Compensating for Changes in Muscle Length in Total Hip Arthroplasty

Effects on the Moment Generating Capacity of the Muscles

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Alterations in the location of the hip center may change the lengths and moment arms of the muscles, and thereby affect their capacity to generate force and moment about the hip. This study demonstrates some of the differences between compensating and not compensating for changes in muscle length that arise from displacement of the hip center. A computer model was developed to estimate the maximum isometric moment generating capacity of the hip muscles under two conditions. In the compensated condition, the hip center was displaced, but the muscles were restored to their original lengths and orientations by altering proximal femoral geometry. In the uncompensated condition, femoral geometry remained constant; thus, muscle lengths and orientations changed with displacement of the hip center. The computer simulations showed large differences between the two conditions. For example, a 2-cm superior displacement of the hip center decreased the moment generating capacity of the hip abductors 18% with compensation and 49% without compensation. Similarly, a 1-cm medial displacement of the hip center increased the moment generating capacity of the abductors 17% with compensation, but decreased it 4% without compensation. In contrast, a 1-cm inferior displacement decreased the moment generating capacity of flexors 6% with compensation, but increased it 12% without compensation. The results presented here demonstrate that compensating for changes in muscle length can be important in terms of preserving the moment generating capacity of the muscles when the hip center is displaced superiorly and medially, but not when the hip center is displaced in the inferior direction.

Total hip arthroplasties (THAs) are performed primarily to relieve pain and restore hip function. Although, after arthro-

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Supported by the Rehabilitation Research and Development Services, Department of Veterans Affairs and the Whitaker Foundation, and National Science Foundation grant BCS 9110741.

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Received: June 17, 1993.

Revised: August 23, 1993.

Accepted: October 14, 1993.

plasty, walking ability usually improves relative to preoperative conditions,[16] normal muscle strength is not always restored.[2,10] Surgical or pathologic changes that alter musculoskeletal geometry can affect the capacity of muscles to generate force and moment about the hip. A decrease in moment generating capacity of the muscles may result in a limp, or in difficulty in performing certain activities, such as rising from a seated position.

Placing the socket in the anatomic hip center and choosing an appropriate femoral component restores normal musculoskeletal relationships (*i.e.*, muscle lengths and moment arms). However, changes in the bony structure of the acetabulum may indicate alternate placement of the acetabular component (the center of hip rotation). If the hip center is displaced, muscle lengths will also change, unless the femoral component of the prosthesis is adjusted. For example, the femoral neck length may be increased to compensate for a decrease in muscle length that results from superior displacement of the hip. Even when muscle lengths are restored, however, the capacity of muscles to generate moment about the hip can be affected if displacement of the hip center changes muscle moment arms.

The isometric moment generating capacity of a muscle is the product of the muscle's maximum isometric force and moment arm, and is a measure of muscle strength.[3] Both muscle force and moment arm of hip muscles are influenced by position of the acetabular component and the size, shape, and orientation of the femoral component. The importance of the location of the hip center of rotation has been reported by many investigators.[1,5,8,14,25,29] Johnston *et al.*[14] used a biomechanical model of the lower extremity to study the effects of acetabular placement, femoral neck length, neck-shaft angle, and trochanteric advancement on the moment generating requirements of muscles (calculated using inverse dynamics), abductor muscle force required for walking, articular contact force, and prosthetic neck bending moment. They found that the location of the hip center had a greater effect on these quantities than did any other parameter.

Delp and Maloney[8] found that location of the hip center can have large effects on the moment generating capacity of the hip muscles, and reported that superior displacement substantially decreased the moment generating capacity of the hip abductors, adductors, and flexors, but that inferior displacement increased the moment generating capacity of these muscle groups. This study also identified the hip centers that maximize and minimize the moment generating capacity of each muscle group. However, Delp and Maloney did not analyze how the moment generating capacities of muscles are affected by compensating for changes in muscle length that arise from alterations of the hip center. The purpose of the current study, therefore, was to quantify the differences between compensating and not compensating for changes in muscle length in terms of the moment generating capacity of the muscles.

