

Dynamic knee loads during gait predict proximal tibial bone distribution

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Abstract

This study tested the validity of the prediction of dynamic knee loads based on gait measurements. The relationship between the predicted loads at the knee and the distribution of bone between the medial and lateral sides of the tibia was examined. The motion and external forces and moments at the knee were measured during gait and a statically determinate muscle model was used to predict the corresponding forces on the medial and lateral tibial plateaus. In particular, the relationship between the knee adduction moment during gait and the ratio or distribution of medial to lateral tibial bone mineral content was studied. Bone mineral content was measured with dual energy X-ray absorptiometry in four regions, two proximal regions 20 mm in height, one medial and one lateral and two distal regions 20 mm in height, one medial and one lateral. The best single predictor of the medial–lateral ratio of proximal bone mineral content (bone distribution) was the adduction moment ($R^2 = 0.31$, $p = 0.003$). Adding weight (negative coefficient, $p = 0.0004$) and the ratio of the average predicted peak force on the medial plateau to the predicted peak force on the lateral plateau (positive coefficient, $p = 0.0033$) to the regression model significantly increased the ability to predict the proximal medial–lateral bone distribution ($R^2 = 0.72$, $p = 0.0001$). Distally neither the subject characteristics nor the gait moments and predicted forces were significant predictors of the bone distribution. The lack of a correlation distally may be reflective of the forces being more evenly distributed further from the tibial plateau. While it has long been suggested that the adduction moment is the primary determinate of the distribution of load between the medial and lateral plateaus, this is the first evidence of its relationship to the underlying bone distribution. © 1998 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Statically determinate muscle models show that the adduction moment is a major determinate of not just the total load across the knee joint but its distribution between the medial and lateral plateaus as well (Schipplein and Andriacchi, 1991). Recent studies using statically determinate muscle models show that during walking approximately 70% of the total load typically passes through the medial compartment of the knee joint. In addition, an increase in the adduction moment during gait is predicted to increase the medial compartment

loading at the knee joint. The prediction of higher forces on the medial side relative to the lateral side in normal subjects is consistent with the fact that the medial side of the tibia has bone that is significantly denser or stronger than that of the lateral side (Akamatsu et al., 1997; Behrnes et al., 1974; Harada et al., 1988; Petersen et al., 1996).

Although the adduction moment during gait is very reproducible with a mean difference between tests on separate days of only 0.1% body weight \times height (80% confidence interval, 0.55% body weight \times height), it does vary substantially between normal subjects (Andrews et al., 1996). Thus, if model predictions based on gait measurements represent true joint loads, it would be expected that variations in the adduction moment would be related to the bone mineral content on the medial side relative to the lateral side of the proximal tibia.

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Variations in the adduction moment should be associated with the distribution of bone between the medial and lateral compartments of the proximal tibia because in other situations, such as injury induced disuse (Kannus et al., 1994; Karlsson et al., 1993) and joint replacement (Bryan et al., 1996; Kiratli et al., 1996), changes in loads applied to the bone are associated with changes in bone mineral content or density. In addition, some studies have found a close association between bone strength and bone mineral density as measured by dual energy absorptiometry (Edmonston et al., 1994; Singer et al., 1995).

Previous studies have only related a few static factors likely to affect the load distribution (tibial femoral knee angle and meniscectomy) to the tibia bone (Akamatsu et al., 1997; Christensen et al., 1982; Hvid, 1988; Hvid and Hansen, 1985; Muller-Gerbl et al., 1993; Petersen et al., 1996) and have not related the actual predicted loads to the tibia bone. The purpose of this study was to test the validity of the dynamic force predictions from gait analysis and a statically determinate muscle model by testing the hypothesis that the distribution of bone mineral content in the proximal tibia was significantly correlated with the knee adduction moment as well as the predicted forces on the medial and lateral tibial plateau during gait. Bone distribution was quantified by the ratio of the bone mineral content on the medial side of the tibia relative to that of the lateral side.

2. Methods

The motion, external moments and intersegmental forces during gait of 26 normal subjects (18 males, 8 females) with an average age of 32 ± 12 yr were calculated and their bone mineral content was measured with dual energy X-ray absorptiometry. All subjects had no significant musculo-skeletal involvement and had an average height of 177 ± 11 cm and an average weight of 738 ± 136 N. To eliminate the confounding effect of bone loss following menopause, only premenopausal female subjects (all less than 45 yr of age) were tested. All subjects were Internal Review Board approved and received informed consent.

