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REGIONAL TRABECULAR ANISOTROPIES SUGGEST A 'TWO-DOMAIN' LOADING REGIME IN THE PROXIMAL FEMUR

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Introduction Determining how strain-related stimuli mediate cortical/trabecular bone maintenance in the human proximal femur can have important implications in orthopaedic practice. For example, interventions aimed at enhancing fracture fixation and healing, and/or ensuring the maintenance, or even the augmentation, of bone mass during normal development or after the implantation of intra-medullary prostheses depend on a clear understanding of the mechanisms that govern the attainment/maintenance of biomechanical competence in this region.

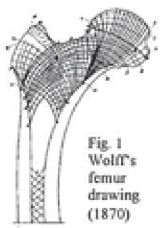

Fig. 1 Wolff's femur drawing (1870)

Conventional wisdom teaches that the proximal femur is functionally adapted for transmission of tension/compression stresses associated with habitual bending. This idea was popularized by Julius Wolff's well-known trajectorial theory of cancellous bone architecture (1,8). According to Wolff, the proximal femur, when viewed as a trajectorial structure, exhibits curvilinear trabeculae with 90° (orthogonal) intersections, which optimally resist/transmit tension/compression stress trajectories (Fig. 1). He went as far as to admonish G.H. Meyer (1867) for not drawing orthogonally intersecting trabeculae (2,8). However, Meyer's drawing appears accurate (Fig. 2). Recent finite-element analyses of physiologic loading of the proximal femur suggest an alternative to the tension/compression interpretation for stress transfer across this region (3,4). These analyses suggest that the expanded trochanteric region allows for the appropriate mechanical advantage and attachment site for muscles rather than for structural integrity of the bone (3), and that the femoral neck is loaded in prevalent shear (4). Investigations of cortical collagen fiber orientation suggest that the intertrochanteric region separates two loading regimes distinguished by differences in predominant loading modes: 1) shear in the torsionally loaded femoral neck, and 2) bending, producing tension/compression, in the lesser trochanter/sub-trochanteric region (5,6). To further test this 'two-domain' hypothesis we examined regional cancellous bone architecture. It was anticipated that in a prevalent bending environment opposing trabecular tracts will exhibit orthogonal intersections and will be symmetrical. In contrast, in regions subject to prevalent shear/torsion the opposing trabecular tracts will be non-orthogonal and non-symmetric.

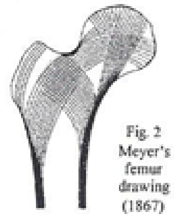

Fig. 2 Meyer's femur drawing (1867)

Methods Thin (5mm) sections of 16 Caucasian human femora (age range: 20-70) were obtained in the plane of anteversion (femoral head and neck) and coronal plane (calcar femorale to sub-trochanteric). Using radiographs, 1 pair of obvious arched trabecular tracts were traced in the femoral neck (FN) and lesser trochanteric (LT) regions. Cartesian data of each trabecular tract (superior & inferior in FN; lateral & medial in LT) (Digitize-Pro v4.1, Y. Danon, Arad, Israel) were fit to linear and non-linear equations ($r^2 > 0.96$) (Table Curve™2Dv4, Jandel, San Rafael, CA). Angles of intersections formed at the trabecular arch apices were also measured. Calcanei from adult sheep and deer served as controls for trabecular architecture in a known tension/compression environment (Fig. 3) (7); ten bones from each species were evaluated using the same methods. Stress trajectories in a mathematically constructed, simply loaded, short, cantilevered beam were similarly analyzed (Fig. 4) (8).

Results In 62.5% (10/16) of the human femora, the best-fit equation for at least one of the intersecting trabeculae in the femoral neck differed from the equation for the trabecular tract s in the trochanteric region. In contrast, all of the trabecular tracts in the trochanteric region and calcanei, and stress trajectories of the mathematically constructed beam were best-fit to the same equation (which typically differed from those in the FN). Trabecular intersections in the human proximal femora were typically non-orthogonal in the neck (69°±12°; range 51°-90°). In contrast, trabecular tracts were typically orthogonal in the trochanteric region (92°±6°; range: 82°-105°) ($p<0.01$ vs. FN) and calcanei (90°±7° vs. FN), and were invariably orthogonal (90°) in the beam.

