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Superior Displacement of the Hip in Total Joint Replacement: Effects of Prosthetic Neck Length, Neck-Stem Angle, and Anteversion Angle on the Moment-Generating Capacity of the Muscles

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Summary: The purpose of this study was to determine the effects of superior displacement of the hip center and changes in three prosthetic parameters (neck length, neck-stem angle, and anteversion angle) on the capacity of muscles to generate force and moment about the hip. A three-dimensional model that calculates the maximum isometric forces and moments generated by 25 muscles crossing the hip over a wide range of body positions was used to evaluate the effects of a 2 cm elevation of the hip center and changes in the prosthetic parameters. After superior displacement of the hip center, the neck length was increased from 0 to 3 cm, the neck-stem angle was varied between 110 and 150°, and the anteversion angle was varied between 0 and 40°. Our analysis showed that a 2 cm superior displacement of the hip center would decrease the moment-generating capacity of the four muscle groups studied (abductors, adductors, flexors, and extensors) if neck length were not increased to compensate for decreased muscle length. In the computer model of an adult man that we used, a 2 cm increase in neck length restored the moment-generating capacity of the muscles by increasing muscle length and force-generating capacity. However, a 3 cm increase in neck length increased passive muscle forces substantially, which potentially could limit joint motion. An increased neck-stem angle (i.e., a valgus neck) decreased the abduction moment arm but increased the moment-generating capacity of the other muscle groups. A change in the anteversion angle from 0 to 40° had a relatively small effect on the isometric moment-generating capacity of the muscles studied.

The success of total hip replacement depends on several factors, including relief of pain, range of motion, and secure fixation of the components. Another important factor, which often is overlooked, is preservation or reestablishment of the capacity of the muscles to develop force and generate moments about the hip. If the moment-generating capacities of the muscles are greatly reduced, the outcome of an otherwise satisfactory hip replacement may be compromised. For example, if the hip flexors, extensors, or abductors cannot generate adequate forces and moments, it may be difficult for the patient to climb stairs, rise from a chair, or walk without a limp (4,18,19,31).

The moment-generating capacities of the muscles crossing the hip may decrease if changes in musculoskeletal geometry before or during total hip replacement affect the moment arms or force-length relationships of the muscles. For instance, changes in the location of the hip center and alterations in the

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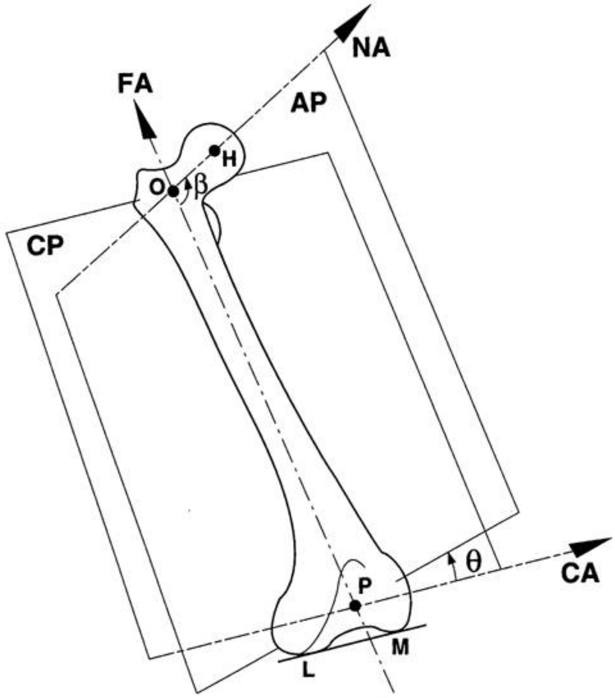

FIG. 1. Description of femoral geometry. H is the center of the femoral head; O is the center of the base of the femoral neck, which was determined by calculating the centroid of the femoral diaphysis on a cross section through the base of the femoral neck; P is the attachment of the posterior cruciate ligament; L is the posterior aspect of the lateral condyle; and M is the posterior aspect of the medial condyle. The femoral neck axis (NA) is defined by points O and H, where OH is the neck length. The femoral axis (FA) is defined by points P and O. The condylar axis (CA) is defined as the vector that passes through P and is parallel to LM. The plane of anteversion (AP) is formed by the axes NA and FA. The condylar plane (CP) is formed by the axes FA and CA. The neck-stem angle (β) and anteversion angle (θ) can be determined on the basis of these definitions (see text). Adapted from Murphy SB, Simon SR, Kijewski PK, Wilkinson RH, Griscom NT: Femoral anteversion. *J Bone Joint Surg [Am]* 69:1170, 1987.

geometry of the prosthesis can change the lengths and moment arms of muscles. Delp and Maloney reported that the moment-generating capacity of the muscles may decrease substantially because of muscle shortening caused by superior displacement of the hip center (14). This study also demonstrated that alterations in the hip center can have different effects on the hip flexors, extensors, abductors, and adductors because of differences in the muscles' lines of action and architecture (such as length of muscle fibers). However, the changes in the moment-generating capacities of the muscles caused by alterations in the geometry of the prosthesis (neck length, neck-stem angle, and anteversion angle) have not been quantified previously.