Proximal tibiae were scanned by dual energy X-ray absorptiometry (Lunar DPX-L, Madison, Wisconsin), using the "orthopedic" software. The lower extremity was fixed in 15° of internal rotation and positioned so that the direction of the scanning was perpendicular to the long axis of the tibia. The scan included the proximal 80 mm of the tibia at a resolution of 0.6 mm in the transverse direction and 1.2 mm in the longitudinal direction. Four regions of interest (PM, proximal medial; PL, proximal lateral; DM, distal medial; and DL, distal lateral) were defined by modifying the four regions provided in the manufacturer's standard automatic analysis mode

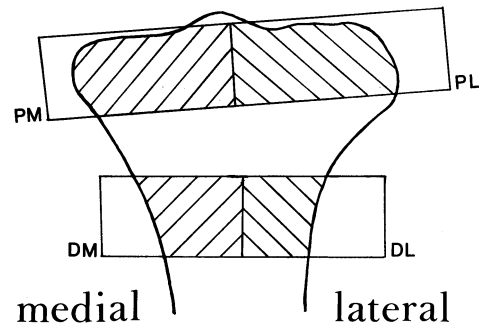


Fig. 1. The bone mineral content was determined in four regions in the tibia: proximal medial (PM), proximal lateral (PL), distal medial (DM) and distal lateral (DL).

(Fig. 1). The bone edges were assigned to the tibia, eliminating the fibula. Each region had a height of 20 mm. The width in the medio-lateral direction was set as one-half the distance between the medial and lateral bone edges along a line midway between the top and bottom of each region. The two proximal regions were positioned so that their top edges were just superior and parallel to the medial and lateral joint surfaces of the tibia. The two distal regions were positioned 25 mm distal to the proximal regions so that their top and bottom edges were perpendicular to the long axis of the tibia. For each region, the bone mineral content was measured for the area bounded by the bone edges and the boundaries of the region positioned within the bone (see hatched areas of Fig. 1). These region locations were chosen to characterize the bone mineral content in the lateral and medial compartment of the subchondral cancellous bone and the cortical bone of the diaphysis. The 20 mm height of the regions of interest were chosen so that at the proximal site the fibula was largely eliminated. To determine the precision of the measurements, four subjects were scanned twice on the same day with repositioning between scans. The coefficient of variation (Kiratli et al., 1992) was 5, 3, 5 and 2% in the proximal medial, proximal lateral, distal medial and distal lateral regions, respectively.

The instrumentation for gait analysis included an optoelectronic system with a passive retroreflective marker system (CFTC—Computerized Functional Testing Corporation, Chicago II, USA) and a multicomponent force plate (Bertec, Columbus, Ohio USA). The average error of the three dimensional coordinates is 7 mm within the calibration volume. The average angular accuracy was 1° with a maximum variation of 3° across the calibration volume.

Motion of the limbs was determined by calculating the three dimensional spatial positions of markers placed on the lateral aspect of the superior most iliac spine, 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., 1979; Andriacchi and Strickland, 1985). Inverse dynamics were used to calculate the three dimensional external moments and intersegmental joint forces 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., 1997; Andriacchi and Strickland, 1985). 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 external moments and forces were transformed into the local coordinate system of each joint which for the knee was aligned with the shank (Schipplein and Andriacchi, 1991). Forces were expressed as a percentage of each subject's body weight and moments as a percentage of each subject's body weight multiplied by height.

A previously published statically determinate muscle model was used to predict the joint reaction forces on the medial and lateral plateaus during gait (Schipplein and Andriacchi, 1991). The joint kinematics (knee flexion angle) and kinetics (sagittal and frontal plane moments, axial and anterior – posterior intersegmental forces) during gait were the input data to the analytical model. This model was based on assumptions similar to those by Harrington (1983) and Morrison (1968). The model consisted of three muscle groups, the quadriceps group (rectus femoris, vastus medialis, vastus intermedius, and vastus lateralis), the knee flexors (hamstrings (long and short head of the biceps, semimembranosus, semitendinosus), gracilis and sartorius) and the gastrocnemius muscles (medial and lateral gastrocnemius head, plantaris). The joint reaction force was the vector sum of the active muscle forces plus the intersegmental knee joint force resolved along the axis of the tibia. The flexion and extension moment was used to determine the muscle forces, assuming no antagonistic muscle activity (Morrison, 1968). The contact point was determined by balancing the abduction and adduction moment (Morrison, 1968). As long as the contact point remained within a predetermined limiting value no forces in the collateral ligaments were required, otherwise appropriate forces in the collateral ligaments were introduced. The average and maximum of the two peak reaction forces on the medial plateau were calculated for each representative trial along with the peak force on the lateral plateau. The predicted forces were expressed as a percentage of body weight.