MATERIALS AND METHODS

Musculoskeletal Model

The three-dimensional biomechanical model of the lower extremity used in this study has been described in detail by Delp *et al.*[6–8] Therefore, only an overview is given here. Musculoskeletal geometry, joint kinematics, and muscle force-generating properties are taken into account in this model, making it possible to compute the isometric moment-generating capacity of each muscle for a range of body positions.

The model represents 43 muscle–tendon compartments. Some muscles (*e.g.*, gluteus medius) were separated into three muscle compartments (anterior, medial, and posterior), because a single origin and insertion do not accurately represent the muscle's action. Intermediate "via points" were also used to characterize muscles that wrap over bony prominences or other structures (*e.g.*, iliacus). The 25 muscle–tendon compartments crossing the hip were divided into four muscle groups: abductors, adductors, extensors,

TABLE 1. Muscles Crossing the Hip, Listed in Order of Decreasing Moment Generating Capacity Within Each Group

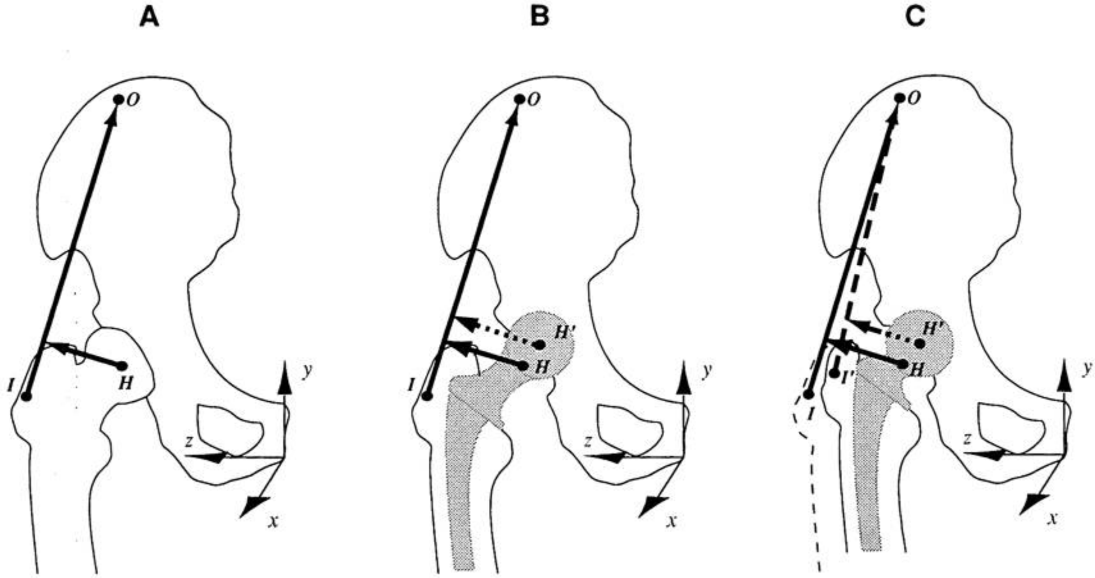
Abductors	Adductors	Flexors	Extensors
Gluteus medius (anterior, medial, and posterior compartments)	Adductor magnus (superior, intermediate, and inferior compartments)	Iliacus	Gluteus maximus (medial, intermediate, and lateral compartments)
Gluteus minimus (anterior, medial, and posterior compartments)	Adductor longus	Psoas	Semimembranosus
Tensor fasciae latae	Adductor brevis	Rectus femoris	Biceps femoris (long head)
Sartorius	Gracilis	Tensor fasciae latae	Semitendinosus
Gluteus maximus (lateral compartment)	Pectinius	Sartorius	Adductor magnus (superior, intermediate, and inferior compartments)
Piriformis	Semimembranosus	Gluteus medius (anterior compartment)	Gluteus medius (posterior compartment)
		Gluteus minimus (anterior compartment)	

and flexors (Table 1). The length and moment arm of each muscle was computed from the coordinates of origins, insertions, and via points, and the relative orientation of the body segments (Fig. 1A). Because the lengths and moment arms of biarticular muscles (*e.g.*, rectus femoris and semitendinosus) are affected by knee angle, it was necessary to characterize knee kinematics as well.

