposition for cam morphology, and a radiographic study found a lower prevalence of cam impingement in Asian patients with osteoarthritis. Variation exists in skeletal segment proportions of different race humans and

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**Figure 5:** Anteroposterior radiograph demonstrating degenerative cam morphology. Note the appearance of congruent cystic and osteophytic changes and trabecular alignment on both sides of the joint.

**Figure 6:** Anteroposterior radiographs demonstrating primary developmental cam morphology (A, B).
endow each with differing capabilities.\textsuperscript{36} Emphasizing the role of phenotypic and developmental plasticity, West-Eberhard\textsuperscript{37} offered an explanation in which morphological innovation can arise from an exogenous initiator and lead to phenotypic reorganization or developmental recombination in an individual.

Cam morphology of the hip and its distribution among the human population may be an example of this phenomenon. Highly evolved complex structures in organisms are not the end result of random genetic mutations and the sieve of natural selection, but also the product of a more potent driving force, such as adaptation through phenotypic plasticity. In this manner, altered behaviors and biomechanical demands brought about by new environments can lead to novel morphologies. If genetic assimilation of the phenotypic alternative occurs, return to the ancestral environment will not result in complete reversion to the ancestral type.\textsuperscript{38}

Phenotypic plasticity itself is variable, and not all individuals exposed to the same biomechanical stimulus will have the same magnitude of response.\textsuperscript{39} Epigenetic changes and mismatch between juvenile and adult environment and lifestyle\textsuperscript{80,91} may lead to maladapted, mature, morphologic phenotypes and prematurity disease. Furthermore, the postdevelopmental skeleton has a reduced ability to adapt to altered biomechanical stimulus and may respond differently than a juvenile specimen. Phenotypic plasticity and epigenetics likely play a fundamental role in the development of numerous widespread conditions, including obesity, cancer, cardiovascular disease, and osteoarthritis.\textsuperscript{91-95}

**Future Directions**

Numerous other exciting directions exist for research for cam morphology and hip impingement. Evidence that the hip is not a precise ball-and-socket joint deserves attention in future studies.\textsuperscript{96,99} The extent that proximal femoral cam morphology mimics other cam-like joints that have undergone evolution in primates and humans, such as the metacarpal head and medial femoral condyle, may elucidate interesting kinematic findings and soft tissue implications as well.\textsuperscript{100-105}

**References**