Subjects were asked to walk at three self-selected speeds of slow, normal and fast. Either the right- or left-side data were randomly chosen for analysis for each subject. A representative walking trial at approximately 1.3 m/s was first chosen for analysis and the average speed of the analyzed trials was 1.3 ± 0.1 m/s. The

chosen trial was then compared with the other trials of the subject to ensure that the magnitudes and patterns of the kinematics and kinetics did not contain any artifacts associated with a miss-step or the contralateral limb striking the force plate. The primary analysis consisted of a multivariate forward stepwise linear regression model ($p_{in} = 0.05$, $p_{out} = 0.1$) to determine if the external knee adduction moment and predicted forces on the medial or lateral plateau during gait were significant predictors of the distribution of bone in the tibia. Height and weight were also included in the regression model. Simple regression analysis with Pearson correlation coefficients was used to determine the individual significant correlations between the gait kinetics, predicted forces and subject characteristics with the bone distribution. An additional regression model was used to check if any of the individual relationships between the gait kinetics or predicted forces with bone distribution were significantly different between males and females after accounting for the effect of weight and height. An ANOVA was used to test if gender or weight had a significant effect on the values of the bone distribution, joint kinetics or the predicted forces. A significance level of $\alpha < 0.05$ was chosen for all analyses.

3. Results

The general characteristics of the external forces, moments and predicted loads on the medial and lateral plateaus were common to all subjects (Fig. 2). However, there were substantial variations in the peak magnitude of the adduction moment, the predicted peak forces on the medial and lateral plateaus and the bone mineral content of the medial side of the tibia relative to that of the lateral side (Fig. 3). None of the joint kinetics or predicted forces were significantly different between males and females. However, the ratio of the proximal bone mineral content on the medial side relative to the lateral side was significantly greater in the females (1.21 ± 0.10) as compared to the males (1.12 ± 0.09) ($p = 0.042$), but this difference was attributable to weight ($p = 0.040$) and not gender ($p = 0.798$). The distal bone distribution was not significantly different between the males and females. As long as weight was included as a predictive factor in the regression equations, the regression equations of the males and females were not significantly different ($p = 0.21$ to $p = 0.96$).

The knee adduction moment was the single best predictor of the distribution of bone in the proximal tibia between the medial side as compared to the lateral side (zones PM and PL) (Table 1, Fig. 4). As the knee adduction moment increased the ratio of the proximal medial bone mineral content relative to the lateral bone mineral content increased ($R^2 = 0.31$, $p = 0.003$). The maximum and average predicted peak force on the medial plateau