The isometric force-generating property of each muscle–tendon compartment was estimated by scaling a generic, Hill-type model of muscle and tendon.[30] The generic model is based on dimensionless force-length curves of active and passive muscle. These curves are scaled by four parameters that are unique to each muscle–tendon compartment: (1) peak isometric muscle force (estimated from measurements of physiologic cross-sectional area), (2) optimal muscle-fiber length (the length at which active muscle force peaks and passive tissue begins to develop force), (3) pennation angle (the angle between muscle fibers and tendon), and (4) tendon slack length (the length at which tendon begins to develop force). To estimate the maximum isometric moment generating potential of the muscles, it was assumed that muscles were fully activated and under isometric conditions. Delp and Maloney[8] provided comparisons of the maximum isometric moments computed with the model and moments measured in human subjects.

Simulation of Two Conditions

In actual surgical procedures, changes in the hip center and muscle lengths are determined by the placement of the acetabular cup and femoral component geometry (*i.e.*, neck length, neck-stem angle, and anteversion angle). Using the computer model, two conditions were analyzed for each position of the hip center. In the first condition, termed the compensated condition, muscle lengths were kept constant as the location of the hip center was changed (Fig. 1B). This simulates the condition in which femoral component geometry is chosen so that all muscle insertions remain in exactly the same location, relative to the pelvis, as with the anatomic hip center. This was accomplished in the model by changing the coordinates of the muscle insertions in the femoral, tibial, and patellar reference frames to simulate changes in the geometry of the proximal femur. Thus, with the hip in 0° flexion, abduction, and rotation (*i.e.*, the anatomic position), muscle lengths were not changed; only moment arms were altered. In certain locations of the hip center, however, the changes in femoral component geometry necessary for compensation may create extreme varus or valgus orientation of the fe-



Figs. 1A–1C. Simplified representation of one muscle crossing the hip. The length and moment arm of each of 25 muscles were calculated from three-dimensional coordinates of the origin (O), insertion (I), and hip center (H). Intermediate via points (not shown) were required to accurately represent several of the muscle paths. (A) Anatomic position of the hip center. (B) Compensating condition in which increased neck length restores muscle lengths after superior and medial placement of the hip center, although muscle moment arms are altered. Postsurgery geometry is indicated with the dashed line. H′ is displaced hip center. (C) Noncompensating condition in which femoral geometry remains constant, such that both moment arms and muscle lengths change. I′ represents the muscle insertion in the postsurgery condition.

mur. In the second condition, the uncompensated condition, femoral geometry remained constant, which resulted in changes in both muscle lengths and moment arms after displacement of the hip center (Fig. 1C). The computer model was used to study hip center locations within 1 cm anterior, posterior, and medial, and 2 cm superior, inferior, and lateral to the anatomic hip center (Fig. 2).

Evaluation

To compare the two conditions, the following quantities were calculated over the range of hip center positions: the moment generating capacity, the force-generating capacity, and the moment arm of each muscle group. Herein, the moment generating capacity of a muscle group is defined as the sum of the moments generated by all the muscles in the group when maximally activated. Similarly, the force-generating capacity of a muscle group is defined as the sum of the forces generated by all the muscles in the group when maximally activated. The moment arm of a muscle group was computed as a weighted average of moment arms of the muscles in the group, with physiologic cross-sectional area as the weighting factor.[10]