It generally is desirable to place the acetabular component as close to the anatomic hip center as possible; however, sometimes it may be necessary to place the hip center superior to the normal anatomic location. For instance, a loss of acetabular bone stock may necessitate superior displacement at revision surgery. Leaving the hip center in a superior location has been criticized (7,21,23,24,32), and bone grafting to bring the acetabular component down to an anatomic position has been supported by several clinical studies (3,8,10,17,36,41). To avoid the problems associated with late collapse of the graft (20) and to support the prosthesis with native bone, others have advocated delevation of the hip center (11,34).

When it is necessary to accept a superiorly displaced hip center, there frequently is an option to compensate for changes in muscle lengths and moment arms by alteration of the geometry of the prosthesis. The objective of this study was to quantify the effects of three prosthetic parameters (neck length, neck-stem angle, and anteversion angle) on the moment-generating capacity of the hip abductors, adductors, flexors, and extensors after superior displacement of the hip center.

MATERIALS AND METHODS

A three-dimensional biomechanical model of the human lower extremity was used to study how changes in musculoskeletal geometry affect the moment-generating capacity of the muscles (13). This model, representing an adult man with a height of approximately 1.8 m, estimates the forces and moments generated by the muscles over a wide range of body positions when the muscles are fully excited under isometric conditions. The location of the hip center and the prosthetic neck length, neck-stem angle, and anteversion angle can be altered to study how each parameter affects the moment-generating capacity of the muscles.

Several definitions are needed to specify femoral geometry (Fig. 1). These definitions are consistent with previous studies except for the definition of the femoral axis, which was defined as passing through point O and the center of the knee (27). Neck length, neck-stem angle, and anteversion angle can be defined on the basis of the definitions in Fig. 1. Neck length is the distance from the center of the femoral head to the intersection of the neck axis and the femoral shaft axis (OH, Fig. 1). The neck-stem angle (β) is the angle formed by the neck axis and the femoral shaft axis. The anteversion angle (θ) is defined as the angle formed in the plane perpendicular

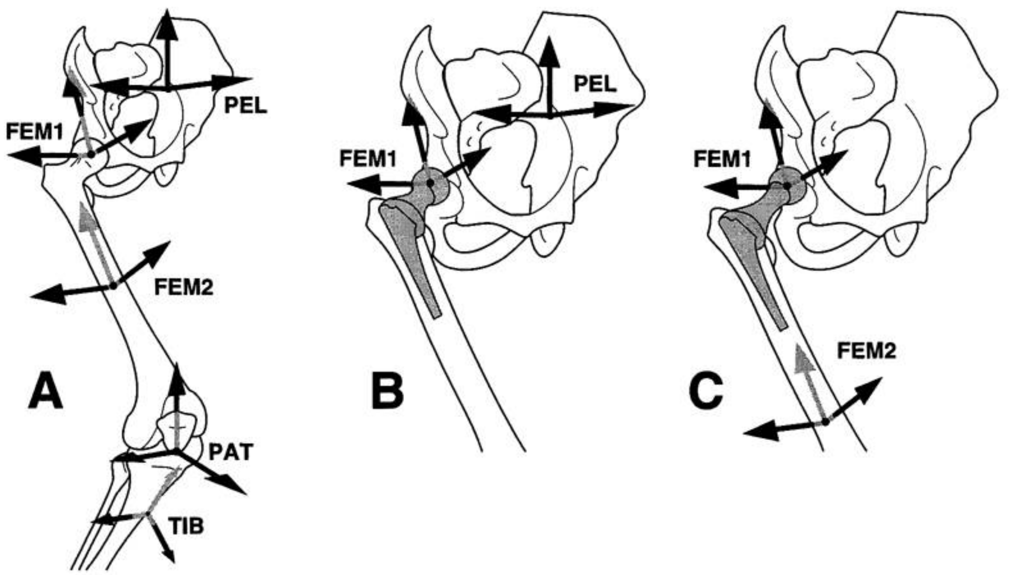

FIG. 2. Reference frames for the pelvis (PEL), femoral head (FEM1), femoral shaft (FEM2), patella (PAT), and tibia (TIB) (**A**). Displacement of the hip center is represented by alteration of the transformation between PEL and FEM1 (**B**). The transformation between FEM1 and FEM2 is determined by the three prosthetic parameters (neck length, neck-stem angle, and anteversion angle) (**C**). Thus, the hip center can be displaced superiorly with the parameters kept constant (as in **B**) or altered (such as increased neck length) to compensate for the superior displacement (as in **C**).

to the femoral axis by the plane of anteversion and the condylar plane. In the normal femur model used here, the neck length is 4.9 cm, the neck-stem angle is 128°, and the anteversion angle is 19°, which are within the normal range (9,16,42).

To characterize changes in musculoskeletal geometry, reference frames were fixed in the pelvis, femoral head, femoral shaft, patella, and tibia (Fig. 2A). A change in the position of the hip center altered the transformation matrix between the pelvic reference frame and the reference frame fixed at the center of the femoral head (Fig. 2B). A change in any of the prosthetic parameters altered the transformation matrix between the reference frame fixed at the center of the femoral head and the reference frame fixed in the femoral shaft (Fig. 2C). The transformation matrices between the femoral shaft, patella, and tibia coordinate systems remained unaltered when there were changes in the position of the hip center and prosthetic parameters.