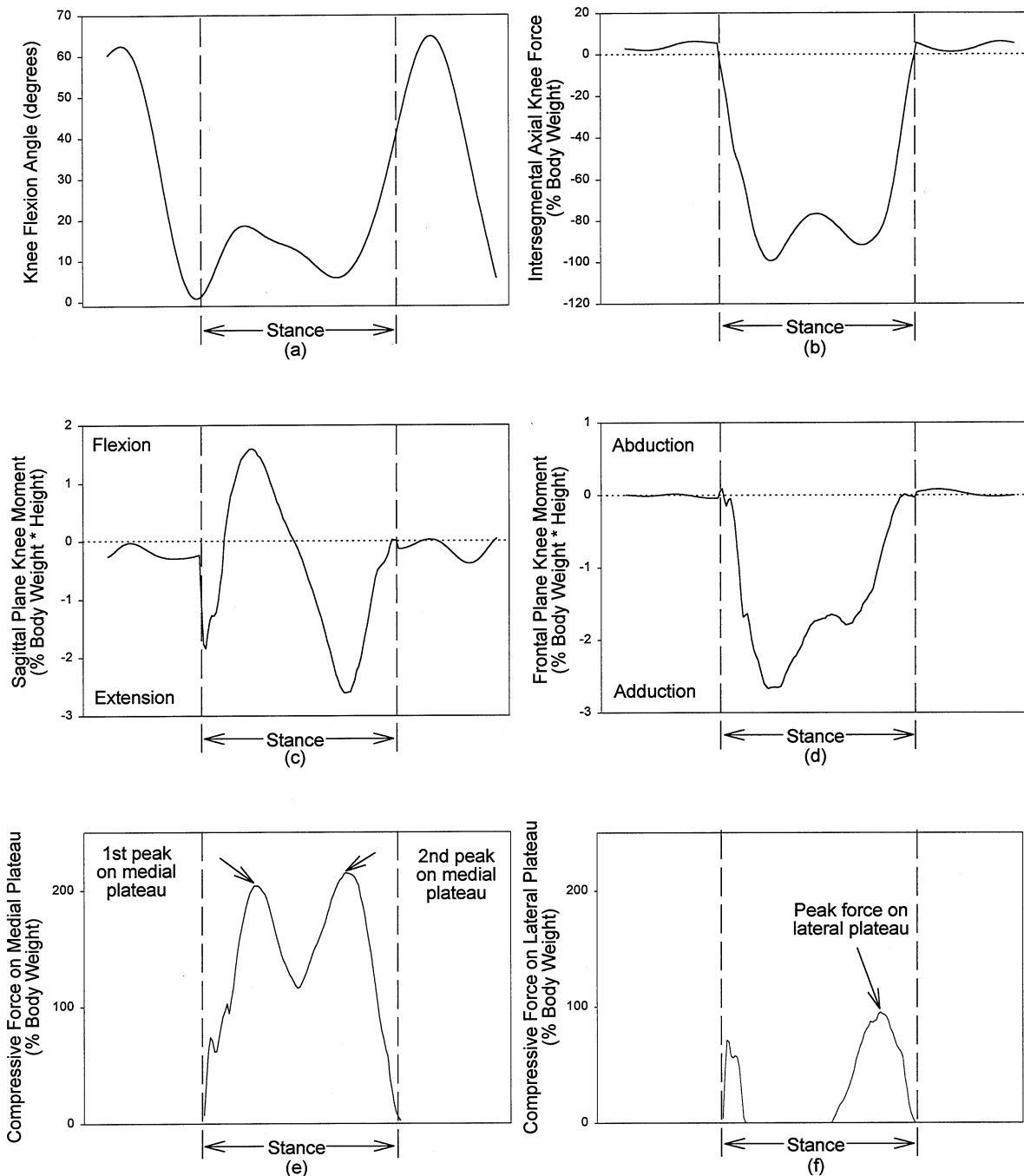


Fig. 2. A representative illustration of the input data used in the statically determinate muscle model along with its corresponding output data. 2a–d are an illustration of the intersegmental forces and external moments that are input into the statically determinate model. 2e–f represent an illustration of the predicted peak forces on the medial and lateral plateaus that are output from the statically determinate muscle model. The maximum and average of the two peak forces on the medial plateau were calculated along with the peak reaction force on the lateral plateau.

as well as the ratio of the predicted force on the medial plateau to the force on the lateral plateau were all significantly correlated with the distribution of proximal bone mineral content ($R^2 = 0.18$ to $R^2 = 0.28$; $p = 0.028$ to $p = 0.001$). The adduction moment and the ratio of the predicted force on the medial plateau to the force on the lateral plateau had a greater ability to predict the distri-

bution of bone mineral content than that of just the predicted forces on the medial plateau.

Accounting for variations in the subject's height or weight further increased the ability to predict the proximal bone distribution. For example weight and adduction moment together accounted for 58% of the variation in the proximal bone distribution ($R^2 = 0.58$, $p < 0.0001$).

