Comparison of human, primate, and canine femora: Implications for biomaterials testing in total hip replacement

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Abstract: The canine model remains an animal of choice for determining the efficacy and safety of various materials and designs used in human total hip replacement (THR). The primate also is used in orthopedic-related research for studying limb anatomy, gait, and age-related bone loss. In order to better understand the appropriateness of these animal models for human THR, external morphologies of thirty-three adult Caucasian human, sixteen adult chimpanzee, and forty-two adult greyhound femora were compared using osteometric methods. Measured parameters included anteversion angle, cervico-diaphyseal angle, femoral head offset in the frontal plane, and anterior bow profiles along the femoral diaphysis. Although some of the measured parameters were approximately similar between species (e.g., mean cervico-diaphyseal angle of humans and chimpan-zees), the majority demonstrated morphologic differences that may be biomechanically significant for interpreting stress transfer across the hip (e.g., mean anteversion angle and mean normalized femoral head offset between species). Additionally, age-related changes in proximal femoral morphology and gait pattern, as well as species-related differences in local muscle and inertial forces, may result in notably different loading conditions across the hip joint of each species. Therefore, discretion must be exercised when evaluating canine or primate THR materials and designs for potential use in the human hip. © 1998 John Wiley & Sons, Inc. *J Biomed Mater Res,* **40,** 475–489, 1998.

Key words: human femur; chimpanzee femur; greyhound femur; femur morphology; total hip replacement

INTRODUCTION

The canine model remains an animal of choice for determining the efficacy and safety of component designs and materials used in human total hip replacement (THR). While justification for its use has been debated in the past,[1–4] a paucity of comparative morphologic, physiologic, and immunologic studies demonstrates that a thorough understanding of its appropriateness for THR research has not been attained.

Despite its phylogenic similarity to humans, the primate is an unpopular model for THR research. High cost, in addition to ethical and biomechanical considerations, limits its use to orthopedic-related studies of limb anatomy,[5–7] gait,[8–11] and age-related bone loss.[12–16]

To better understand the limitations of the canine as a model for human THR, and the primate as a potentially useful model, this study compares various external morphologic features between adult human, chimpanzee, and canine femora. Comparative human and animal studies of hip anatomy, locomotion, and bone physiology also are reviewed in the context of THR, normal hip function, biomaterials research, and age-related changes in these parameters.

Literature review

Canine

Advocates of the canine model base their support for its use on documented similarities with the human hip in terms of cortical bone microstructure,[2] femoral blood supply,[2,17] and load orientation across the hip.[1] In a study supporting the use of canines, Goel et al.[4] described similar internal (e.g., cancellous bone distribution along the medullary canal of the femur) and external (e.g., cervico-diaphyseal angle) morphologic features between human and canine femora. Based on these data, they suggested that, during walking, the canine generates, as a percentage of body weight,

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loads similar to the human hip. In a similar study of proximal femoral morphology, Bloebaum et al.[18] demonstrated statistically significant differences in various external features (including anteversion and cervico-diaphyseal angles) between human and canine (greyhound) femora. They argued that these differences reflect dissimilar loading environments across the hip joint of each species.

Summer and co-workers[3] reported that various external angles, as well as cross-sectional geometry, in the proximal canine (mongrel) femur differed substantially from those documented in humans.[18–21] The anteversion angle, the cervico-diaphyseal angle, and the medullary canal relative to the external dimensions of the femur were notably larger in canines than in humans.

Sumner et al.[3] also reported that, unlike previous findings in human femora,[19] there was no apparent functional relationship between the anteversion angle and the orientation of principal axes of cross-sectional moment of inertia (CSMI) of transverse sections taken from the proximal femoral diaphysis. It has been suggested that the correspondence of anteversion and principal CSMI axes in the proximal human femur represents the presence of customary, directionally consistent anterolateral to posteromedial bending across the hip joint during typical weight-bearing activities.[19] Differences in this and other morphologic relationships suggest that there may be important disparities in characteristics of customary functional loadings across human and canine hip regions.

Although the above-mentioned studies addressed important criteria for selecting a THR model, other biologic processes, including aging and bone remodeling, may influence the clinical longevity of human THRs. For example, age-related changes in the proximal femur are important factors to consider when attempting to provide elderly patients with femoral endoprostheses designed to last at least twenty years. Unlike canines, proximal human femora, especially among females, undergo age-related changes in various morphologic features,[18,19,21–27] including decreases in the cervico-diaphyseal angle and increases in subperiosteal dimensions and cross-sectional moments of inertia (CSMI) of transverse sections taken from the proximal femoral diaphysis. Despite data from greyhounds up to ten years of age,[18] similar age-related changes in proximal femoral morphology have not been identified for canines. This suggests that an experimentally successful long-term performance of THR in a canine model may not lead to a similar outcome in elderly patients.

Primate

At a Canadian Orthopaedic Association meeting, Grobbelaar[28] advocated the development of a primate

THR model with immunologic responses similar to humans. To date, limited use of nonhuman primates in THR-related research can be attributed to differences in locomotion and bone physiology as compared to humans. Other factors, such as cost and ethical concerns, also have been impediments. The chimpanzee, for example, has been termed a 'knuckle walking' quadruped that occasionally assumes bipedal postures.[9,11,29] Despite having hindlimb dominance similar to humans, its walking pattern differs in terms of velocity and muscle utilization.[8–10] These differences, and others, may have important implications for extrapolating THR results from implant studies using this species to the human clinical condition.

Locomotion–all three species

By exhibiting different gait patterns and relative limb-weight distributions, each species commonly may experience different loading conditions across its hip. More simply, the canine walks on four limbs, the chimpanzee on four with occasional bipedal postures, and the adult human exclusively on two.

Adrian et al.[30] estimated that during a typical gait cycle the canine places three paws on the ground most of the time. They concluded that if a canine hip or hindlimb were injured, its weight-bearing contribution would be reduced by compensatory changes in the animal's walking pattern and relative limb-weight distributions. This degree of compensation is not possible in the human and must be carefully considered when extrapolating data from canine studies[31–36] using unilateral THRs to the human clinical condition.

During the two- or three-legged stance of gait, the single weight-bearing hip of the canine is subject to a force of 1.5 to 1.7 times body weight.[37,38] In human single-legged stance, this corresponding force is approximately 2.4 to 5.0 times body weight.[39–45] Similar studies of hip loading forces in the chimpanzee could not be located.

Grelsamer et al.[38] showed that the canine body weight acts at a point on the spine approximately 40% of the distance from the shoulders to the pelvis. Consequently, a canine typically can place at least twice as much weight on its forelimbs than on its hindlimbs,[46] using the former primarily for deceleration and the latter primarily for propulsion.[47] Humans perform both functions with their hindlimbs. Stance time during gait additionally has been shown to be longer for canine forelimbs than for hindlimbs.[48] This suggests that during a typical gait cycle greater force of relatively longer duration is applied to the forelimbs than to the hindlimbs of the canine.

In a study comparing gait patterns of humans, chimpanzees, and canines, Kimura[49] concluded that forelimbs of nonprimate quadrupeds (e.g., canines)

are more important than hindlimbs for braking, steering, and support. Similarly, he postulated that forelimbs of nonhuman primates are used primarily for steering and braking, with hindlimbs acting in support and acceleration. He called nonprimate quadrupedal locomotion ''front steering—front driving'' and nonhuman primate locomotion ''front steering—rear driving.''

Using electromyography (EMG), Ishida et al.[50] detailed muscular activity in 18 regions of 16 hindlimb muscles in chimpanzees during bipedal standing. Compared to humans, chimpanzees exhibited increased EMG readings for regions of the gluteus maximus, the vastus medialis, the vastus lateralis, and the long head of biceps femoris. These data suggest that chimpanzees expend relatively greater energy than humans to maintain bipedal stance, presumably applying greater stress across their hip joints.

