

# Hip motion and moments during gait relate directly to proximal femoral bone mineral density in patients with hip osteoarthritis

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## Abstract

The present study examined the loads at the hip joint during gait and the bone mineral density of the proximal femur in 25 patients with end-stage hip osteoarthritis. Dual energy X-ray absorptiometry was used to determine the bone mineral density of the greater trochanter, femoral neck and Ward's triangle of the osteoarthritic group. The bone mineral density was normalized for the patient's age, gender, weight and ethnic origin (*Z* score). Gait analysis was used to determine the external hip joint moments and motion during walking for the osteoarthritic group and a control group of 21 normal subjects. The gait parameters of the osteoarthritic group which were significantly diminished compared to the normal group ( $p < 0.001$ ) accounted for as much as 42% ( $p < 0.001$ ) of the variation in the normalized bone mineral density. Specifically, the dynamic sagittal plane hip motion during gait (maximum flexion minus maximum extension) and peak external rotation and adduction moments were significantly correlated with greater trochanter ( $R = 0.429-0.648$ ,  $p = 0.032-0.0001$ ) and Ward's triangle ( $R = 0.418-0.532$ ,  $p = 0.038-0.006$ ) normalized bone mineral density while the adduction moment was also significantly correlated with the femoral neck normalized bone mineral density ( $R = 0.5394$ ,  $p = 0.005$ ). The normalized bone mineral density of the femoral neck and Ward's triangle was elevated while that of the greater trochanter was decreased as compared to normal reference values. The significant correlation between the hip joint moments during gait and femoral bone mineral density indicate that hip joint loads need to be included when explaining local variation in bone mineral density in hip osteoarthritis. © 1998 Elsevier Science Ltd. All rights reserved.

**Keywords:** DXA; Gait analysis; Bone loss; Osteoarthritis; Disuse osteoporosis

## 1. Introduction

Unloading of bone results in bone loss experimentally (Kannus et al., 1996; Rubin et al., 1988; Skerry and Lanyon, 1995) and in clinical situations which have presumably led to disuse (Kale et al., 1995; Kiratli et al., 1996). Thus, changes in femoral bone commonly reported in patients with hip osteoarthritis and total hip replacements may be related to changes in the hip joint loads during activities of daily living. Hip osteoarthritis has been associated with increased bone mineral density at the femoral neck and Ward's triangle (Bruno et al., 1998;

Cooper et al., 1991; Nevitt et al., 1995) as well as at remote sites (Carlsson et al., 1979; Roh et al., 1974). However, both increases (Nevitt et al., 1995) and decreases in greater trochanter bone mineral density (Bruno et al., 1998) have been reported. To date increased bone mineral density associated with hip osteoarthritis has been attributed to the disease itself, but limb disuse may have an additional confounding effect on the bone causing localized disuse osteopenia. Bone loss in patients with osteoarthritis may limit the surgical options for those patients requiring total hip replacements and possibly compromise the long term outcome. To better understand bone changes associated with hip osteoarthritis a better understanding of the relationship between limb loading and bone mineral density is required. This improved understanding of bone changes associated with

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limb loading would also provide a better basis for examining stress shielding due to implants. Femoral bone changes associated with total hip replacements have been primarily attributed to stress shielding and osteolysis with minimal attention directed at the confounding effect that limb disuse may have on the bone changes.

Gait studies of preoperative patients for total hip replacement indicate that these patients walk in a manner that reduces the hip joint loads on the affected side (Hurwitz et al., 1997; Long et al., 1993; Olsson, 1986). For example, preoperative total hip replacement patients walk with significant reductions in the external hip moments as compared to normal subjects (Hurwitz et al., 1997). The external moments during gait are reflective of the net muscle activity and the internal loads at the hip joint (Andriacchi et al., 1995, Andriacchi and Hurwitz, 1997). In order for mechanical equilibrium to be maintained the muscles and soft tissues surrounding the hip joint must generate a net moment that is equal and opposite to the external moment. For example, in the absence of antagonistic activity, the abductor muscles must produce a moment equal and opposite to that of the external hip adduction moment. If antagonist muscles are active (hip adductors) then the hip abductors must produce a moment equal and opposite to the external moment and the moment produced by the antagonists (adductors). Decreased external moments are reflective of decreased muscle forces and decreased forces at the hip joint and femur when there is not an increase in antagonistic muscle activity.