For each muscle group, the moment generating capacity was plotted over a range of hip motion (Fig. 3). From this moment-versus-joint-angle curve, the average moment was computed over a range of joint angles used during walking, rising from a chair, and stair climbing. The ranges used in this study were 10° extension to 60° flexion for flexors and extensors, and 10° adduction to 20° abduction for abductors and adductors. In all cases, the knee was maintained in full extension. For instance, the average moment generated over the shaded region in Figure 3 was used as a measure of the average moment generating capacity of the abductors in a functional range of motion. The average values for

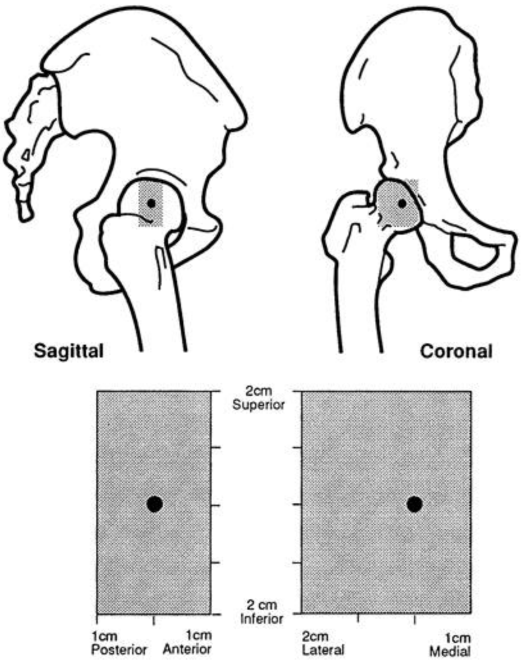


Fig. 2. Range of positions of the hip center that were investigated.

each condition were compared with the moment generating capacity calculated with the hip center in its anatomic location.

RESULTS

Effects of Superior-Inferior Displacement

Moving the hip center in the superior or inferior direction affects all four muscle groups substantially. In the compensated condition, abductor muscle moment generating capacity changes oppositely to the other groups (Fig. 4A), because the lines of action of the abductor muscles lie superior and lateral to the hip center, but the lines of action of other muscle groups generally pass inferior to the hip center. Thus, as the hip center is moved 2 cm superiorly, abductor muscle moment generating capacity decreases by 18%, but the moment generating capacities of the adductors, flexors, and extensors increase 18%, 11%, and 20%, respectively.

When the decrease in muscle length is not compensated, superior displacement of the hip center decreases the moment generating capacity of all muscle groups by reducing muscle force (Fig. 4B). For example, when the hip center is displaced 2 cm superiorly, abductor force-generating capacity decreases 44% and average moment arm decreases 12%, leading to a 49% loss of moment generating capability. The moment generating capacities of the other muscle groups also decrease between 5% and 25% with superior displacement. Because the muscle force-length curve is nonlinear, the changes in moment generating capacity are generally nonlinear in the noncompensating condition.

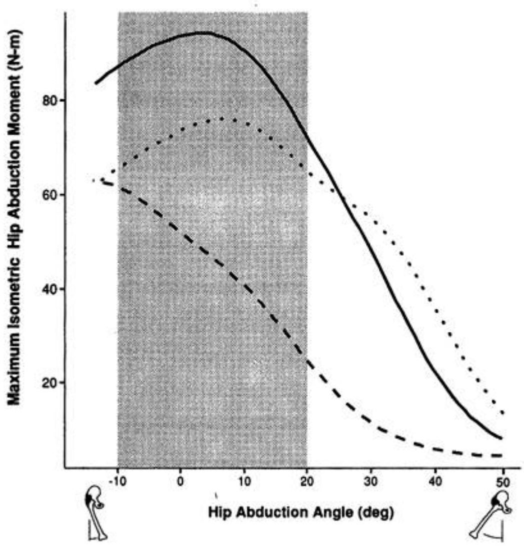
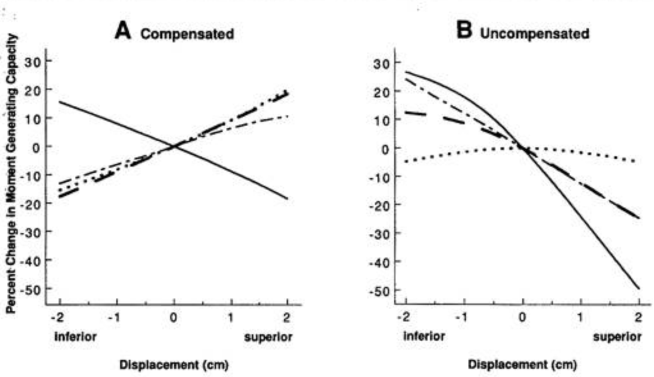