The pelvic reference frame and muscle attachments on the pelvis remained fixed when there were changes in the hip center and prosthetic parameters. Muscle insertions on the femur, patella, and tibia, however, were displaced, with their respective osseous reference frames, if the hip center or the prosthetic parameters were altered. Thus, muscle lengths and moment arms were changed by these alterations. The musculoskeletal model was used to determine how these changes affected the maximum isometric force and moment generated by four muscle groups.

Musculoskeletal Model

We studied four muscle groups: (a) the abductors—gluteus medius, minimus, and maximus (anterior fibers); tensor fasciae latae; piriformis; and sartorius; (b) the adductors—adductor magnus, longus, and brevis; pectineus; semimembranosus; and gracilis; (c) the extensors—gluteus maximus, semimembranosus, semitendinosus, biceps femoris (long head), adductor magnus, and gluteus medius (posterior fibers) and minimus (posterior fibers); and (d) the flexors—iliacus, psoas, rectus femoris, sartorius, tensor fascia latae, and gluteus medius (anterior fibers) and minimus (anterior fibers). Muscles that contribute to moments with respect to more than one axis were included in multiple groups. The musculoskeletal model used in this study has been described in detail in previous publications (13,14); therefore, only a brief description is given here.

The lines of action of 25 muscle-tendon complexes that cross the hip were defined on the basis of their anatomical relationships to three-dimensional representations of the bones. Each muscle was described as a line segment or as a series of line segments. The kinematics of the hip and knee were characterized so that the moment arms and the origin-to-insertion length of each muscle-tendon complex could be determined for any combination of hip and knee angles. The moment arm of an individual muscle i (ma_i) for a particular degree of freedom was calculated as the partial derivative of the muscle's origin-to-insertion length ($\partial \ell_i$) with respect to the joint angle (1):

$$ma_i = \partial \ell_i / \partial \theta \tag{1}$$

where θ is the joint angle.

The isometric force-generating property (active and passive force developed at any length) of each muscle-tendon complex was derived by scaling of a generic model of muscle and tendon (43). Four parameters scale the generic model to represent a specific muscle-tendon complex: peak isometric muscle force, optimal muscle-fiber length, tendon slack length, and pennation angle. The peak isometric force was estimated from data on muscle physiologic cross-sectional areas reported by Brand et al. (5). Optimal fiber lengths and pennation angles of muscles were taken from Wickiewicz et al. (38) and Friederich and Brand (15), and tendon slack lengths were taken from Delp (12).

The maximum isometric moment generated by each muscle (the moment developed when muscle is maximally excited under isometric conditions) was calculated as the product of the muscle's maximum isometric force and moment arm at each hip angle. This calculation was repeated for a range of hip angles to calculate the maximum isometric moment versus joint angle curve of the muscle. The maximum isometric moment versus joint angle curves for all the muscles in a group were added to determine the maximum isometric moment versus joint angle curve of the muscle group, which then was compared with isometric joint moments that have been measured during maximum voluntary contractions at a variety of body positions (6,19,25,28-30,35,37). The comparisons between the model and experimentally measured moments demonstrate that the model represents normal moment-generating characteristics well (14).

The average moment ($\overline{M}$) generated by a muscle group over a specified range of joint angles (from θ_o to θ_f) was calculated from the curve for maximum moment versus joint angle with use of

$$\overline{M} = \frac{\sum_{\theta=\theta_o}^{\theta_f} M_\theta}{k} \tag{2}$$

where M_θ is the maximum isometric moment generated by the muscle group at a particular joint angle, and k is the number of samples of M_θ between θ_o and θ_f. The ranges of motion over which the moments were averaged were based on the range of hip angles over which moments are generated during a variety of activities (2,22,26,33,40). For the abductors and adductors, θ_o was 10° of adduction and θ_f was 20° of abduction; the knee was maintained in full extension. For the flexors, θ_o was 10° of extension and θ_f was 60° of flexion; the knee was flexed 45°. For the extensors, θ_o was 0° of flexion and θ_f was 70° of flexion; the knee was flexed 70°.

The average force ($\overline{F}$) was calculated by first summing the curves for maximum isometric force versus joint angle for all muscles in a group and then computing

$$\overline{F} = \frac{\sum_{\theta=\theta_o}^{\theta_f} F_\theta}{k} \tag{3}$$

where F_θ is the maximum isometric force generated by the muscle group at a particular joint angle and k is the number of samples of F_θ taken in the range of joint angles (from θ_o to θ_f).

The moment arm of a muscle group (ma) for a particular degree of freedom was calculated as the sum of the moment arms of each muscle (ma_i) for that degree of freedom multiplied by the muscle's peak isometric force $(F_o^M)_i$ divided by the sum of the peak forces of all the muscles in the group. Thus, for n muscles

$$ma = \frac{\sum_{i=1}^{n} ma_i \times (F_o^M)_i}{\sum_{i=1}^{n} (F_o^M)_i} \tag{4}$$

which represents a weighted average moment arm of the muscle group. The moment arm of the muscle group (ma) was plotted versus joint angle, and then the average moment arm ($\overline{ma}$) was determined with

$$\overline{ma} = \frac{\sum_{\theta=\theta_o}^{\theta_f} ma_\theta}{k} \tag{5}$$

where ma_θ is the moment arm of the muscle group (ma) at a particular joint angle and k is the number of samples of ma_θ taken in the range of joint angles (from θ_o to θ_f).