Decreases in the joint moments during gait would be expected to cause decreases in bone mass. There are two studies showing that decreased moments during gait influence bone mineral density. The first study showed that asymmetry in tibial bone mass in long term post-operative patients with total hip replacements was significantly correlated with asymmetry in intersegmental tibial axial force during gait (Bryan et al., 1996) while the second study showed that the distribution of bone between the proximal medial and lateral tibial plateaus in normal subjects was significantly correlated with the knee adduction moment during gait (Hurwitz et al., in press). This study examined the relationship between hip joint loads and bone mineral density in the same cohort of patients with hip osteoarthritis. The hypothesis tested in this study was that the external moments and dynamic motion at the hip joint during gait were significantly correlated with proximal femoral bone mineral density in patients with hip osteoarthritis.

## 2. Methods

Twenty-five patients (14 males, 11 females) all with a diagnosis of primary unilateral osteoarthritis, were evaluated just prior to total hip replacement surgery with

gait analysis and dual energy X-ray absorptiometry. The average age, height and weight of the osteoarthritic group was  $63 \pm 9$  yr,  $1.71 \pm 0.10$  m and  $84.3 \pm 15.5$  kg, respectively. The average Harris hip score (Harris, 1969) was  $55 \pm 15$  and none had any other significant joint involvement. All received a total hip replacement within 2 months of their evaluations. To identify the gait adaptations of the osteoarthritic group, a group of 21 normal subjects (12 males, 9 females) without significant musculoskeletal involvement was also tested. The normal subjects were chosen to have a comparable age, gender, height and weight distribution as the osteoarthritic group ( $62 \pm 10$  yr,  $1.71 \pm 0.09$  m and  $76.8 \pm 12.2$  kg). The age, height and weight of the normal and osteoarthritic group were not significantly different ( $p = 0.774$ ,  $p = 0.948$ ,  $p = 0.077$ ). All subjects were Internal Review Board approved and informed consent was obtained.

Each subject's proximal femur was scanned by dual energy X-ray absorptiometry (Lunar DPX-L, Madison, Wisconsin), following the manufacturer's instructions. With the subject in the supine position, the entire lower extremity was held in  $15^\circ$  of internal rotation by strapping the foot of the leg to be scanned to a triangular brace, with the femoral shaft perpendicular to the direction of the scan path. The sample size was  $1.2 \times 1.2$  mm. The data were analyzed with the auto analysis mode and the bone mineral density ( $\text{g cm}^{-2}$ ) and age-, gender-, weight- and ethnic origin-matched Z scores for the femoral neck, Ward's triangle and greater trochanter were determined. The Z score is referred to as the normalized bone mineral density. A normal population would have a Z score of 0 with a standard deviation of 1. Therefore, a patient with a negative Z score has bone mineral density less than the average of the reference normal population supplied by the manufacturer and conversely for a patient with a positive Z score. The normalized bone mineral density was not significantly correlated with age ( $p = 0.484$ ), height ( $p = 0.533$ ) or weight ( $p = 0.513$ ) and there were no significant differences attributable to gender ( $p = 0.583$ ).

The motion and external moments during level walking were calculated from data collected with an optoelectronic system with a passive retroreflective marker system (CFTC — Computerized Functional Testing Corporation, Chicago, IL, U.S.A.) and a multicomponent force plate (Bertec, Columbus, OH, U.S.A.). The spatial accuracy of the system is 7 mm, resulting in an average resolution of  $4^\circ$  when measuring hip flexion angles. Subjects were asked to walk at three self-selected speeds of slow, normal and fast. A minimum of six stride cycles were evaluated per side. Motion of the limbs was determined by measuring the spatial position of markers placed on the lateral aspect of the most superior portion of the iliac crest, at the center of the greater trochanter, over the mid-point of the lateral joint line of the knee, on the lateral aspect of the malleolus, and at the base of the