Fig. 3. Maximum isometric hip abduction moment-versus hip abduction angle. The solid line indicates the normal abduction moment (*i.e.*, with hip center in anatomic position). The dotted line shows the abduction moment with the hip center displaced 2 cm superiorly with muscle length compensated. The dash line represents abduction moment with the hip center displaced 2 cm superiorly without compensation. The shaded area indicates the range of motion over which the abduction moment was averaged (see text).



Figs. 4A–4B. Percent change in the moment generating capacity of four muscle groups with displacement of the hip center in superior and inferior directions. The solid line represents abductor moment; the dashed line, adductors; the dotted line, extensors; and the dashed-dot line, flexors. (A) Compensating condition. (B) Noncompensating condition.

When moving the hip center inferiorly with compensation, the moment generating capacity of the abductor muscles increases 16%, but the moment generating capacities of other muscle groups decrease between 13% and 18% (Fig. 4A). These changes arise from changes in the moment arm only. When moving the hip center 2 cm inferiorly without compensation, the moment generating capacity of the abductors, adductors, and flexors increase 27%, 12%, and 24%, respectively, and extensor moment generating capacity decreases 5% (Fig. 4B).

Effects of Medial-Lateral Displacement

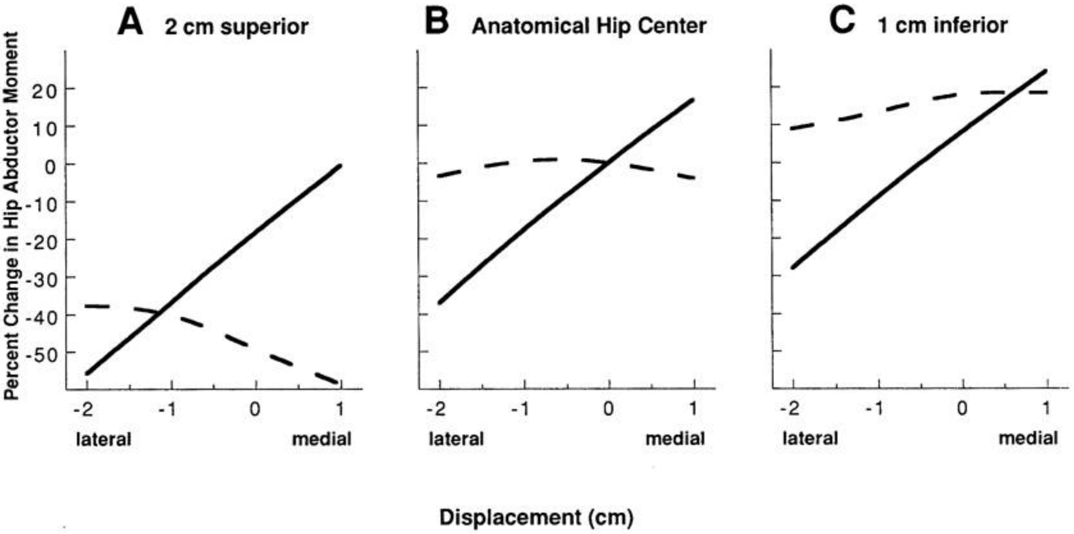
Moving the hip center medially or laterally has a substantial effect on the abductors and adductors only. With compensation, a 1-cm medial displacement increases the moment generating capacity of abductors 17% and decreases the capacity of adductors 18%. Without compensation, however, the moment generating capacity of abductors decreases 4%, and the moment generating capacity of the adductors decreases 25% with medial displacement.