Morphometric study of human, primate, and canine femora

External morphologic features examined in the present study have been suggested by previous investigators[3,4,18,19] as being important for understanding the biomechanics of the human hip. Several studies[3,4,18,19] have described these various features in humans and canines, discussing them in the context of THR, normal hip function, biomaterials research, and age-related changes. Despite an extensive literature review, studies that quantified and compared these morphologic features in primates could not be located.

The present study attempts to clarify the potential use of canines and primates as animal models for human THR by statistically quantifying, examining, and comparing various external morphologic features among adult human, chimpanzee, and canine femora. Interspecies and intraspecies analyses of age-related morphologic changes in the proximal femur also were conducted.

MATERIALS AND METHODS

Bone specimens examined included thirty-three Caucasian femora (20 males, 13 females; all skeletally mature; mean age 49 ± 16 years, range 17–89 years), sixteen chimpanzee femora (5 males, 5 females, and 6 unspecified age and gender; all skeletally mature; mean age 23 ± 10 years, range 8–39 years), and forty-two greyhound femora (19 males, 23 females; all skeletally mature; mean age 3 ± 1.75 years, range 1–10 years). Morphometric parameters measured included (see Table I Abbreviations and Symbols): cervico-diaphyseal angle [CD, Fig. 1(a)]; total bone length [L_t, Fig. 1(a)]; biomechanical length (the segment from one-half the distance between the inferior distal condyles to the

TABLE I
Abbreviations and Symbols

AV	anteversion angle
CD	cervico-diaphyseal angle
L_t	total bone length
L_b	biomechanical length
L_{ho}	femoral head offset in the frontal plane
L_{ht}	distance from the femoral head center to the lateral margin of the greater trochanter
L_{hd}	distance from the femoral head center to the longitudinal axis of the diaphysis
HD_{ap}	femoral head diameter in the anteroposterior direction
HD_{si}	femoral head diameter in the superoinferior direction perpendicular to the cervical axis of the femoral neck
AB	anterior bow
AB_{max}	maximum anterior bow of the femur
AB_{index}	(AB_{max} − 10 cm)/biomechanical length
Z axis	longitudinal axis of the femoral diaphysis
C axis	cervical axis of the femoral neck

intersection between the longitudinal diaphyseal axis and the external surface of the proximal femoral cortex) [L_b, Fig. 1(a)]; femoral head diameter in the superoinferior direction perpendicular to the cervical axis of the femoral neck (C axis) [HD_{si}, Fig. 1(a)]; femoral head offset in the frontal plane [L_{ho}, Fig. 1(a,c)]; distance from the femoral head center to the lateral margin of the greater trochanter [L_{ht}, Fig. 1(b)]; distance from the femoral head center to the longitudinal axis of the diaphysis [L_{hd}, Fig. 1(b)]; femoral head diameter in the anteroposterior direction [HD_{ap}, Fig. 1(c)]; anteversion angle [AV, Fig. 1(c)]; and anterior bow profiles along the femoral diaphysis (Fig. 2).

Anatomical axes and three-dimensional orientation of each femur were established with the posterior condyles placed flat on an osteometric table, as described by Ruff.[19] The only modification made was in the determination of the longitudinal axis (Z axis) in the lateral view of the greyhound femoral diaphysis. Unlike human femoral diaphyses, oriented greyhound femoral diaphyses do not display a distinct anterior ''low'' point along the anterior cortex of their supracondylar region[18,19] (see Fig. 2). Consequently, the distal mark used to determine the longitudinal axis (Z axis) in the lateral view of the greyhound femoral diaphysis was made at the proximal extent of the prominent epicondylar tubercle.

Marking of the femoral head center, and measurements of bone length, anterior bow, and femoral angles all were made with each specimen oriented on an osteometric table.[18,19] Biomechanical and total bone lengths were measured using a sliding vernier caliper fixed to the side of the table. Other measurements were determined with a hand-held sliding digital caliper. The femoral head center was determined with the use of a transparent template with imprinted concentric circles and a central drill hole. With the template placed against the femoral head, the head center was marked through the drill hole while viewing the head through the template. This was done while viewing in both anteroposterior and superoinferior directions.

Figure 1(a–c) illustrates most of the measurements made on each specimen. Biomechanical and total bone lengths
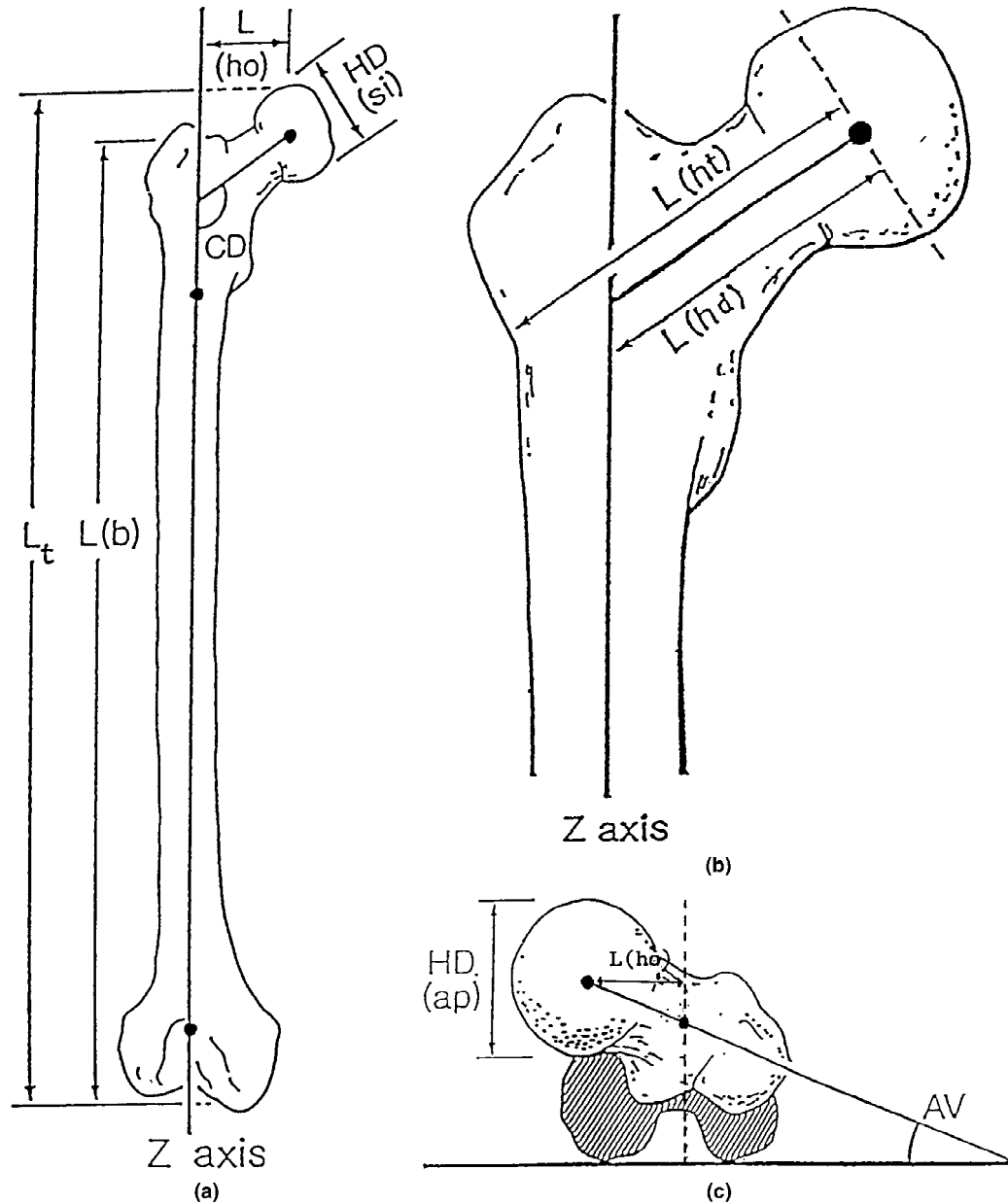
Figure 1. (a) Morphometric parameters measured in this study for the comparison between human, chimpanzee, and greyhound femora. These parameters included: total bone length (L_t), biomechanical length (L_b), cervico-diaphyseal angle (CD), femoral head offset in the frontal plane (L_{ho}), and femoral head diameter in the superoinferior direction perpendicular to the cervical axis of the femoral neck (HD_{si}). The Z axis represents the longitudinal diaphyseal axis. (b) The distance from the femoral head center to the lateral margin of the greater trochanter (L_{ht}) and the distance from the femoral head center to the longitudinal axis of the diaphysis (L_{hd}) were both measured in the anteversion plane parallel to the cervical axis of the femoral neck. The Z axis represents the longitudinal diaphyseal axis. (c) Illustration depicting the femoral head diameter measured in the anteroposterior direction (HD_{ap}) and the femoral head offset measured in the frontal plane (L_{ho}) (projected here in an axial view). The point and the dotted line are in the same plane, perpendicular to the longitudinal axis of the diaphysis (directed straight at the viewer). The anteversion angle (AV) is formed by the inclination of the proximal femoral head and neck from the transcondylar axis of the distal femur in the frontal plane of the axial view.