fifth metatarsal (Andriacchi et al., 1995; Andriacchi and Strickland, 1985). The sagittal plane hip angle was determined by the positions of the first three of these markers. The three-dimensional external moments were calculated at the hip joint center with inverse dynamics using the force and position data in conjunction with the inertial properties of the limb segments. The external moments thus represent the net moment due to the ground reaction force vector as well as that due to inertial forces. The moments were calculated by first modeling the leg as a collection of rigid links or segments (slender rods) representing the thigh, the shank and the foot (Andriacchi et al., 1995). The link model included the assumption that no axial rotation about the long axis of each segment occurred. The inertial properties for each rigid segment were lumped at its mass center (lumped mass approximation) and were included in the calculation of the external moments and intersegmental forces. The hip joint center was located at a point 2.5 cm inferior to the midpoint of a line from the anterior–superior iliac spine to the pubic symphysis (Andriacchi and Strickland, 1985). The external moments and forces were transformed into the local coordinate system of each joint which for the hip was aligned with the thigh. The local axes are orthogonal. For the transformation to the local coordinate system, the local  $z$ -axis (longitudinal axis) of the hip joint coordinate system is determined by a vector from the center of the head of the femur to the center of the knee joint. The local  $y$ -axis (anterior–posterior direction) is defined by the cross product of the local  $z$ -axis and the global  $x$ -axis. The local  $x$ -axis (medial–lateral) is defined by the cross product of the local  $z$ -axis and the local  $y$ -axis. The moment about the local  $z$ -axis or longitudinal axis is the rotational moment (internal–external), the moment about the local  $y$ -axis, the frontal plane moment (abduction–adduction) and the moment about the local  $x$ -axis, the sagittal plane moment (flexion–extension). Moments were expressed as a percentage of each subject's body weight multiplied by height.

For the osteoarthritic group, a representative trial on the affected side was chosen such that the speed of the trial was as close as possible to the average of their minimum and maximum walking speed recorded during the test session. For the normal subjects a trial with a speed as close as possible to those in the osteoarthritic group was chosen. The average walking speed of the osteoarthritic group was  $0.86 \pm 0.28 \text{ ms}^{-1}$  and that of the normal group,  $0.97 \pm 0.11 \text{ ms}^{-1}$  and there was no significant difference in the speed of the two groups ( $p = 0.090$ ).

Student's  $t$  tests were used to determine if the dynamic hip range of motion (maximum flexion minus maximum extension during gait) or the peak external hip moments in the three planes (flexion–extension, adduction–abduction, internal rotation–external rotation) were significantly different between the osteoarthritic group and the

normal group. A significance level of  $\alpha < 0.025$  was used to account for the multiple comparisons being made. For analyzing the dual energy X-ray absorptiometry data, Sign tests (binomial distributions) were used to determine if the percentage of osteoarthritic patients with positive or negative  $Z$  scores was significantly different from that of the reference normal population. Pearson correlation coefficients were used to test for significant relationships between the normalized bone mineral density and the hip joint gait parameters that were significantly different from the normal group. A stepwise forward multivariate linear regression model ( $\text{pin} = 0.05$ ,  $\text{pout} = 0.1$ ) was used to determine which combinations of gait kinetics were significant predictors of the normalized bone mineral density. To ensure that gender, age, height and weight had no significant effect on the bone mineral density in the presence of any of the gait parameters, they were also included in the multivariate regression model. A significance level of  $\alpha < 0.05$  was used for the correlation and multivariate regression models.

### 3. Results

The peak external hip moments and dynamic hip range of motion during gait were positively correlated with the normalized bone mineral density in patients with hip osteoarthritis (Table 1). More specifically, in the area of the greater trochanter and Ward's triangle, the

Table 1

Pearson correlation coefficients and associated significance levels for the dynamic hip range of motion and peak external moments with the normalized bone mineral density ( $Z$  score) on the osteoarthritic side. The correlation coefficients in bold are those that are statistically significant. The gait parameters in bold are those that were significantly less than normal