Analysis

The effect of alteration of each prosthetic parameter was determined as follows. First, we calculated

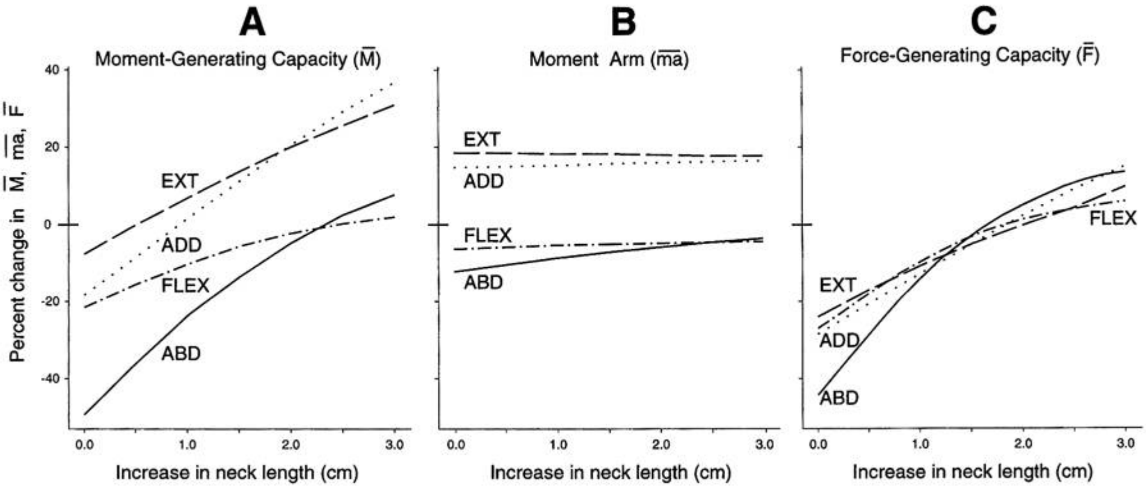

FIG. 3. The percentage of change in (**A**) moment-generating capacity ($\overline{M}$), (**B**) moment arm ($\overline{ma}$), and (**C**) force-generating capacity ($\overline{F}$) of each muscle group versus the increase in neck length. The hip center was displaced 2 cm superiorly, and the neck-stem angle (128°) and anteversion angle (19°) were kept constant. $\overline{M}$, $\overline{ma}$, and $\overline{F}$ for the abductors (ABD), adductors (ADD), flexors (FLEX), and extensors (EXT) are shown as a percentage of change from their values at the anatomical hip center and with the normal dimensions of the femur.

$\overline{M}$, $\overline{F}$, and $\overline{ma}$ of each muscle group with the hip at the anatomical hip center and the normal femur geometry. These are termed $\overline{M}_{anat}$, $\overline{F}_{anat}$, and $\overline{ma}_{anat}$. Second, the hip center was displaced 2 cm superiorly, and $\overline{M}$, $\overline{F}$, and $\overline{ma}$ were calculated with this new hip center. A 2 cm superior displacement was analyzed in detail because superior displacement of the hip occurs frequently in patients with total arthroplasty (16,34). Next, one prosthetic parameter was varied while the other two remained fixed at their default values. For example, the neck length was increased from 0 to 3 cm in 5 mm increments while the neck-stem angle and anteversion angle were held at 128 and 19°, respectively. The percentage of change in $\overline{M}$, $\overline{F}$, and $\overline{ma}$ with respect to $\overline{M}_{anat}$, $\overline{F}_{anat}$, and $\overline{ma}_{anat}$ for each increase in neck length was calculated. A similar method was used to evaluate the effect of a change in the neck-stem angle. The hip center was displaced 2 cm superiorly, and the neck-stem angle was varied from 110-150°, while the neck length and anteversion angle remained fixed at 4.9 cm and 19°, respectively. The percentage change in $\overline{M}$, $\overline{F}$, and $\overline{ma}$ with respect to $\overline{M}_{anat}$, $\overline{F}_{anat}$, and $\overline{ma}_{anat}$ from this variation of neck-stem angle was calculated. Similarly, with the hip displaced 2 cm superiorly, the effect of varying anteversion between 0 and 40° was determined, while the other two parameters were fixed at their default values.

How neck-stem angle and anteversion angle alter the effects of increasing neck length also was analyzed. After the hip center had been displaced 2 cm superiorly, the neck length was increased from 0 to 3 cm with three different neck-stem angles (120, 130, and 140°). The anteversion angle remained constant (19°) in this analysis. In each case, the percentage change in $\overline{M}$, $\overline{F}$, and $\overline{ma}$ with respect to $\overline{M}_{anat}$, $\overline{F}_{anat}$, and $\overline{ma}_{anat}$ were calculated for each muscle group. The effects of increases of neck length with anteversion angles of 10, 20, and 30° also were studied with a constant neck-stem angle of 128°.

RESULTS

Effects of Altered Neck Length

The moment-generating capacity of each muscle group decreased as a result of superior displacement of the hip center if there was no compensatory increase in neck length. Thus, $\overline{M}$ was less than 0 for all muscle groups when there was no increase in neck length (Fig. 3A). However, there was a substantial increase in the moment-generating capacity of each muscle group with increasing neck length. Lengthening of the prosthetic neck altered the moment arms ($\overline{ma}$) of the muscle groups very little (Fig. 3B) but increased the force-generating capacity ($\overline{F}$) of all the muscle groups substantially (Fig. 3C). The abductors were the only exception because the $\overline{ma}$ increased slightly with an increase in neck length.