were measured parallel to the longitudinal axis of the diaphysis (Z axis). Biomechanical length (L_b), a segment defining the "true" longitudinal axis through the proximal and distal regions of the femur,[19] was measured from one-half the distance between the inferior (distal) condylar edges (when viewed in the anteroposterior direction) to the point where the longitudinal axis of the diaphysis intersects the external surface of the proximal femoral cortex [Fig. 1(a)].[18,19] A location at one-half the distance between inferior condylar edges was used to reduce variability due to asymmetrical sizes between femoral condyles, which occurs in normal adult humans,[18,19] occasionally in chimpanzees (unpublished data), but rarely in greyhounds.[18] Total bone length (L_t) was defined as the distance measured from the
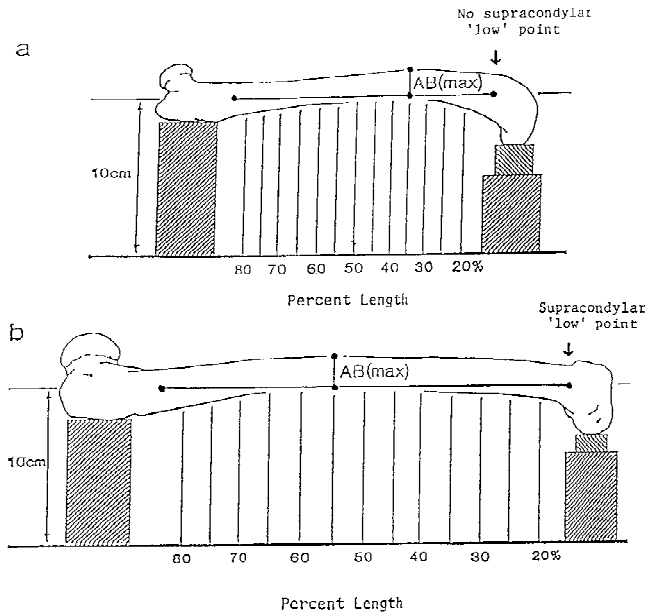
Figure 2. Anterior bow (AB) measurements were made with the bone oriented on an osteometric table. Prior to making these measurements, each femur was elevated 10 cm above the original level of the longitudinal axis in the lateral view. Measurements were made along the femoral diaphysis at 5.0% increments (percent length), from the 20% (distal) location to the 80% (proximal) location of the biomechanical length (L_b). The illustration depicts how these measurements were made on a greyhound femur (a) and a human femur (b). AB_{max} represents the point of maximum anterior bow on each femur. Note that the greyhound femoral diaphysis (a), unlike the human femoral diaphysis (b), does not have a distinct anterior "low" point along the anterior cortex of its supracondylar region.

superior point of the femoral head or the greater trochanter to the location one-half the distance between the most inferior edges of the condyles [Fig. 1(a)]. This depended on the species used. In contrast to humans and chimpanzees, greyhounds exhibit a more proximal greater trochanter relative to the femoral head [see Fig. 2(a)].

Lengths from the femoral head center to the lateral margin of the greater trochanter (L_{ht}) and to the longitudinal axis of the diaphysis (L_{hd}) both were measured in the plane of anteversion parallel to the cervical axis of the femoral neck [C axis, Fig. 1(b)].[18,19] Additionally, the femoral head offset (L_{ho}) was measured in the frontal plane as the perpendicular distance from the femoral head center to the longitudinal diaphyseal axis of the oriented femur [Z axis, Fig. 1(a)]. Femoral head diameters were measured in the anteroposterior (HD_{ap}) and superoinferior (HD_{si}) directions [Fig. 1(a,c)]. The latter was measured perpendicular to the cervical axis of the femoral neck [C axis, Fig. 1(a)].

Anteversion (AV) and cervico-diaphyseal (CD) angles were measured using a goniometer, similar to methods employed by Ruff[19] [Fig. 1(a,c)]. In order to reduce measurement errors, the present study avoided any use of indirect radiographic techniques to measure external angles of the proximal femur.[51,52] These indirect techniques have been used by previous authors.[3,18,52]

Anterior bow (AB) measurements also were made with

the bone oriented on an osteometric table.[18,19] Prior to making these measurements, each oriented femur was elevated 10 cm above the original level of the longitudinal axis in the lateral view [Fig. 2(a,b)]. This elevation allowed measurements to be made in the same plane of reference so that subsequent interspecies and intraspecies comparisons could be made.[18] Anterior bow measurements were made along the femoral diaphysis at 5.0% increments, from the 20% (distal) location to the 80% (proximal) location of the biomechanical length. At each percent length, the distance from the anterior cortex to the surface of the osteometric table was measured. To compare the degree of relative curvature along the femoral diaphysis within and between species, an anterior bow index (AB_{index}) was calculated:

$$AB_{index} = \frac{(AB_{max} - 10 \text{ cm})}{\text{Biomechanical Length}}$$

where AB_{max} = point of maximum anterior bow at one of the measured locations.[18,53,54]

In previous studies,[18,23,55] variability due to animal size was reduced by dividing measurements by the biomechanical length and multiplying by 100. This approach is supported by results from an ontogenetic study of human femora, conducted by Ruff,[56] which showed isometry between bone length and cross-sectional geometric properties. In accordance with Ruff, and in order to allow intraspecies and possibly interspecies comparisons between previous and future investigations, data in the present study were similarly normalized (where appropriate) to the biomechanical length. Absolute mean values and standard deviations also are provided in most cases.

Differences between parameters were evaluated statistically using a nonparametric Mann–Whitney test with significance set at $p < .05$. Analyses were conducted on all data for interspecies and intraspecies comparisons, including comparisons between different age groups (Table II).

RESULTS

The means and standard deviations of various measurements made in the three species are presented in Table III. Percent or degree differences between means for interspecies comparisons are listed in columns five through seven of Table III.

In interspecies comparisons, without distinguishing age or gender, several statistically significant morphologic differences were identified (Table III). Human bones have a smaller mean anteversion angle (mean AV 10.0° ± 3.4°, $p < .05$) and a smaller mean cervico-diaphyseal angle (mean CD 131.5° ± 7.5°, $p < .05$) than greyhounds (mean AV 14.9° ± 3.7°; mean CD 136.7° ± 4.5°). In contrast, human bones have a similar mean cervico-diaphyseal angle, but a larger mean anteversion angle ($p < .05$) than chimpanzees (mean CD 130.2° ± 3.3°; mean AV 2.6° ± 9.8°). Of the sixteen chimpanzee femora, five (31 %) were retroverted. No human or greyhound femora were retroverted.