	Normalized bone mineral density		
	Greater trochanter	Femoral neck	Ward's triangle
Gait parameters			
<b>Dynamic hip range of motion</b>	<b><math>R = 0.4981</math></b> $p = 0.011$	$R = 0.3305$ $p = 0.107$	<b><math>R = 0.4176</math></b> $p = 0.038$
Peak flexion moment	<b><math>R = 0.3993</math></b> $p = 0.048$	$R = -0.0197$ $p = 0.926$	$R = 0.0871$ $p = 0.679$
<b>Peak extension moment</b>	$R = 0.2519$ $p = 0.224$	$R = 0.0003$ $p = 0.999$	$R = 0.1546$ $p = 0.461$
Peak adduction moment	$R = -0.1225$ $p = 0.560$	$R = -0.3320$ $p = 0.105$	$R = -0.1899$ $p = 0.363$
<b>Peak adduction moment</b>	<b><math>R = 0.4293</math></b> $p = 0.032$	<b><math>R = 0.5394</math></b> $p = 0.005$	<b><math>R = 0.5147</math></b> $p = 0.008$
<b>Peak external rotation moment</b>	<b><math>R = 0.6478</math></b> $p < 0.001$	$R = 0.3663$ $p = 0.072$	<b><math>R = 0.5320</math></b> $p = 0.006$
<b>Peak internal rotation moment</b>	$R = -0.2472$ $p = 0.185$	$R = -0.1310$ $p = 0.532$	$R = -0.2390$ $p = 0.250$

dynamic hip range of motion and peak external rotation and peak adduction moments were all significantly correlated with the normalized bone mineral density, while in the femoral neck only the peak hip adduction moment was significantly correlated with the normalized bone mineral density or Z score (Fig. 1, Table 1). The hip range of motion and peak adduction and peak external rotation moments were all much less for the patient with the lowest greater trochanter normalized bone mineral density as compared to the patient with the greatest greater trochanter bone mineral density (Fig. 2). Not only were the peak values reduced for this patient but the magnitudes of these moments throughout much of the stance phase of gait were reduced as well. For example, the hip motion, adduction moment and external rotation moment of the patient with the lowest greater trochanter normalized bone mineral density were much less than

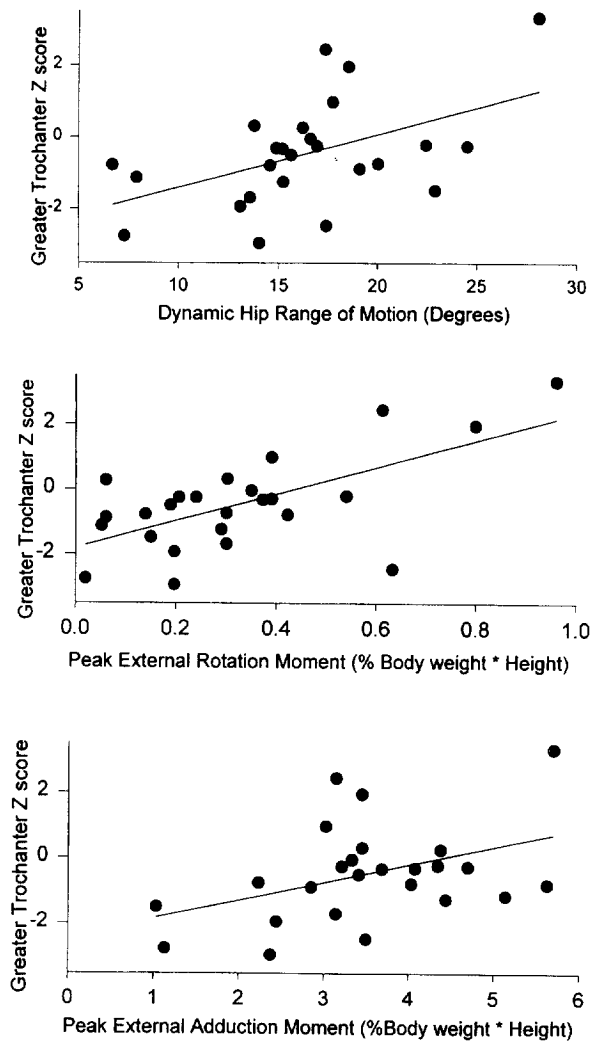


Fig. 1. The dynamic hip range of motion ( $p < 0.011$ ) and peak adduction ( $p < 0.032$ ) and peak external rotation ( $p < 0.001$ ) moments were all significant predictors of normalized greater trochanter bone mineral density.

those of the patient with the greatest greater trochanter bone mineral density throughout the gait cycle.