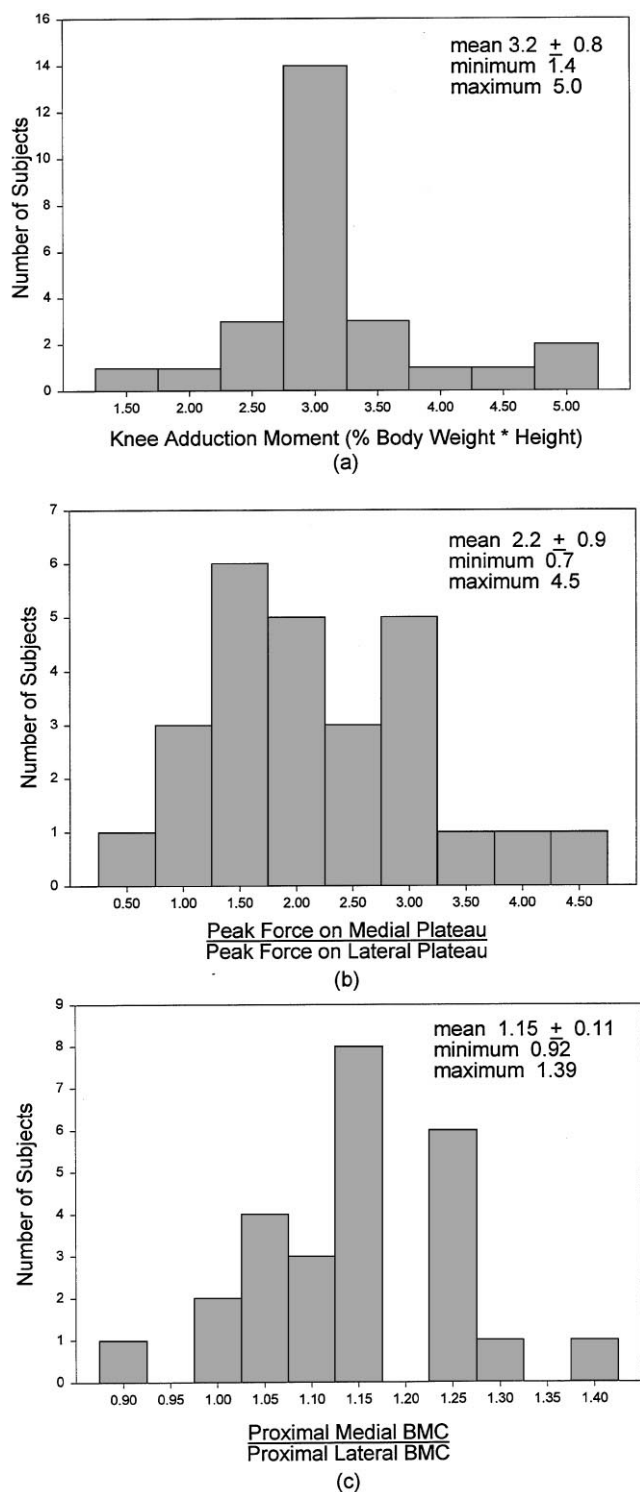


Fig. 3. There was considerable variation in the knee adduction moment (a) and predicted peak forces on the medial and lateral plateaus. The ratio of the peak force on the medial plateau relative to that on the lateral plateau and the ratio of the medial to lateral proximal tibial bone mineral content also showed considerable variation (b and c).

Table 1

The coefficient of determinations (R^2 value) from simple regression analysis and associated p values for the proximal bone distribution and the gait kinetics, predicted forces on the proximal and medial plateaus and the subject characteristics. Statistically significant correlations are in bold

	Medial BMC/lateral BMC (PM/PL)	
<i>Gait Kinetics</i>		
Adduction moment	$R^2 = 0.31$	$p = 0.003$
Adduction moment (negative correlation)	$R^2 = 0.05$	$p = 0.250$
Flexion moment	$R^2 = 0.05$	$p = 0.290$
Extension moment (negative correlation)	$R^2 = 0.00$	$p = 0.870$
Intersegmental axial force	$R^2 = 0.05$	$p = 0.260$
<i>Predicted joint forces</i>		
Maximum peak on medial plateau	$R^2 = 0.18$	$p = 0.028$
Average peak on medial plateau	$R^2 = 0.24$	$p = 0.011$
Peak force on lateral plateau (negative correlation)	$R^2 = 0.14$	$p = 0.053$
<i>Ratio of specified medial force to lateral force</i>		
Maximum peak force on medial plateau	$R^2 = 0.28$	$p = 0.005$
Peak force on lateral plateau		
Average peak force on medial plateau	$R^2 = 0.26$	$p = 0.007$
<i>Peak force on lateral plateau</i>		
<i>Subject Characteristics</i>		
Weight (negative correlation)	$R^2 = 0.30$	$p = 0.004$
Height (negative correlation)	$R^2 = 0.18$	$p = 0.031$