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TABLE II
General Information on Interspecies and Intraspecies Comparisons of Different Age Groups

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Age Groups	Total Number of Specimens	Mean Age (Years)	Age Range (Years)	Average Life Span (Years)	Comments
HUMAN					
Younger age group:	$n = 17$ (9M, 8F)	38 ± 11	17 to 51		Three specimens of unknown age (all males) were excluded from the age-related analysis. Maximum age for the younger age group was set at 55, higher than the commonly accepted age of 51 for menopause.
Older age group:	$n = 13$ (8M, 5F)	63 ± 8	58 to 89	74 to 75	
CHIMPANZEE					
Younger age group:	$n = 5$ (2M, 3F)	15 ± 5	8 to 20		Six specimens of unknown age were excluded from the age-related analysis. Maximum age for the younger age group was set at 25, which was based on age-related changes in skeletal and reproductive biology observed in nonhuman primates from natural habitats and/or captivity.[7,57–59]
Older age group:	$n = 5$ (3M, 2F)	32 ± 5	27 to 39	36 to 37*	
GREYHOUND					
Younger age group:	$n = 19$ (10M, 9F)	1.5 ± 0.4	1 to 3		Maximum age for the younger age group was arbitrarily set at 3 years.
Older age group:	$n = 23$ (9M, 14F)	4.33 ± 1	4 to 10	12[†]	

*Chimpanzees are known to live past 40 years in the wild and 50 years in captivity.[57]
[†]See reference 60. M = males; F = females; n represents the number of specimens in a sample.

Chimpanzees, on average, have a 4.6% longer mean normalized distance from the femoral head center to the lateral margin of the greater trochanter (L_{ht}/L_b) than have greyhounds ($p < .05$). Humans, on average, have a 7.1% and an 11.7% shorter corresponding mean normalized distance (L_{ht}/L_b) than have greyhounds and chimpanzees, respectively ($p < .05$). Humans and greyhounds have a comparable mean normalized femoral head offset (L_{ho}/L_b) and mean normalized distance from the femoral head center to the longitudinal axis of the diaphysis (L_{hd}/L_b). In chimpanzees, the former (L_{ho}/L_b) was 25.4% longer than in humans and 30.1% longer than in greyhounds ($p < .05$); the latter (L_{hd}/L_b) was 30.3% longer than in humans and 25.1% longer than in greyhounds ($p < .05$).

No statistically significant differences were observed in the comparisons of mean normalized femoral head diameters (HD_{ap}/L_b and HD_{si}/L_b) within each species (Table IV). However, comparisons between species demonstrated statistically significant differences in these features (HD_{ap}/L_b and HD_{si}/L_b; $p < .05$); (Tables III and IV).

The point of maximum anterior bow (AB_{max}) measured on greyhound bones was located at 35% of the biomechanical length (Fig. 3). This differed from the point of maximum anterior bow measured on humans and chimpanzees, which was 55% of the biomechanical length (Fig. 3). Additionally, compared to humans,

chimpanzees and greyhounds have a greater degree of relative curvature along their femoral diaphyses (AB_{index}; $p < .05$); Table III.

The means, standard deviations, and percent or degree differences between means for age-related comparisons are presented in Table V. In humans, two significant age-related differences were identified with increasing age: a 13.4% increase in mean normalized femoral head offset (L_{ho}/L_b; $p < .05$) and a 6.6° decrease in mean cervico-diaphyseal angle (CD; $p < .05$). In chimpanzees and greyhounds, only one statistically significant difference was detected with age in each species: a 6.5% decrease in mean normalized anteroposterior femoral head diameter (HD_{ap}/L_b) of the chimpanzee ($p < .05$) and a 3.1° decrease in mean anteversion angle (AV) of the greyhound ($p < .05$).

Table VI lists similarities and differences found in gender comparisons between human bones. In comparison to male bones, female bones exhibited a 5.1% shorter mean biomechanical length (L_b; $p < .05$), a 16.9% shorter mean normalized femoral head offset (L_{ho}/L_b; $p < .05$), a 5.5% shorter mean normalized femoral head diameter in the anteroposterior direction (HD_{ap}/L_b; $p < .05$), a 4.6% shorter mean normalized femoral head diameter in the superoinferior direction (HD_{si}/L_b; $p < .05$), and a 10.2% greater degree of relative curvature along the femoral diaphysis (AB_{index}; $p < .05$). Compared to male bones, female bones also

TABLE III
Means, Standard Deviations (in Parentheses), and Percent or Degree Differences Between Means (% or Deg. Diff.) of Compared Parameters Between Human, Chimpanzee, and Greyhound Femora

Parameters	Human	Greyhound	Chimpanzee	Human vs. Greyhound (% or deg. diff.)*	Human vs. Chimpanzee (% or deg. diff.)*	Chimpanzee vs. Greyhound (% or deg. diff.)*
n =	33(20M,13F)	42(19M,23F)	16(5M,5F,6unk.)			
L_b	426.7 mm	219.4 mm[†]	273.7 mm	+71.5[‡]	+45.9[‡]	+22.3[‡]
	(27.6)	(9.4)	(14.4)			
L_t	457.1 mm	229.2 mm	291.4 mm	+74.6[‡]	+46.6[‡]	+24.2[‡]
	(29.6)	(8.7)	(14.5)			
L_t/L_b	107.1	104.5	106.5	+2.5[‡]	+0.6	+1.9[‡]
	(1.6)	(2.0)	(1.1)			
HD_{ap}	46.7 mm	23.4 mm	33.9 mm	+74.7[‡]	+32.6[‡]	+37.9[‡]
	(4.1)	(1.3)	(1.6)			
HD_{ap}/L_b	11.0	10.7	12.4	+2.8	−12.0[‡]	+14.8[‡]
	(0.7)	(0.4)	(0.6)			
HD_{si}	46.9 mm	23.2 mm	33.3 mm	+76.3[‡]	+34.9[‡]	+36.9[‡]
	(3.7)	(1.3)	(1.7)			
HD_{si}/L_b	11.0	10.6	12.3	+3.7[‡]	−11.2[‡]	+14.9[‡]
	(0.8)	(0.5)	(0.5)			
L_{ht}	76.1 mm	42.5 mm	54.7 mm	+61.6[‡]	+33.6[‡]	+25.5[‡]
	(8.4)	(4.4)	(4.1)			
L_{ht}/L_b	17.8	19.1	20.0	−7.1[‡]	−11.7[‡]	+4.6[‡]
	(1.7)	(1.1)	(1.7)			
L_{hd}	57.5 mm	31.3 mm	50.1 mm	+64.6[‡]	+13.8[‡]	+48.8[‡]
	(7.8)	(3.1)	(4.6)			
L_{hd}/L_b	13.5	14.2	18.2	−5.1	−30.3[‡]	+25.1[‡]
	(1.7)	(1.3)	(1.6)			
L_{ho}	38.9 mm	19.5 mm	32.1 mm	+74.7[‡]	+19.3[‡]	+51.9[‡]
	(7.8)	(2.5)	(3.4)			
L_{ho}/L_b	9.1	8.7	11.7	+4.5	−25.4[‡]	+30.1[‡]
	(1.7)	(0.7)	(1.3)			
AV	10.0°	14.9°	2.6°[§]	−4.9°[‡]	+7.4°[‡]	−12.3°[‡]
	(3.4°)	(3.7°)	(9.8°)			
CD	131.5°	136.7°	130.2°	−5.2°[‡]	+1.3°	−6.5°[‡]
	(7.5°)	(4.5°)	(3.3°)			
AB_{index}	5.9	6.7	6.9	−12.7[‡]	−15.7[‡]	+2.9
	(0.9)	(0.6)	(1.0)			

Parameters measured included: anteversion angle (AV), cervico-diaphyseal angle (CD), total bone length (L_t), biomechanical length (L_b), femoral head diameter in the anteroposterior direction (HD_{ap}), femoral head diameter in the superoinferior direction perpendicular to the cervical axis of the femoral neck (HD_{si}), distance from the femoral head center to the lateral margin of the greater trochanter (L_{ht}), distance from the femoral head center to the longitudinal axis of the diaphysis (L_{hd}), femoral head offset in the frontal plane (L_{ho}), and degree of relative curvature along the femoral diaphysis [$AB_{index} = (AB_{max} - 10$ cm$)$/biomechanical length]. Parameter abbreviations presented as a ratio indicate normalized data. Differences between parameters were evaluated statistically using a nonparametric Mann–Whitney test with statistical significance set at $p < .05$.