The external rotation moment was the single best predictor of both the greater trochanter and Ward's triangle normalized bone mineral density while the adduction moment was the best single predictor of the femoral neck normalized bone mineral density (Table 1). Once the single best gait predictor was included in the multivariate regression model, no other gait parameters or age, height or weight significantly increased the ability to predict the normalized bone mineral density. To better understand why combinations of the single predictors did not significantly increase the ability to predict normalized bone mineral density the correlation between the single predictors were evaluated. The hip range of motion was significantly correlated with the external rotation moment ( $R = 0.5357$ ,  $p = 0.006$ ) but not the adduction moment ( $p = 0.757$ ). The external rotation moment and adduction moment occurred at the same time in the gait cycle in five of the osteoarthritic patients while in 17 patients the peak adduction moment occurred later in stance than the external rotation moment. There was a trend for these two moments to be correlated ( $R = 0.3686$ ,  $p = 0.07$ ).

The three gait parameters that were significantly correlated with normalized bone mineral density were all significantly diminished in the osteoarthritic group as compared to the normal group (Fig. 3). For example, the hip range of motion of the osteoarthritic group ( $16 \pm 5^\circ$ ) was 56% of that of the normal group ( $29 \pm 5^\circ$ ) ( $p < 0.001$ ) while the peak adduction and peak external rotation moments were 70 and 51%, respectively, of the normal group values ( $p < 0.001$ ).

The significant positive correlation between the gait parameters and normalized bone mineral density occurred regardless of whether the normalized bone mineral density was decreased (greater trochanter) or increased (Ward's triangle, femoral neck) relative to the reference values. The percentage of osteoarthritic subjects (19 of 25 or 76%) with decreased greater trochanter normalized bone mineral density (negative Z score) was significantly higher than would be expected for the normal reference population ( $p = 0.006$ ) (Table 2). In contrast, the percentage of osteoarthritic patients with increased femoral neck bone mineral density (18 of 25 or 72%) was significantly greater than would be expected ( $p = 0.024$ ) with a similar trend for Ward's triangle (17 of 25 or 68%) ( $p = 0.071$ ).

#### 4. Discussion

The mechanics of gait were significantly correlated with the bone mineral density in the proximal femur in this end-stage osteoarthritic population. Specifically, the hip range of motion and peak adduction and peak external rotation moments were all significantly correlated