Discussion These results corroborate previous investigations of anisotropy in cortical collagen fiber orientation (CFO) suggesting that disparate loading conditions, distinguished by differences in prevalent loading modes, exist in the proximal femur (5). This 'two-domain' loading regime questions the validity of using a quasi-cantilevered beam subject to habitual bending as the "gold standard" for modeling stress transfer across this region (9). In turn, the mechanisms that mediate the attainment/maintenance of these disparate regional trabecular and cortical CFO morphologies may be fundamentally different. For example, habitual non-uniform strain distributions may affect cellular accommodation such that there are important regional differences in sensitivities to specific strain characteristics (e.g., mode, magnitude, rate) (10), which, in turn, affect/govern remodeling and modeling activities.

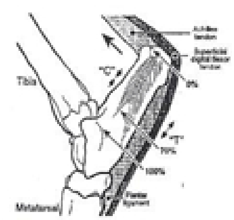

Fig. 3 Deer Calcaneus
C = compression., T = tension

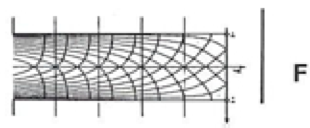

Fig. 4 Simply loaded cantilevered beam

Rigorous evaluation of typical loading patterns across the proximal femur is complicated by difficulties in obtaining in vivo strain measurements. In the only study reporting in vivo strain data that we are aware of, Aamodt et al. (11) attached a rosette strain gauge to the lateral trochanteric region of two patients. Based on data showing predominant tension in this region, they inferred that bending prevails here (Fig. 5). Previous CFO data (5) and data reported herein are consistent with this interpretation.

Non-orthogonal/non-symmetric trabeculae in the femoral neck contrast with the orthogonal/symmetric (O/S) tracts in the lesser trochanteric region and calcanei, ***and*** O/S stress trajectories in the simple beam. Such regional disparities suggest that prevalent loading in the femoral neck differs from the calcanei and lesser trochanteric region. Finite-element analyses suggest that the non-orthogonal intersections in the femoral neck may be optimized for shear stresses produced by habitual torsion (4). Wolff's conception that the proximal femur closely approximates a trajectorial structure, however, is pervasive in current thought and literature. This appears to be rooted in the "obvious" correspondence of preferred trabecular orientations with presumed stress trajectories. In contrast, data showing anisotropic trabecular architecture and cortical CFO patterns suggest that fundamentally different 'typical' loading conditions exist in the femoral neck and lesser trochanteric regions.

References **1)** Wolff, 1870; **2)** Meyer, 1867; **3)** Lotz et al., 1995, Osteop Int; **4)** Pidaparti & Turner, 1997, J. Biomech; **5)** Skedros et al., 1999, J Bone Min Res, abst; **6)** Kalmey & Lovejoy 2002, Bone; **7)** Su et al., 1999, J Exp Biol; **8)** Roesler, 1981, In: Mech Prop of Bone, ASME (by S. Cowin); **9)** Demes et al., 2000, J Human Evol; **10)** Martin & Burr, 1989, Struct, Func, Adapt Compact Bone, Raven Press, 162-3; **11)** Aamodt et al., 1997. J Orthop Res.

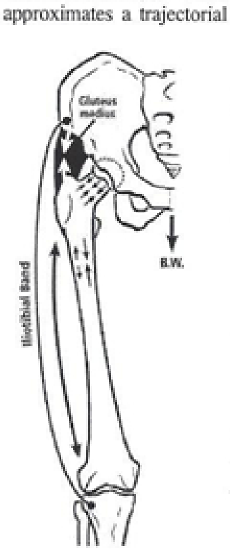

Fig. 5 Hypothesized 'two-domain' loading regime (torsion/compression prevail in the neck)