*% Difference between means was calculated as: {[(Species I − Species II)/Species I] + [(Species I − Species II)/Species II]}/2 × 100. ''+'' and ''−'' are defined as: larger and smaller, respectively, than the second species being compared. For example, in human vs. greyhound, AV −4.9° indicates that the human femur has a 4.9° smaller mean anteversion angle than the greyhound femur.

[†]Bloebaum et al.[18] reported a mean biomechanical length (L_b) of 291.6 mm (9.9) for their sample of greyhound femora. This is approximately 72.2 mm longer than the mean biomechanical length reported here. This may represent a typographical error in their reported mean value. M = males; F = females; unk. = age and gender unknown; n represents the number of specimens in a sample.

[§]Sample included 5 retroversions. [‡]$p < .05$.

exhibited a 4.3° larger mean cervico-diaphyseal angle (CD), but this difference was not statistically significant.

Table VII lists percent or degree differences between means for comparisons among the entire greyhound sample to each of the younger and older human and chimpanzee age groups. In the case of greyhound versus younger humans, greyhounds displayed an 8.8% longer mean normalized distance from the femoral head center to the lateral margin of the greater trochanter (L_{ht}/L_b; $p < .05$), a 5.0° larger mean anteversion angle (AV; $p < .05$), and a 12.7% greater degree of relative curvature along the femoral diaphysis (AB_{index}; $p < .05$) than younger humans. When com-

TABLE IV
Intraspecies Comparisons of Femoral Head Diameters in Anteroposterior (HD_{ap}) and Superoinferior (HD_{si}) Directions.

Parameters	Human	Chimpanzee	Greyhound
L_b	426.7 mm (27.6)	273.7 mm (14.4)	219.4 mm (9.4)
HD_{ap}	46.7 mm (4.1)	33.9 mm (1.6)	23.4 mm (1.3)
HD_{ap}/L_b	11.0 (0.7)	12.4 (0.6)	10.7 (0.4)
HD_{si}	46.9 mm (3.7)	33.3 mm (1.7)	23.2 mm (1.3)
HD_{si}/L_b	11.0 (0.8)	12.3 (0.5)	10.6 (0.5)
HD_{ap}/L_b vs. HD_{si}/L_b (p value)	$p = .94$	$p = .32$	$p = .20$

Standard deviations are presented in parentheses. Parameter abbreviations presented as a ratio indicated normalized data. L_b represents the biomechanical length of the femur.

pared to older humans, greyhounds displayed a 9.9% shorter mean normalized femoral head offset (L_{ho}/L_b; $p < .05$) and a 6.4% shorter mean normalized femoral head diameter in the superoinferior direction (HD_{si}/L_b; $p < .05$). In contrast, greyhounds exhibited a 4.6° larger mean anteversion angle (AV; $p < .05$), an 8.6° larger mean cervico-diaphyseal angle (CD; $p < .05$), and a 12.7% greater degree of relative curvature along the femoral diaphysis (AB_{index}; $p < .05$) than older humans.

In greyhound versus younger and older chimpanzees, most parameters were statistically different ($p < .05$). An exception was the degree of relative curvature along the femoral diaphysis (AB_{index}), which was similar between species regardless of age (Table VII).

Comparisons between humans and chimpanzees showed several similarities (Table VII). Older humans and older chimpanzees have similar mean cervico-diaphyseal angles (CD), mean normalized femoral head diameters in the superoinferior direction (HD_{si}/L_b), mean normalized distances from the femoral head center to the lateral margin of the greater trochanter (L_{ht}/L_b), and degrees of relative curvature along the femoral diaphysis (AB_{index}). Likewise, younger humans and younger chimpanzees have similar mean anteversion angles (AV), mean cervico-diaphyseal angles (CD), and degrees of relative curvature along the femoral diaphysis (AB_{index}).

In the above-mentioned comparisons, interspecies differences in mean normalized data frequently are the consequence of important *dissimilarities* between absolute magnitudes of morphologic parameters measured in human, chimpanzee, and greyhound femora (e.g., L_{ho}, L_{ht}, and L_{hd}). In several cases, these measured parameters supersede biomechanical length (L_b) as the primary cause of interspecies differences observed in mean normalized data. For example, in grey-

hounds versus younger and older human and chimpanzee age groups, three of four (75%) age-related mean normalized femoral head offset (L_b) comparisons demonstrated that differences between species were primarily a consequence of *interspecies dissimilarities* in absolute magnitudes of the femoral head offset (L_{ho}) and not a consequence of *interspecies dissimilarities* in the biomechanical length (L_b; Tables III, V, VII).

DISCUSSION

Clinical and experimental studies of THR have shown that a close geometric fit between the femoral component and the supporting surgically prepared bone is essential for initial implant fixation and subsequent clinical longevity.[61–63] Therefore, it is of cardinal importance that the morphology of the bone be precisely known. The present study provides an anatomical database that complements a previous study that investigated proximal femoral morphologies of humans and canines in the context of THR.[18] These data should prove to be useful for future studies that specifically use greyhound or chimpanzee femora to model THR designs and materials for potential use in the human hip.

External morphologies of human, chimpanzee, and canine femora

Using a radiographic biplanar technique to measure external angles of the proximal femur, Montavon et
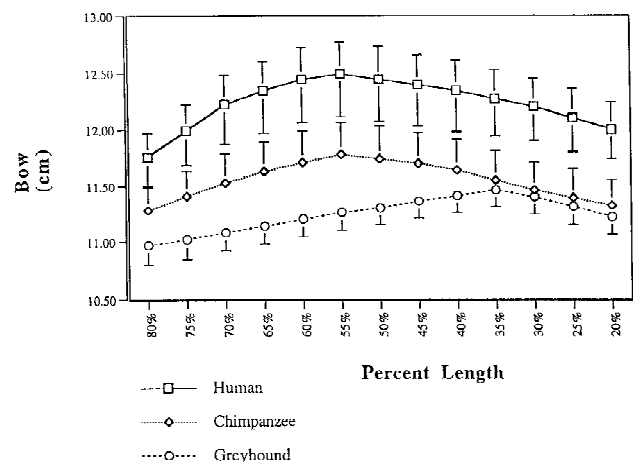
Figure 3. Plot of means and standard deviations of anterior bow measurements at each percent length for human, chimpanzee, and greyhound femora. Humans and chimpanzees both have a point of maximum anterior bow located at 55% of the biomechanical length. Greyhounds have a point of maximum anterior bow located at 35% of the biomechanical length.