Displacement of the hip center 2 cm superiorly decreased the moment-generating capacity of the abductors 49% if neck length was not increased (solid line in Fig. 3A). An increase of neck length of 2 cm restored $\overline{M}$ to 5% less than normal. Although

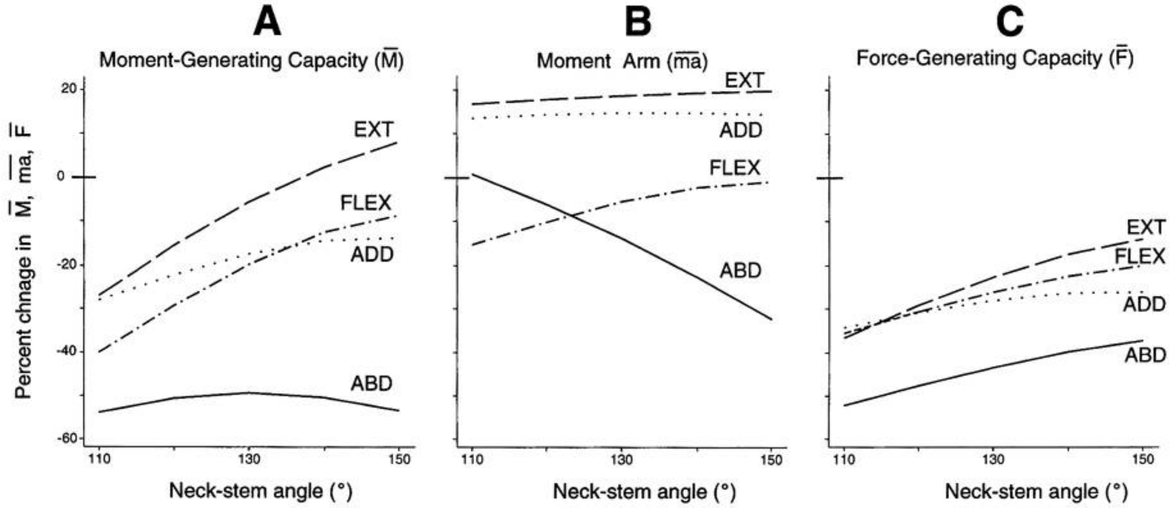

FIG. 4. The percentage of change in (**A**) moment-generating capacity ($\overline{M}$), (**B**) moment arm ($\overline{ma}$), and (**C**) force-generating capacity ($\overline{F}$) of each muscle group versus the prosthetic neck-stem angle. The hip center was displaced 2 cm superiorly, and the neck length (4.9 cm) and anteversion angle (19°) were kept constant. $\overline{M}$, $\overline{ma}$, and $\overline{F}$ for abductors (ABD), adductors (ADD), flexors (FLEX), and extensors (EXT) are shown as a percentage of change from their values at the anatomical hip center and with the normal dimensions of the femur.

a 2 cm increase in neck length restored $\overline{F}$ to normal, the $\overline{ma}$ of the abductors remained slightly less than normal because of the superiorly displaced hip center. An increase in neck length of 3 cm restored $\overline{M}$, mainly by increasing $\overline{F}$, which was greater than normal for the 3 cm increase in neck length. It should be noted, however, that the increase in $\overline{F}$ was due partly to an increase in passive muscle force, which increased rapidly when neck length was increased more than 2 cm.

Displacement of the hip center 2 cm superiorly decreased $\overline{M}$ of the adductors 18% if neck length was not increased (dotted line in Fig. 3A). Even though $\overline{ma}$ was greater than normal with superior displacement, $\overline{M}$ decreased because of a large decrease in $\overline{F}$. A 1 cm increase in neck length restored $\overline{M}$ to normal, but $\overline{F}$ remained less than normal. A 3 cm increase in neck length increased $\overline{M}$ to 37% greater than normal. The increase in $\overline{M}$ was caused by an increase in adduction moment arm from the superior displacement of the hip center and an increase in force from the increase in neck length.

Displacement of the hip center 2 cm superiorly decreased $\overline{M}$ of the flexors 22% if neck length was not increased. An increase in neck length restored $\overline{F}$ but had no effect on $\overline{ma}$, which remained less than normal. A 2 cm increase in neck length restored $\overline{M}$ to slightly less than normal, mainly by restoring $\overline{F}$. A 3 cm increase in neck length restored $\overline{M}$ to normal; however, passive muscle forces were approximately two times normal, with a 3 cm increase in neck length.

Displacement of the hip 2 cm superiorly decreased $\overline{M}$ of the extensors only slightly. The decrease in $\overline{M}$ was small because the decrease in $\overline{F}$ was offset by an increase in $\overline{ma}$. A 2 cm increase in neck length restored $\overline{M}$ to greater than normal without a substantial increase in passive muscle force. In contrast, a 3 cm increase in neck length greatly increased passive muscle force in the extensors.