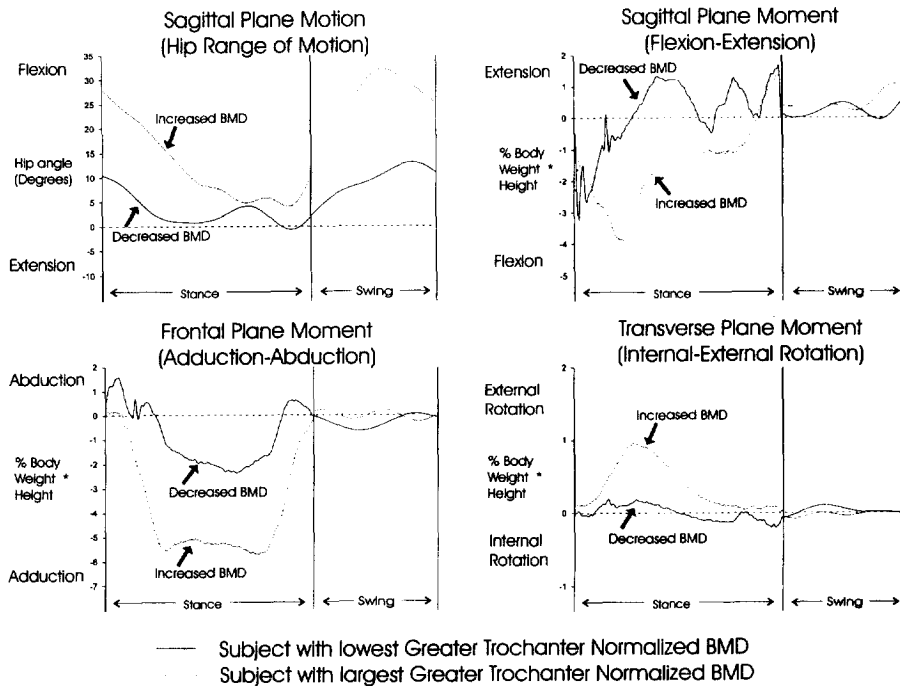


Fig. 2. A comparison of the dynamic hip range of motion and external moments for the subject with the lowest normalized greater trochanter bone mineral density ( $Z = -2.75$ ) and the subject with the greatest normalized greater trochanter bone mineral density ( $Z = 3.32$ ). The hip range of motion, adduction moment and external rotation moment were much less for the subject with the lowest normalized bone mineral density as compared to the subject with the greatest normalized bone mineral density.

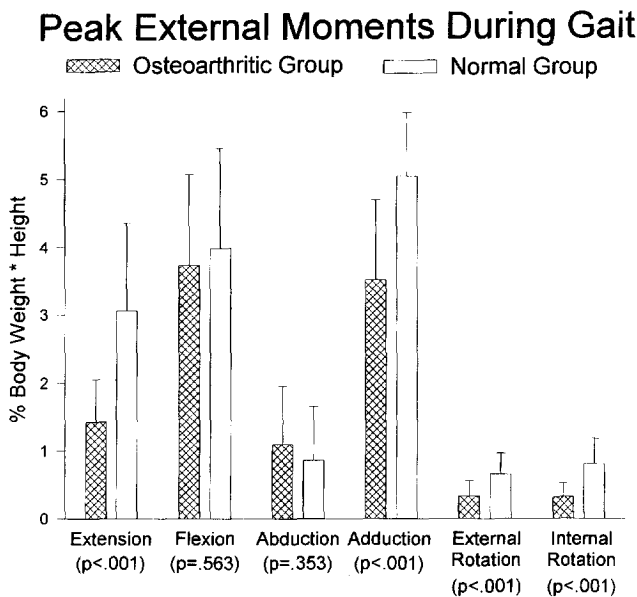


Fig. 3. The osteoarthritic patients walked with significantly reduced peak external hip extension, adduction and internal and external rotation moments as compared to the normal group ( $p < 0.001$ ).

with the normalized bone mineral density. The positive correlations between loading during gait and bone mineral density occurred both in regions with an overall decrease in bone mineral density relative to the reference

population of normals (negative Z score, greater trochanter) and in regions with elevated bone mineral density (positive Z score, femoral neck, Ward's triangle).

Although subjects with hip osteoarthritis rarely have systemic osteoporosis (Cooper et al., 1991; Healey et al., 1985) it has been suggested that localized osteopenia in osteoarthritic patients can be caused by decreased limb loads (Bruno et al., 1998; Kale et al., 1995; Ruegsegger et al., 1986). The present study provides new data to support this interpretation and points out that the net effect can vary in different anatomical regions of the proximal femur, resulting in net bone gain in the femoral neck and net bone loss in the greater trochanter at the time the patients have a total hip replacement. Thus, while the pathogenesis of the osteoarthritis has been associated with increased bone mineral density or content (Carlsson et al., 1979; Nevitt et al., 1995; Roh et al., 1974), the data from the present study indicate that loss of bone associated with decreased limb loading may be great enough to actually negate the bone gain associated with the disease process.