TABLE V
Means, Standard Deviations (in Parentheses), and Percent or Degree Differences Between Means (% or Deg. Diff.) for Age-Related Comparisons

Parameters	Human (Young)	Human (Old)	% or deg. diff.*	Chimpanzee (Young)	Chimpanzee (Old)	% or deg. diff.*	Greyhound (Young)	Greyhound (Old)	% or deg. diff.*
n =	17	13		5	5		19	23	
	(9M, 8F)	(8M, 5F)		(2M, 3F)	(3M, 2F)		(10M, 9F)	(9M, 14F)	
L_b	428.0 mm	425.2 mm	+0.7	261.5 mm[†]	290.1 mm[†]	−10.4[‡]	219.3 mm	219.4 mm	0.0
	(20.4)	(36.4)		(7.8)	(10.1)		(10.5)	(8.9)	
HD_{ap}	46.4 mm	47.3 mm	−1.9	33.6 mm	34.8 mm	−3.5	23.2 mm	23.6 mm	−1.7
	(4.2)	(4.2)		(0.9)	(1.6)		(1.5)	(1.2)	
HD_{ap}/L_b	10.8	11.1	−2.7	12.8	12.0	+6.5[‡]	10.6	10.7	−0.9
	(0.6)	(0.9)		(0.3)	(0.5)		(0.5)	(0.4)	
HD_{si}	46.2 mm	47.8 mm	−3.4	32.8 mm	34.7 mm	−5.6	22.9 mm	23.4 mm	−2.2
	(3.6)	(3.9)		(1.3)	(1.4)		(1.5)	(1.2)	
HD_{si}/L_b	10.8	11.3	−4.5	12.5	12.0	+4.1	10.5	10.7	−1.9
	(0.6)	(1.0)		(0.4)	(0.5)		(0.6)	(0.4)	
L_{ht}	75.1 mm	76.5 mm	−1.8	53.2 mm	54.4 mm	−2.2	41.9 mm	43.0 mm	−2.6
	(9.6)	(7.4)		(5.2)	(2.3)		(3.0)	(5.4)	
L_{ht}/L_b	17.5	18.0	−2.8	20.3	18.8	+7.7	19.1	19.2	−0.5
	(1.7)	(1.7)		(2.1)	(1.3)		(0.9)	(1.2)	
L_{hd}	57.1 mm	57.4 mm	−0.5	49.4 mm	50.2 mm	−1.6	31.2 mm	31.4 mm	−0.6
	(9.0)	(6.8)		(7.4)	(2.0)		(2.0)	(3.9)	
L_{hd}/L_b	13.3	13.5	−1.5	18.4	17.3	+6.2	14.2	14.3	−0.7
	(2.0)	(1.5)		(2.4)	(0.8)		(1.0)	(1.5)	
L_{ho}	36.0 mm	41.0 mm	−13.0	31.6 mm	32.8 mm	−3.7	19.5 mm	19.7 mm	−1.0
	(7.2)	(7.9)		(5.4)	(1.4)		(1.5)	(3.3)	
L_{ho}/L_b	8.4	9.6	−13.4[‡]	12.0	11.3	+6.0	8.9	8.7	+2.3
	(1.6)	(1.5)		(2.1)	(0.5)		(0.6)	(0.8)	
AV	9.9°	10.3°	−0.4°	−1.6°	3.3°	−4.9°	16.6°	13.5°	+3.1°[‡]
	(3.5°)	(3.8°)		(15.3°)	(5.8°)		(3.1°)	(3.7°)	
CD	134.7°	128.1°	+6.6°[‡]	130.4°	130.0°	+0.4°	136.0°	137.4°	−1.4°
	(6.8°)	(7.0°)		(3.7°)	(3.0°)		(4.4°)	(4.6°)	
AB_{index}	5.9	5.9	0.0	6.5	6.4	+1.6	6.7	6.7	0.0
	(1.0)	(0.7)		(1.0)	(1.2)		(0.6)	(0.7)	

Parameters measured included: anteversion angle (AV), cervico-diaphyseal angle (CD), femoral head diameter in the anteroposterior direction (HD_{ap}), femoral head diameter in the superoinferior direction perpendicular to the cervical axis of the femoral neck (HD_{si}), distance from the femoral head center to the lateral margin of the greater trochanter (L_{ht}), distance from the femoral head center to the longitudinal axis of the diaphysis (L_{hd}), femoral head offset in the frontal plane (L_{ho}), and degree of relative curvature along the femoral diaphysis [$AB_{index} = (AB_{max} - 10\ cm)/biomechanical\ length$]. Parameter abbreviations presented as a ratio indicate normalized data. L_b represents the biomechanical length of the femur. Differences between parameters were evaluated statistically using a nonparametric Mann–Whitney test with statistical significance set at $p < .05$.

*% Difference between means was calculated as: {[(Species I − Species II)/Species I] + [(Species I − Species II)/Species II]}/2 × 100. ''+'' and ''−'' are defined as: larger and smaller, respectively, than the second species being compared. For example, in younger human vs. older human, AV −0.4° indicates that the younger human femur has a 0.4° smaller mean anteversion angle than the older human femur.

[†]Differences in the mean biomechanical length (L_b) of the femur between younger and older chimpanzees may represent: 1.) a ''selective survival''[19] of larger and more robust animals in the older age group and/or 2.) random sampling errors during specimen selection. These differences are probably not a consequence of ontogenetic changes in the chimpanzee femur. M = males; F = females; n represents the number of specimens in a sample.

[‡]$p < .05$.

al.[52] reported, from a sample of adult mongrel dogs, a mean anteversion angle (AV) and a mean cervico-diaphyseal angle (CD) of 31.3° and 144.7°, respectively. Using identical methods for a different sample of adult mongrel dogs, Summer et al.[3] corroborated these results by measuring similar values of 34.2° (mean AV) and 147.4° (mean CD). Despite imitating the techniques used by these authors,[3,52] Bloebaum et al.[18] described in a series of adult greyhound femora a mean anteversion angle (AV) and a mean cervico-

diaphyseal angle (CD) of 27.0° and 139.8°, respectively. They suggested that these relatively smaller mean values may reflect potential differences between external morphologies of greyhound and mongrel femora. In the present study, all external angles of greyhound femora were *directly* measured on oriented specimens. Consequently, unlike previous *indirect* radiographic studies of greyhound and mongrel femora (e.g., biplane radiography),[3,18,52] the mean anteversion angle (mean AV, 14.9°) and the mean cervico-

TABLE VI
Means, Standard Deviations (in Parentheses), and Percent or Degree Differences Between Means (% or Deg. Diff.) of Compared Parameters Between Human Male and Female Femora

Parameters	Human (Male)	Human (Female)	% or deg. diff.* Male vs. Female
n =	20	13	
L_b	435.3 mm	413.6 mm	+5.1[‡]
	(20.8)	(32.3)	
HD_{ap}/L_b	11.2	10.6	+5.5[‡]
	(0.6)	(0.8)	
HD_{si}/L_b	11.2	10.7	+4.6[‡]
	(0.6)	(1.0)	
L_{ht}/L_b	18.1	17.5	+3.4
	(1.3)	(2.1)	
L_{hd}/L_b	13.9	12.9	+7.5
	(1.7)	(1.7)	
L_{ho}	42.3 mm	33.7 mm	+22.9[‡]
	(5.8)	(7.7)	
L_{ho}/L_b	9.7	8.2	+16.9[‡]
	(1.3)	(1.8)	
AV	9.9°	10.1°	−0.2°
	(3.7°)	(3.0°)	
CD[†]	129.8°	134.1°	−4.3°
	(7.6°)	(6.8°)	
AB_{index}	5.6	6.2	−10.2[‡]
	(1.0)	(0.5)	

Parameters measured included: anteversion angle (AV), cervico-diaphyseal angle (CD), femoral head diameter in the anteroposterior direction (HD_{ap}), femoral head diameter in the superoinferior direction perpendicular to the cervical axis of the femoral neck (HD_{si}), distance from the femoral neck center to the lateral margin of the greater trochanter (L_{ht}), distance from the femoral head center to the longitudinal axis of the diaphysis (L_{hd}), femoral head offset in the frontal plane (L_{ho}), and degree of relative curvature along the femoral diaphysis [$AB_{index} = (AB_{max} − 10 cm)$/biomechanical length]. Parameter abbreviations presented as a ratio indicate normalized data. L_b represents the biomechanical length of the femur. Differences between parameters were evaluated statistically using a nonparametric Mann–Whitney test with statistical significance set at $p < .05$.