A lateral displacement of 2 cm decreases abductor moment generating capacity 37% with compensation, but only 3% without compensation. Because abductor force-generating capacity increases (13%), but moment arm decreases (14%), the uncompensated condition produces only a small change in the moment generating capacity. The change is larger with compensation, because the authors' definition of compensation would place the femoral neck in a valgus orientation with a lateral hip center. Adductor moment generating capacity increases substantially with lateral displacement in both conditions: 38% in the compensating condition, and 51% in the noncompensating condition.

Because the lines of action of flexor and extensor muscles are perpendicular to the medial-lateral axis, their moment arms do not change with medial and lateral displacement of the hip center, and force-generating capacities change very little. Thus, all changes in moment generating capacities of flexors and extensors with medial or lateral displacement are less than 3% with and without compensation.

Effects of Combined Superior-Inferior and Medial-Lateral Displacements

The changes in abductor muscle moment generating capacity from displacing the hip center medially or laterally depend on the location of the hip center along the superior-inferior axis (Fig. 5). At the anatomic position on the superior-inferior axis, medial (lateral) displacement increases (decreases) the moment generating capacity of the hip abductors when the change in muscle length is compensated (Fig. 5B, solid line). In con-



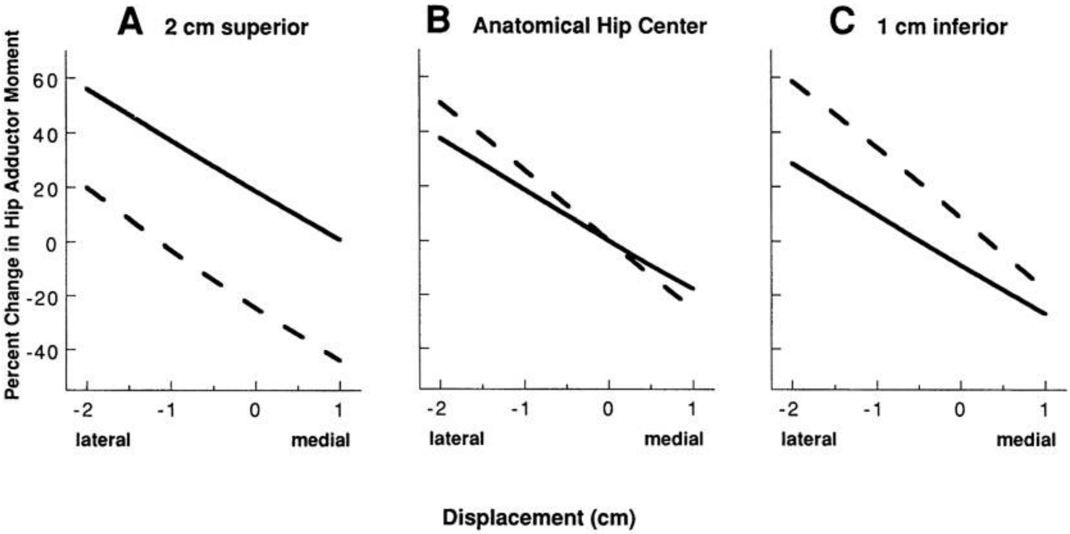
Figs. 5A–5C. Changes in the moment generating capacity of the abductors as the hip center is displaced along a medial-lateral axis at three distinct superior-inferior positions. The solid line represents the compensating condition, and the dashed line represents no compensation. (A) Hip center displaced 2 cm superiorly. (B) Hip center in the anatomic superior-inferior position. (C) Hip center displaced 1 cm inferiorly.