Effects of Altered Neck-Stem Angle

The moment-generating capacity of each muscle group decreased as a result of a 2 cm superior displacement of the hip center if there was no change in the neck-stem angle (Fig. 4A). Thus, $\overline{M}$ was less than 0 for all muscle groups with a neck-stem angle of 128°. The moment-generating capacity of the hip flexors, adductors, and abductors was not restored by a change in the neck-stem angle alone. $\overline{M}$ was restored for the extensors by an increase of the neck-stem angle, which increased muscle length. However, this restoration was possible only because the decrease in $\overline{M}$ with superior displacement was small for the hip extensors. Neck-stem angle had almost no effect on the moment arm of the hip extensors and adductors but had a relatively large effect on the moment arm of the abductors and flexors (Fig. 4B). An increase in the neck-stem angle increased $\overline{F}$ for all four muscle groups (Fig. 4C).

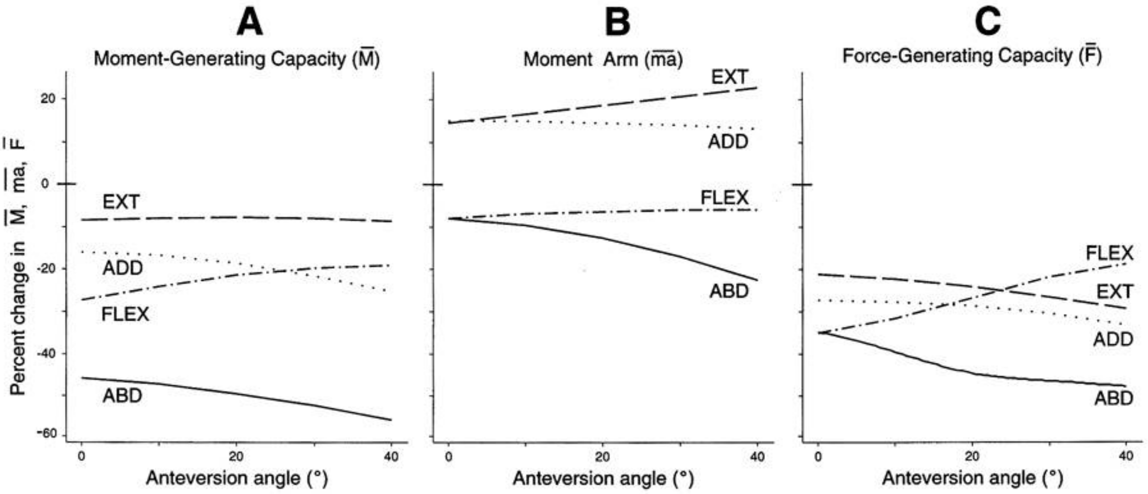

FIG. 5. The percentage of change in (**A**) moment-generating capacity ($\overline{M}$), (**B**) moment arm ($\overline{ma}$), and (**C**) force-generating capacity ($\overline{F}$) of each muscle group versus the anteversion angle. The hip center was displaced 2 cm superiorly, and the neck length (4.9 cm) and neck-stem angle (128°) were kept constant. $\overline{M}$, $\overline{ma}$, and $\overline{F}$ for abductors (ABD), adductors (ADD), flexors (FLEX), and extensors (EXT) are shown as a percentage of change from their values at the anatomical hip center and with the normal dimensions of the femur.

Abduction moment-generating capacity changed very little with changes in neck-stem angle. An increase of this angle from the normal model decreased the abduction moment arm but increased the abduction force. Conversely, a decrease in the neck-stem angle from the normal model increased the abduction moment arm but decreased the abduction force. The moment-generating capacity of the adductors increased very slightly with an increase in the neck-stem angle, due to an increase in muscle length and force. Flexion moment-generating capacity increased 10% with a 22° increase in neck-stem angle (when neck-stem angle was increased from 128 to 150°). This was caused by a slight increase in both moment arm and force.

Effects of Altered Anteversion Angle

The moment-generating capacity of each muscle group changed less than 10% over a 40° range in anteversion angle (Fig. 5A). Increased anteversion decreased the moment-generating capacity of the abductors, due to a decrease in both abduction moment arm (Fig. 5B) and force (Fig. 5C). Anteversion decreased adduction moment-generating capacity slightly, due to reduced muscle force. The moment-generating capacity of the flexors increased slightly, due to an increase in flexion force. The flexors were the only muscle group for which moment-generating capacity increased with anteversion. The moment-generating capacity of the extensors was nearly constant with anteversion, because the extension moment arm increased slightly and the extension force decreased by an equal proportion.

Interaction of Neck-Stem Angle and Increased Neck Length

After displacement of the hip center 2 cm superiorly, a 2 cm increase in neck length with neck-stem angles of 120-130° restored the moment-generating capacity of the abductors to within 5% of normal (Fig. 6A). However, when neck length was increased 2 cm with a neck-stem angle of 140°, $\overline{M}$ remained below normal. This occurred because the abduction moment arm was much smaller for a 140° neck-stem angle (Fig. 6B) and was not offset by the greater abduction force-generating capacity (Fig. 6C).

Displacement of the hip 2 cm superiorly decreased $\overline{M}$ for the adductors 18% with the normal femoral geometry. The decrease was slightly greater with a neck-stem angle of 120° and slightly less with a neck-stem angle of 140°, due to changes in muscle length (Fig. 6D). A 1 cm increase in neck length with a neck-stem angle of 120-140° restored the moment-generating capacity of the adductors to within 5% of normal. The adduction moment arm did not change much with increasing neck length, regardless of the neck-stem angle (Fig. 6E). However, a neck-stem angle of 140° increased adduction force-generating capacity more than a neck-stem angle of 120° (Fig. 6F).