*% Difference between means was calculated as: {[(Species I − Species II)/Species I] + [(Species I − Species II)/Species II]}/2 × 100. ''+'' and ''−'' are defined as: larger and smaller, respectively, than the second species being compared. For example, in male vs. female, AV −0.2° indicates that the human male femur has a 0.2° smaller mean anteversion angle than the human female femur.

[†]Although not statistically significant, the mean cervico-diaphyseal angle (CD) in human females is relatively larger than the corresponding value in human males. This difference is probably the consequence of sexual dimorphism and not the consequence of sampling errors and/or age-related changes. Notice that in Table V, each age group contains similar sample sizes for human males and females. When these two age groups (young and old) were separated based on gender, the dissimilarities between young and old males and females (e.g., young males vs. young females) were relatively smaller in magnitude than the dissimilarities observed between males and females alone (see table above). In other words, human females consistently displayed a relatively larger mean cervico-diaphyseal angle (CD) than their male counterparts *regardless of age* and younger specimens consistently displayed a significantly ($p < .05$) larger mean cervico-diaphyseal angle (CD) than their older counterparts *regardless of gender. Younger male* age group, mean CD 133°; *younger female age group,* mean CD 137°; *older male age group,* mean CD 127°; *older female age group,* mean CD 129°. *n* represents the number of specimens in a sample
[‡]$p < .05$.

diaphyseal angle (mean CD, 136.7°) of the present greyhound sample were (as expected) relatively smaller (Table III).

In the present Caucasian human sample, the mean anteversion angle was 10.0° (Table III). When these Caucasian femora were separated based on gender, the mean anteversion angle for males was 9.9° and for females 10.1° (Table VI). Hoaglund and Low[64] previously reported that Caucasian males and females have, on average, an anteversion angle of 7.0° and 10.0°, respectively. When compared to studies cited by Clark et al.[65] (reported range of anteversion angle in humans: 10° to 20°), these mean values are at the lower end of a normal range.

In the present human sample, the mean cervico-diaphyseal angle was 131.5° (Table III). This is similar to mean values reported by previous investigators.[4,18,65] However, when these Caucasian femora were separated based on gender, the mean cervico-diaphyseal angle for males was 129.8° and for females 134.1° (Table VI). Although not statistically significant, this gender discrepancy, along with others (e.g., male L_b, L_{ho}/L_b, HD_{ap}/L_b, and HD_{si}/L_b are greater than their female counterparts; Table VI), suggests that gender differences may be important for interpreting stress transfer across the hip joint of human males and females.[18,19]

In the present human sample, the mean perpendicu-

TABLE VII
Percent or Degree Differences Between Means (% or Deg. Diff.) for Age-Related Interspecies Comparisons

Parameters	Greyhound vs. Younger Humans % or deg. diff*	Greyhound vs. Older Humans % or deg. diff.*	Greyhound vs. Younger Chimpanzees % or deg. diff.*	Greyhound vs. Older Chimpanzees % or deg. diff.*	Younger Humans vs. Younger Chimpanzees % or deg. diff.*	Older Humans vs. Older Chimpanzees % or deg. diff.*
L_b	$-71.9^\dagger$	$-71.1^\dagger$	$-17.6^\dagger$	$-28.3^\dagger$	$+51.3^\dagger$	$+39.2^\dagger$
HD_{ap}/L_b	-0.9	-3.7	$-18.0^\dagger$	$-11.5^\dagger$	$-17.1^\dagger$	$-7.8^\dagger$
HD_{si}/L_b	-1.9	$-6.4^\dagger$	$-16.6^\dagger$	$-12.4^\dagger$	$-14.7^\dagger$	-6.0
L_{ht}	$-60.1^\dagger$	$-62.2^\dagger$	$-22.6^\dagger$	$-24.9^\dagger$	$+35.2^\dagger$	$+34.8^\dagger$
L_{ht}/L_b	$+8.8^\dagger$	$+5.9$	$-6.1^\dagger$	$+1.6$	$-14.9^\dagger$	-4.3
L_{hd}	$-63.8^\dagger$	$-64.4^\dagger$	$-47.2^\dagger$	$-49.0^\dagger$	$+14.5$	$+13.4^\dagger$
L_{hd}/L_b	$+6.6$	$+5.1$	$-26.2^\dagger$	$-19.9^\dagger$	$-33.0^\dagger$	$-25.1^\dagger$
L_{ho}	$-65.2^\dagger$	$-81.3^\dagger$	$-50.2^\dagger$	$-54.4^\dagger$	$+13.1^\dagger$	$+22.5^\dagger$
L_{ho}/L_b	$+3.5$	$-9.9^\dagger$	$-32.7^\dagger$	$-26.4^\dagger$	$-36.4^\dagger$	$-16.4^\dagger$
AV	$+5.0^{\circ\dagger}$	$+4.6^{\circ\dagger}$	$+16.5^{\circ\dagger}$	$+11.6^{\circ\dagger}$	$+11.5^\circ$	$+7.0^{\circ\dagger}$
CD	$+2.0^\circ$	$+8.6^{\circ\dagger}$	$+6.3^{\circ\dagger}$	$+6.7^{\circ\dagger}$	$+4.3^\circ$	-1.9°
AB_{index}	$+12.7^\dagger$	$+12.7^\dagger$	$+3.0$	$+4.6$	-9.7	-8.1

Parameters measured included: anteversion angle (AV), cervico-diaphyseal angle (CD), femoral head diameter in the anteroposterior direction (HD_{ap}), femoral head diameter in the superoinferior direction perpendicular to the cervical axis of the femoral neck (HD_{si}), distance from the femoral head center to the lateral margin of the greater trochanter (L_{ht}), distance from the femoral head center to the longitudinal axis of the diaphysis (L_{hd}), femoral head offset in the frontal plane (L_{ho}), and degree of relative curvature along the femoral diaphysis [$AB_{index} = (AB_{max} - 10 \text{ cm})/\text{biomechanical length}$]. Parameter abbreviations presented as a ratio indicate normalized data. L_b represents the biomechanical length of the femur. Differences between parameters were evaluated statistically using a nonparametric Mann–Whitney test with statistical significance set at $p < .05$.
*% Difference between means was calculated as: {[(Species I − Species II)/Species I] + [(Species I − Species II)/Species II]}/2 × 100. "+" and "−" are defined as: larger and smaller, respectively, than the second species being compared. For example, in greyhound vs. younger humans, AV +2.0° indicates that the greyhound femur has a 2.0° larger mean anteversion angle than the younger human femur. $^\dagger p < .05$.

lar distance from the femoral head center to the diaphyseal axis of the human femur (absolute magnitude of the femoral head offset in the frontal plane) was 38.9 mm (Table III). This segment is relatively shorter than mean distances reported by Noble et al.[62] (mean 43.0 mm; range 23.6 to 61.0 mm), Clark et al.[65] (mean 44.8 mm; range 34 to 57 mm), and Rubin et al.[66] (mean 47.0 mm; range 33.2 to 62.8 mm). But these latter means and ranges were obtained using different methodologies and variations in the "offset" definition.

Chimpanzee femora in the present study exhibited a mean anteversion angle (AV) and a mean cervico-diaphyseal angle (CD) of 2.6° and 130.2°, respectively (Table III). When compared to present samples of human and greyhound femora, the former (mean AV) was significantly smaller than that of both species ($p < .05$); the latter (mean CD) was similar to that of humans, but significantly smaller than that of greyhounds ($p < .05$; Table III).