trast, the moment generating capacity of the abductors changes very little with medial-lateral displacement without compensation (Fig. 5B; solid and dashed lines). With a 2-cm superior displacement, there is a substantial decrease in abductor moment generating capacity when combined with lateral displacement in both conditions (Fig. 5A). However with superior and medial displacement, the loss in moment generating capacity is large (approximately 60%) in the uncompensated condition, whereas abduction strength is restored to normal with compensation. When the hip center is moved 1 cm inferiorly, the uncompensated condition increases the moment generating capacity of the abductors at all medial-lateral positions (Fig. 5C).

For the adductors, compensation produces a slightly smaller decrease in moment generating capacity with pure medial displacement (Fig. 6B). Both conditions provide increased moment generating capacity with pure lateral displacement, although the increase is larger without compensation. The compensated condition results in greater than normal adductor moment generating capacity for both superior-medial and superior-lateral displacement (Fig. 6A). The uncompensated condition also increases adduction moment generating capacity with superior-lateral displacement, but decreases moment generating capacity with superior-medial displacement. The uncompensated condition provides a greater increase in adductor moment generating capacity with inferior and lateral displacements, and a smaller decrease for inferior and medial positions (Fig. 6C).

Effects of Anteroposterior Displacement

Moving the hip center anteriorly increases extensor and decreases flexor moment generating capacity. Moving the hip center posteriorly has the opposite effect. Because anteroposterior displacement affects moment generating capacity of the hip flexors and extensors primarily by altering muscle moment arms, the differences between compensating and not compensating are small. A 1-cm anterior displacement from the ana-



Figs. 6A–6C. Changes in the moment generating capacity of the adductors as the hip center is displaced along a medial-lateral axis at three distinct superior-inferior positions. The solid line represents the compensating condition, and the dashed line represents no compensation. (A) Hip center displaced 2 cm superiorly. (B) Hip center in the anatomic position in the superior-inferior direction. (C) Hip center displaced 1 cm inferiorly.

tomic hip center decreases the flexor moment generating capacity 20% (17%) with (without) compensation; the increase in extensor moment generating capacity is 18% (16%) with (without) compensation. A 1-cm posterior displacement increases the flexor moment generating capacity slightly more with compensation (19%) than without compensation (16%). The decrease in extensor moment with posterior displacement is approximately the same (17%) for both conditions. Moving the hip center in the anteroposterior direction has a negligible effect on the abductors and adductors.

Effects of Combined Superior-Inferior and Anteroposterior Displacements

Combinations of anterior or posterior displacement along with superior or inferior location of the hip center affect the moment generating capacities of flexors and extensors. For example, with 1-cm anterior displacement and 2-cm superior displacement, the moment generating capacity of the flexors decreases by 12% with compensation and 40% without compensation, and the moment generating capacity of extensors increases by 40% (11%) with (without) compensation. For a 1-cm posterior and 2-cm superior displacement, however, the moment generating capacity of flexors increases 31% with compensation and decreases 10% without compensation; the moment generating capacity of extensors increases 2% with compensation and decreases 21% without compensation. In comparison, the changes in flexor moment generating capacity with only 2-cm superior displacement are a 10% increase with compensation and a 24% decrease without compensation; the corresponding changes in extensor moment generating capacity are a 20% increase with compensation and a 5% decrease without compensation. For all combinations of displacements involving anterior or posterior displacements, superior position of the hip center indicates larger increases or smaller decreases in moment generating capacity with compensation; in-