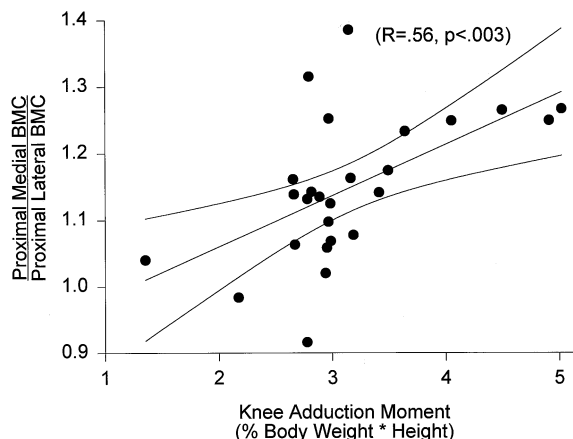


Fig. 4. The knee adduction moment was a significant predictor of the distribution of the bone mineral content between the medial and lateral proximal zones.

When adduction moment, weight and the ratio of the predicted peak forces from the muscle model were all used in the regression equation the ability to predict the proximal bone distribution increased even further (Table 2).

Table 2
The first set of equations are the best fit regression lines for predicting the proximal bone distribution obtained using forward stepwise regression. The second set of equations are the other triplet combinations that were significant predictors of the proximal bone distribution. The gait kinetics, predicted forces and subject characteristics served as the independent predictors of proximal BMC distribution

R^2	p	Stepwise regression equations
0.31	0.0031	7.7* Adduction + 91
0.58	0.0001	7.2* Adduction – 0.04* Weight + 122
0.72	0.0000	6.3* Adduction – 0.04* Weight + 4.7*(Ratio average peak force medial plateau to peak force lateral plateau) + 113
		Other significant regression lines involving three predictors
0.71	0.0000	6.3* Adduction – 0.04* Weight + 4.3*(Ratio maximum peak force medial plateau to peak force lateral plateau) + 112
0.69	0.0000	7.6* Adduction – 0.04* Weight – 7.4* Peak force lateral plateau + 126
0.67	0.0000	10.6* Average peak force on medial plateau – 0.04* Weight + 4.3*(Ratio average peak force medial plateau to peak force lateral plateau) + 112
0.66	0.0000	10.7* Average peak force on medial plateau – 0.04* Weight + 3.9*(Ratio maximum peak force medial plateau to peak force lateral plateau) + 111
0.64	0.0000	13.1* Average peak force on medial plateau – 0.04* Weight – 6.4*(Peak force lateral plateau + 123
0.62	0.0001	7.3* Maximum peak force on medial plateau – 0.04* Weight + 5.0*(Ratio average peak force medial plateau to peak force lateral plateau) + 114
0.59	0.0002	6.8* Maximum peak force on medial plateau – 0.04*Weight + 4.4*(Ratio maximum peak force medial plateau to peak force lateral plateau) + 115
0.59	0.0002	4.4* (Ratio maximum peak force medial plateau to peak force lateral plateau) – 0.03* Weight + 6.0* Extension moment + 91

The knee adduction moment (positive coefficient), the weight (negative coefficient) and the ratio of the average predicted peak force on the medial plateau to that on the lateral plateau were the best three predictors of proximal bone distribution ($R^2 = 0.72$, $p < 0.0001$; Table 2). Adding a fourth predictor did not significantly increase the predictive ability of the regression equation. The flexion, extension, and adduction moments as well as the axial force were not significantly correlated with the proximal bone distribution.

In the distal region none of the subject characteristics, joint kinetics or predicted forces were significant predictors of the distribution of bone between the medial and lateral regions.