Compared to greyhounds and mongrels, the proximal human femur is less anteverted and has a relatively smaller mean cervico-diaphyseal angle that places the human hip in a relatively more varus orientation. But the mean normalized femoral head offset between these two species is similar (mean L_{ho}/L_b from the present study: human 9.1, greyhound 8.7; see Table III). This similarity suggests that marked differ-

ences in biomechanical lengths *and/or* absolute values of measured parameters (e.g., absolute magnitude of the femoral head offset in the frontal plane) may significantly influence differences observed in *interspecies* comparisons of normalized data (Tables III and VII). In other words, normalizing data to reduce variability due to size may not be appropriate for some *interspecies* comparisons since, unlike most *intraspecies* comparisons,[18,19,23,67–69] developmental and functional relationships among biomechanical length, hip loading forces, gait patterns, and animal size are not well understood and probably differ with each species studied. Consequently, the present study included (where appropriate) both normalized *and* absolute magnitudes for most measured parameters (e.g., L_{ho}, L_{ht}, and L_{hd}; Tables III–VI).

In contrast to present samples of human and greyhound femora, the mean normalized femoral head offset of the chimpanzee was 11.7 (Table III). This relatively larger mean normalized distance may reflect, in addition to problems with *interspecies* comparisons of *normalized* data (see above), differences between customary patterns and magnitudes of bending moments, and other physical characteristics of stress transfer across the hip joint of the chimpanzee. Hence, a femoral endoprosthetic design, modeled in the chimpanzee, may not be appropriate for approximating relative magnitudes of bending moments applied to

the human hip. The fact that five of sixteen chimpanzee femora (31%) were retroverted additionally suggests that anatomical placement of femoral endoprostheses in these animals may not mimic functional anteversion angles typically used in human THR designs (Table III).

The above-mentioned *interspecies* differences in measured parameters (e.g., mean anteversion angle, mean cervico-diaphyseal angle, and mean normalized femoral head offset) may alter femoral head positions relative to the femoral diaphysis in each species. Therefore, examples of varus or valgus orientation of the proximal femur, and changes in the femoral head offset and/or anteversion angle, may significantly influence instantaneous, gait-related bending moments and stress transfer across the hip joint of each species. Consequently, accurate determination of these morphologic parameters, along with appropriate interpretation of *interspecies* differences in *ligamentous, muscular* and *gait-related* contributions to static and dynamic loading of the hip, must be considered when attempts are made to extrapolate experimental data from THR studies using these nonhuman animal models to the human clinical condition.

Since proper cortical contact and fit into the proximal medullary canal of the femur are critical design features for predicting stress shielding and optimal fixation of a femoral endoprosthesis,[70–82] differences in the curvature between human, chimpanzee, and canine femora must be considered when THR designs and materials are experimentally tested in animal models prior to human use. The present study demonstrated differences between maximum anterior bows of human, chimpanzee, and greyhound femora. Both humans and chimpanzees exhibited a point of maximum anterior bow located at 55% of the biomechanical length (Fig. 3). This is similar to results reported by Bloebaum et al.[18] (approximately 55% of the biomechanical length), Ruff[19] (approximately 50% of the biomechanical length), Stewart[83] (approximately 54% to 55% of the bone length), and Walensky[53] (approximately 40% to 46% of the bone length), but is more proximal in location than the point of maximum anterior bow measured on greyhound femora by Bloebaum et al.[18] and the present study (35% of the biomechanical length; Fig. 3). This relatively more distal apex of the greyhound femoral diaphysis may influence how an endoprosthesis, straight or curved, is stressed after THR implantation.[18] For example, an anatomical curved stem designed to improve canal filling in the proximal human femur, but modeled experimentally in the relatively straighter proximal femoral diaphysis of the greyhound, may not optimally achieve the degree of cortical contact necessary for successful fixation of an endoprosthesis in the human femur.

Hip mechanics and age-related changes

The magnitude of an instantaneous, gait-related bending moment across the proximal femoral diaphysis, among other factors, is influenced by the femoral head offset, the angulation of the femoral head and neck in three-dimensional space, and geometric dimensions of the adjacent pelvis (e.g., the biacetabular breadth—the distance between the midpoints of the two acetabulae).[84] In order to maintain the original balance of abductor and joint reaction forces so that loading conditions remain in physiologic range after THR implantation, endoprostheses closely must approximate normal geometric relationships at the hip joint.[39,85,86] If the femoral head offset is relatively increased, as is the case of a reduced cervico-diaphyseal angle and/or a less anteverted femoral head and neck (e.g., increased varus orientation with age[18,19] or planned alignment during total hip surgery), then the functional stability of the hip in stance phase may be maintained with reduced forces exerted by the abductor muscles.[84,87] These and other mechanical aspects of hip loading were mathematically analyzed in Ruff's[84] investigation of hip mechanics in early *Homo* and modern humans. Ruff showed that if the biomechanical neck length of the femur (a structural analog of the femoral head offset in the frontal plane) is increased by 16% from normal, then the corresponding abductor muscle force and the joint reaction force will decrease by 10% and 7%, respectively. In turn, the magnitude of the mediolateral bending moment across the proximal femoral diaphysis will increase by 13%. Ruff's data[84] and those of others[87–89], suggest that the femoral head offset, a strong correlate of stress transfer across the hip, is an important biomechanical variable that may be used to predict human THR failures secondary to instability, limp, and increased joint reaction forces.

Data from Ruff's comprehensive study[19] of age-related changes in an anthropologic sample of human femora showed that with age, particularly in females, decreases occurred in the anteversion angle and the cervico-diaphyseal angle (females: AV −6.8°, CD −1.1°; males: AV −1.3°; CD −0.1°). Ruff suggested that these age-related changes, particularly in the anteversion angle, may represent ''. . . a 'protective' mechanism in the proximal femur'' that reduces ''. . . tensile stresses in the femoral neck''[19 (pp. 440,441)] He concluded that these morphologic changes in the proximal human femur along with other structural features ''. . . serve as 'protective' devices for the highly stressed and fracture vulnerable femoral neck''[19 (p. 441)].

In the present study, no age-related changes in mean anteversion angle for human femora were found. However, an age-related decrease in mean cervico-diaphyseal angle of 6.6° ($p < .05$) and a small but statistically significant age-related increase in mean normalized femoral head offset (+1.2, $p < .05$) in hu-

man femora were identified (Table V). Similar age-related changes in greyhounds and chimpanzees were not observed.

Unlike previous canine data,[18] the present greyhound sample showed an age-related decrease of 3.1° in mean anteversion angle (Table V). Though statistically significant ($p < .05$), this age-related difference may be influenced by interobserver and intraobserver errors inherent with the use of hand-held goniometers. Despite appropriate and proper use in humans,[90] chimpanzees (unpublished data), and greyhounds (unpublished data), these hand-held devices can cause mean errors of ±4.0°.

CONCLUSIONS

Data from this study and biomechanical issues addressed in the literature review demonstrate that the proximal regions of chimpanzee and canine femora are distinctly different from each other in several morphologic and functional anatomic features. External femoral morphologies of chimpanzees and canines also differ in important ways from human femora. In accordance with the idea that skeletal form reflects habitual functions[91–93], these interspecies differences in external femoral morphologies suggest that there are marked disparities in characteristics of stress transfer across the hip joint of each species. Since greyhound and chimpanzee femora do not display similar age-related changes seen in humans, testing THR materials and designs in these animal models to predict bone responses in human THRs (e.g., in elderly patients) may not satisfactorily mimic clinical conditions.

This study primarily provides a database that may be used by clinicians, bioengineers, and biomaterials scientists to make rational decisions, appropriate extrapolations, and accurate interpretations of results from studies using these nonhuman animal models for human THR research. In order to make proper inferences regarding normal hip function and stress transfer across human, chimpanzee, and canine femora, these data, along with others, must be interpreted in a broader context of complex interactions among aging, gender (especially in humans), hip-loading forces, gait patterns, relative limb-weight distributions, muscular activities (e.g., abductor muscles), ligamentous contributions, and pelvo-femoral musculoskeletal mechanics. Information provided by this study strongly suggests that discretion must be exercised when extrapolating experimental results and bone tissue responses from THR studies using these nonhuman animal models to the human clinical condition.

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