The significant correlation between the femoral neck and Ward's triangle normalized bone mineral density and the peak adduction moment likely resulted from a decreased contact force and bending moment in the femoral neck from decreases in the peak adduction moment. The primary hip abductors (gluteus medius and minimus) are the primary structures responsible for

Table 2

Normalized bone mineral density for the affected side of the osteoarthritic group. *p* values are significance level resulting from comparing osteoarthritic group to the reference normal population supplied by the manufacturer. The normal control population would have a normalized bone mineral density (*Z* score) of  $0 \pm 1$ . Fifty percent of the normal population would have a normalized bone mineral density above the average value and 50% below the average value

	Mean and standard deviation of normalized bone mineral density ( <i>Z</i> score)	Number and percentage with bone mineral density less than the average value of the normal population	<i>p</i> value for proportion
Affected side			
Greater trochanter	$-0.46 \pm 1.50$	19 (76%)	0.006
Femoral neck	$0.66 \pm 1.42$	7 (28%)	0.024
Ward's triangle	$0.59 \pm 1.68$	8 (32%)	0.071

balancing the adduction moment. Since the abductors insert on the greater trochanter, a reduced adduction moment may reflect reduced forces in this region and may result in bone loss. Similarly, the anterior fibers of the gluteus medius and minimus are recognized as primary internal rotators (Kapandji, 1987; Mansour and Pereira, 1987; Moore, 1985; Spence and Mason, 1979). Thus, the decreased peak external rotation moment in early stance may also be reflective of decreased abductor muscle forces. This could explain why although the peak external rotation moment is relatively small as compared to the moments in the other planes, it is still significantly correlated with the bone mineral density. The peak adduction and external rotation moments when considered together did not significantly increase the ability to predict the normalized bone mineral density compared to using just the best single predictor. The two peaks can occur at the same time during stance (20% of the patients) and there was a trend for the two moments to be correlated. This further substantiates the idea that the two moments are both reflective of abductor muscle forces.

Several variables may be important in explaining some of the variance in normalized bone mineral density not accounted for by the gait parameters. Although the patients with osteoarthritis were all preoperative candidates for total hip replacement, the stage of the osteoarthritis or extent of femoral lesions was likely variable. Since increased bone density has been associated with osteoarthritis, variations in the stage of the disease as well as the length of time from the onset of the disease may further affect the bone distribution. In addition, although gait is a frequently performed activity, patients perform other activities with different load distributions that may also affect bone. The activity level of the patients would also be expected to vary. Hip loads during gait can be affected by changes in pain level (Hurwitz et al., 1997) and the use of assistive devices, which were not permitted during the gait test but may have been used by some of the patients throughout the day. Differences in how each individual's bone adapts to the loading environment would further

account for some of the variance not accounted for by the gait parameters.

The model used to calculate the external moment was a link model in which it is assumed that there is no rotation about the long axis of the femur. Other studies have demonstrated that the transverse rotations during gait are relatively small (Lafortune, 1992) and the magnitudes of the moments of the control subjects in this study are consistent with those reported by other investigators (Apkarian et al., 1989; Kadaba et al., 1989; Winter, 1991). The external moments are an approximation for the hip joint loads and actual stresses and strains in the femur. Determining the actual femoral stresses and strains first requires an analytical musculoskeletal model with a method for solving the indeterminate problem of assigning the muscle activation levels and then a finite element model. Understanding the relationship between the external moments and bone mineral density is a first step towards understanding the relationship between the actual forces, stresses and strains in the femur and the bone changes.

Understanding the causes of preoperative bone loss may help improve the long-term outcome of total hip replacement. Periprosthetic bone loss associated with uncemented femoral stems has been well documented (Bryan et al., 1996; Engh and Bobyn, 1988; Engh et al., 1992; Kiratli et al., 1996) and concerns have been raised with regards to the long-term clinical implications of this phenomenon (Sumner, 1998). Extensive bone loss, which can result from preoperative limb unloading, could minimize the surgical options available for a total hip replacement and may even be related to the extent of subsequent periprosthetic bone loss (Engh et al., 1992; Maloney et al.).

This study demonstrated that variations in proximal femoral bone mineral density, which have primarily been attributed to the disease process (osteoarthritis), are also related to the loads applied to the proximal femur during daily activities. Even in regions with increased bone mineral density, the loads were related to the normalized bone mineral density. Thus, the presence of preoperative

gait adaptations and their associated effect on the loads at the hip joint may partially account for variations in the extent of bone changes associated with osteoarthritis.

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