The decrease in $\overline{M}$ of the flexors with superior displacement was less when the neck-stem angle

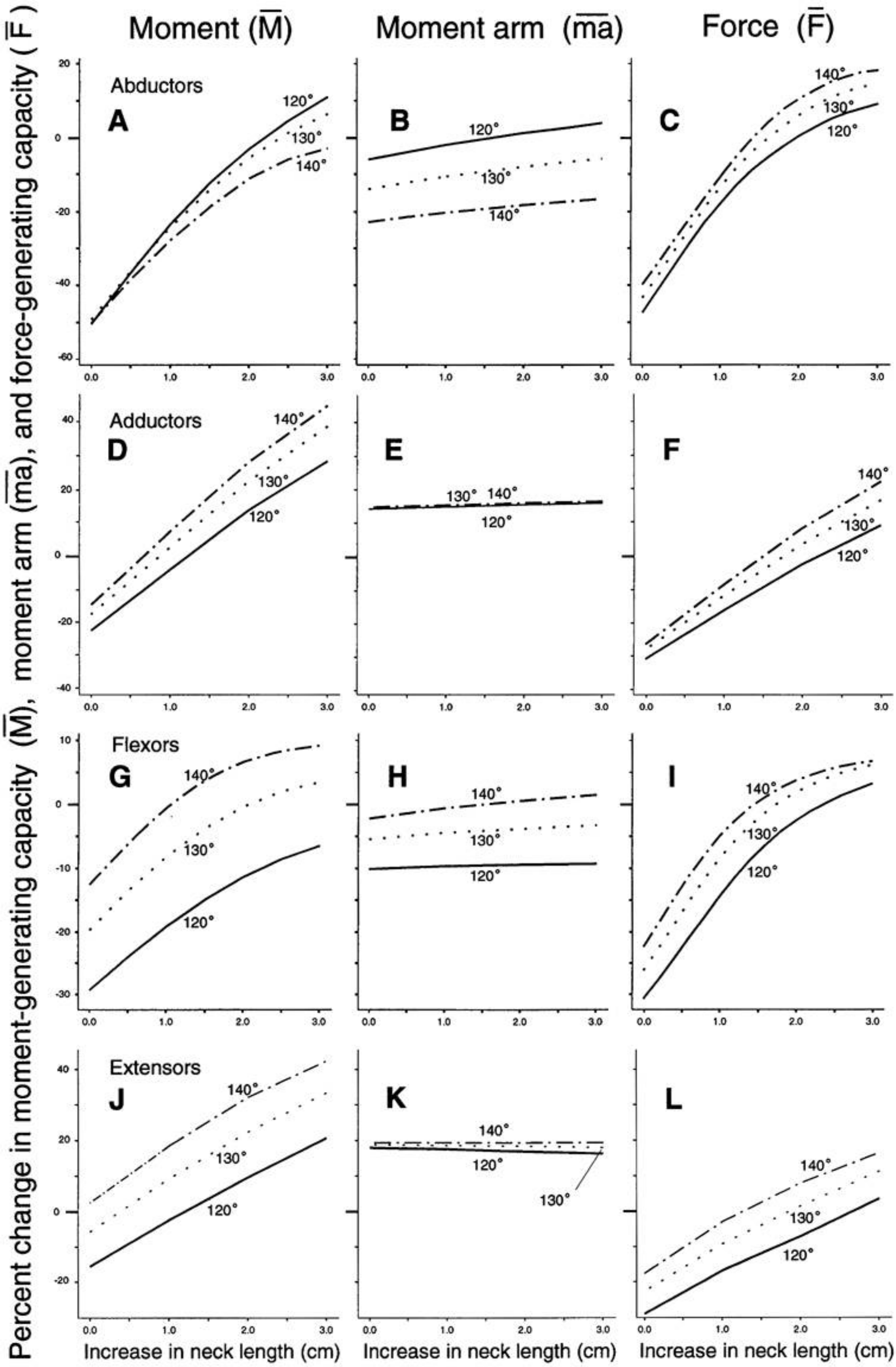

FIG. 6. The percentage of change in (**A**) moment-generating capacity ($\overline{M}$), (**B**) moment arm ($\overline{ma}$), and (**C**) force-generating capacity ($\overline{F}$) versus the increase in neck length for three distinct neck-stem angles: 120°, 130°, and 140°. The abductors are shown in **A-C**; the adductors, in **D-F**; the flexors, in **G-I**; and the extensors, in **J-L**. $\overline{M}$, $\overline{ma}$, and $\overline{F}$ are calculated as a percentage of change from their values at the anatomical hip center and with normal dimensions of the femur.

was greater than normal (such as 140°). Conversely, the decrease in $\overline{M}$ with superior displacement was greater when the neck-stem angle was less than normal (Fig. 6G). The decrease was greater with a neck-stem angle of 120° because of the larger decrease in moment arm (Fig. 6H) and force (Fig. 6I).

Displacement of the hip 2 cm superiorly decreased $\overline{M}$ of the extensors only 7% with normal femoral geometry (Fig. 6J). The decrease was small because the increase in the moment arm (Fig. 6K) from superior displacement was offset by a decrease in force (Fig. 6L).