4. Discussion

The significant positive correlation between the adduction moment measured during walking and the distribution of bone between the medial and lateral sides of the proximal tibia indicated that the adduction moment was a valid predictor of the medial to lateral load distribution across the knee. The best predictors of bone distribution included the adduction moment, the weight and the ratio of the average peak force on the medial plateau to the peak force on the lateral plateau ($R^2 = 0.72$). The kinetic

variables that were not significant predictors of the bone distribution were associated with overall joint loading (sagittal plane moments and vertical axial intersegmental force) and not the distribution of forces between the two plateaus. The lack of correlation between the dynamic loads during gait and the bone distribution in the distal zones may be reflective of the fact that as one proceeds distally the forces are more likely to be evenly distributed as expected from Saint Venant's principle (Timoshenko and Goodier, 1934).

The loads acting at the knee have important implications for the progression of degenerative joint disease of the knee and outcome from both surgical (Prodromos et al., 1985) and nonsurgical treatment modalities. The most accurate method for determining the loading on the tibia would be to measure the forces *in vivo*. The applicability of an *in vivo* method is clearly limited and not feasible in normal subjects or in patients with a pathology not requiring a total knee replacement. Thus, using the dynamic measurements during gait to infer the loading conditions at the knee joint is an extremely valuable tool that can be used with a diverse group of individuals, including those with and without knee pathologies. This study provided the most direct validation of these force predictions to date.

Limitations do exist when estimating the tibial forces from the gait data and the analytical muscle model. The

muscle model did not account for antagonistic muscle activity or differences in muscle activation levels within the agonist muscle groups. Thus, the muscle model provided a lower boundary on the predicted forces. The actual distribution of forces may also be affected by the tibia femoral knee angle, which was not measured in this study group. Among normal subjects the adduction moment has been correlated with the tibia femoral knee angle (Andrews et al., 1996). It is possible, however, that in patients with knee pain, ligamentous injury or disease a relationship between the tibia femoral knee angle and adduction moment may not persist because subjects may adapt their gait to decrease pain and loads, which would not be reflected in static measurements of the knee angle. Some studies have demonstrated a relationship between the tibia femoral knee angle and the adduction moment in osteoarthritic patients (Hilding et al., 1995) while others have not demonstrated such a relationship in this and other types of patient populations (Noyes et al., 1992; Prodromos et al., 1985; Wang et al., 1990). Despite the limitations of this study the peak axial knee forces measured *in vivo* in a single patient with a distal femoral replacement and rotating knee hinge were very similar to those predicted by the analytical model. The *in vivo* axial peak forces varied between 2.3 and 2.5 body weight (Taylor et al., 1997) while the average peak predicted force on the medial plateau for this study was 2.4 body weight.

The sensitivity of the bone distribution in the proximal tibia to the expected dynamic load distribution in this study was very consistent with findings from other studies that examined the relationship between the tibial bone distribution and static factors likely to alter loading conditions at the knee (Akamatsu et al., 1997; Christensen et al., 1982; Muller-Gerbl et al., 1993; Petersen et al., 1996). Akamatsu et al. (1997) demonstrated that the tibial femoral knee angle in osteoarthritic knees and its resulting change following high tibial osteotomy resulted in consistent changes in tibial bone distribution while Petersen et al. (1996) showed that knees with a total or partial meniscectomy had a greater discrepancy between the medial and lateral bone distribution as compared to normal knees. Both of these studies were based on a pathologic population and did not examine how the resulting change in the static factor (tibial femoral knee angle or meniscectomy) would actually effect the magnitudes of the loads at the knee.

The ability to predict the proximal bone distribution increased when the predicted forces on the tibial plateaus were used in conjunction with the adduction moment. In a patient population the predictive ability of the regression equation may increase even further with the inclusion of the force predictions from the statically determinate muscle model. In a patient population with knee pain or disease greater variation in the sagittal plane moments may result, which would be reflected in

greater variations in both the magnitude of the predicted forces on the tibial plateaus as well as the relative ratio of the peak forces on the medial to lateral plateau. For example if a patient had an increased sagittal plane moment when the peak force on the lateral plateau were to occur (during the peak abduction moment) then the ratio of the forces on the medial to lateral plateaus would be decreased while if a patient had an increased sagittal plane moment when the peak force on the medial plateau were to occur (during the peak adduction moment) then the ratio of the forces on the medial to lateral plateaus would be increased.

While previous studies have related the clinical outcome of high tibial osteotomy to the adduction moment during gait (Prodromos et al., 1985; Wang et al., 1990), this was the first validation of the dynamic force predictions during gait as seen by the significant correlation between the dynamic medial–lateral load distribution and the corresponding bone distribution.

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