Interaction of Anteversion Angle and Increased Neck Length

Variation of the anteversion angle between 10 and 30° did not have a strong influence on the effects of increasing neck length. The moment-generating capacity of each muscle group increased monotonically with neck length, regardless of the anteversion angle. The moment-generating capacity for the abductors and adductors was slightly greater with 10° of anteversion for all neck lengths. In contrast, the moment-generating capacity for the flexors and extensors was slightly greater with 30° of anteversion for all neck lengths. The maximum difference in $\overline{M}$, $\overline{F}$, and $\overline{ma}$ caused by a change in anteversion angle was less than 8%.

DISCUSSION

The purpose of this study was to determine how superior displacement of the hip center and changes in three prosthetic parameters (neck length, neck-stem angle, and anteversion angle) affect the moment-generating capacity of four muscle groups. Before the implications of our results are discussed, the effects of several modeling assumptions and limitations should be considered.

First, we studied the effects of superior hip displacement and prosthetic parameters on the moment-generating capacity of the muscles only. However, changes in musculoskeletal geometry may affect several other important factors. For example, increased neck length has been shown to increase bending moments in the prosthetic neck (23). Changes in prosthetic parameters also may influence the stress in cement, at the bone-cement interface, or at the bone-prosthesis interface. Clearly, these and other factors, which were not analyzed in this study, must be considered when designing prosthetic components and when choosing an implant for a particular application. Nonetheless, the effects of these parameters on the moment-generating capacity of the muscles, as analyzed here, also is an important factor.

Second, our simulations kept constant each muscle's peak isometric force, optimal fiber length, and tendon slack length. These parameters may change, however, through adaptation of the muscle-tendon complex, either before or after hip replacement. For example, the number of sarcomeres in a muscle fiber may decrease, changing the optimal fiber length, as a muscle-tendon complex adapts to altered conditions (39). Muscle atrophy may produce changes in physiologic cross-sectional area and decrease peak muscle force. Such changes in muscle force-generating properties certainly could have a major effect on the moment-generating capacity of muscles. By keeping the properties of each muscle-tendon complex constant, we isolated the effects of changing musculoskeletal geometry on the moment-generating capacity of the muscles.

Third, we analyzed only four muscle groups: abductors, adductors, flexors, and extensors. Our results indicate that a 40° change in anteversion angle has little effect on the moment-generating capacity of these muscle groups. However, changes in anteversion may have large effects on the hip rotators. We did not simulate the effects of changes in anteversion angle on the hip rotators because experimental data sufficient to test our models of these muscles are not yet available. Future studies must address this issue.

Fourth, the results presented here were obtained with use of a computer model representing an average-sized adult man. Musculoskeletal geometry and muscle force-generating capacities, however, vary widely among individuals. Because of these variations, we present the results in terms of percentage of changes, to emphasize trends rather than absolute values. Since values for neck length and hip displacement are given in absolute terms (such as a 2 cm increase in neck length), these values will require adjustment when individuals of different sizes are considered.

It is helpful to put the results reported here into context by comparing them with the results of previous studies. Johnston et al. reported that joint force increased with superolateral displacement of the hip center, whereas inferior, medial, and anterior positioning of the hip center minimized joint force (23). They advocated inferior-medial positioning of the hip center to reduce joint contact force and the moment-generating requirements of the muscles. Other investigators reported that inferomedial positioning of the hip center also is desirable in terms of maintenance or improvement of the moment-generating capacity of the muscles (14). With inferior positioning of the hip center, no changes in femoral component geometry are required to maintain the moment-generating capacities of the muscles.

However, in some instances, and particularly in revision surgery, a superiorly displaced hip center may be difficult to avoid. A number of clinical studies reporting the outcome of cemented acetabular components showed poorer results when the acetabular component was left in a superior position (7,21,24,32). Other studies, in which there was only superior placement of the hip center without lateral placement, showed satisfactory results, with no increased rate of loosening or alteration in hip score (34). With acetabular deficiency, the alternative to acceptance of a high hip socket is grafting with either autogenous or allogeneic bone grafts. Although there have been many reports of success with this technique, Jasty and Harris, in a longer term study, found a 43% incidence of late failure of fixation with this method (20). To avoid the use of large segmental allografts, they recommended bone-ingrowth cups for fixation and nonstructural grafting of defects. Russotti and Harris advocated high placement of the hip center as an alternative to structural segmental bone grafting in the acetabulum (34). D'Antonio recommended accepting a 2 cm superior placement of the hip center before resorting to grafting of the acetabulum (11).

Our results indicate that the moment-generating capacity of all the muscles decreased with superior displacement of the hip and that the largest decrease occurred in the hip abductors. It therefore is critically important to compensate for the changes in muscle lengths and moment arms that occur with superior displacement. After a 2 cm superior displacement of the hip center, the moment-generating capacity of the muscles was restored to near normal with a 2 cm increase in neck length; this suggests that a purely superiorly displaced hip center would not cause a major functional loss if muscle lengths were restored. In our simulations, a 3 cm increase in neck length increased passive muscle forces, which may limit the range of motion.

We found that abduction moment-generating capacity increased more with a varus neck (a neck-stem angle of 120°) than with a valgus neck (a neck-stem angle of 140°) because the varus neck produced a larger abduction moment arm. The moment-generating capacity of other muscle groups, by contrast, improved more with a neck-stem angle of 140°. A neck-stem angle of 130° provides a reasonable compromise.

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