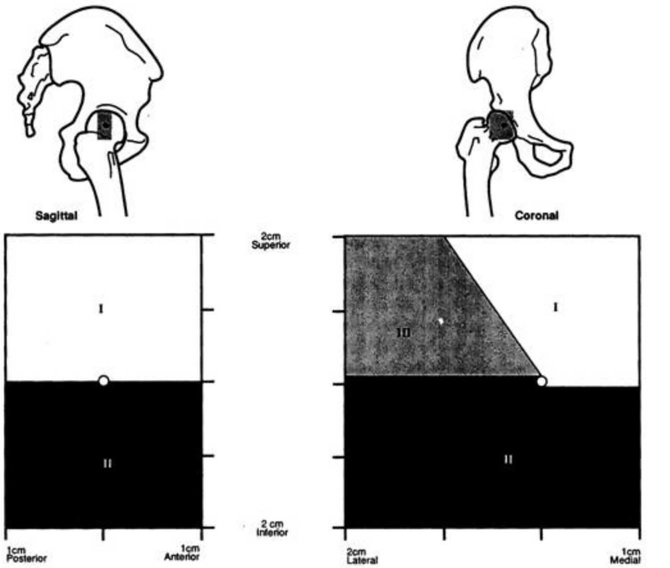


Fig. 7. Condition that provides a greater moment generating capacity of the muscles for the specific definition of compensation used here (*i.e.*, the muscle insertions restored to exactly the same location, relative to the pelvis, as with the anatomic hip center). Region I (white) indicates the positions of the hip center for which the compensating condition provides a greater increase or smaller decrease in moment generating capacity than the uncompensated condition for all muscle groups. Region II (black) indicates the hip center locations for which no compensation provides a greater increase or smaller decrease in moment generating capacity than the compensated condition. Region III (grey) indicates hip center locations for which compensation provides a smaller decrease in abductor moment generating capacity but larger decreases or smaller increases in the moment generating capacity of the other muscle groups. The large dot at the origin is the anatomic hip center.

ferior placement, however, indicates larger increases or smaller decreases in moment generating capacity without compensation.

Comparison of Compensated and Uncompensated Conditions

For most locations of the hip center, one of the two conditions (compensated or uncompensated) provides a greater increase, or a smaller decrease, in moment generating capacity of all four muscle groups (Fig. 7, Regions I and II). However, in some hip center positions, the condition that produces greater moment generating capacity for the abductors results in a smaller moment generating capacity for other groups (Region III).

In general, when the hip center is moved to a position that shortens the muscles, the compensated condition produces greater increases or smaller decreases in the moment generating capacities than the uncompensated condition. For hip center positions that lengthen the muscles, the uncompensated condition produces greater increases or smaller decreases in the moment generating capacities, and retains the anatomic varus/valgus orientation of the femur. Anteroposterior displacements affect the percent changes in moment generating capacity, but not the condition that provides a greater increase or smaller decrease in moment generating capacity.

When the hip center is moved purely superiorly, compensation increases the moment generating capacity of extensors, flexors, and adductors, and provides a smaller decrease in the moment generating capacity of the abductors. Similarly, for pure medial displacements, compensation increases the moment generating capacity of abductors and provides a smaller decrease in moment generating capacity of adductors; however, flexor and extensor moment generating capacities remain constant. Therefore, in terms of preserving muscle strength, it is advantageous to compensate when the hip center is displaced superiorly, or medially, or both. For pure lateral displacements, the uncompensated condition provides a smaller decrease in the moment generating capacity of abductors and a larger increase for the adductors; flexors and extensors are minimally affected. For pure inferior displacements, moment generating capacities of all muscle groups increase or remain nearly constant without compensation. With inferomedial displacements, no compensation produces a greater increase or smaller decrease than compensation for the adductors, extensors, and flexors; for the abductors, both conditions provide an increase in moment generating capacity, although the increase is larger with compensation. These results demonstrate that, in terms of preserving muscle moment generating capacity, it is better not to compensate with inferior displacement, but it is better to compensate with superior and medial combinations of displacements.

Superior and lateral positions of the hip center produce changes in muscle moment generating capacities that do not always clearly indicate whether the compensated or uncompensated condition is more effective in restoring or improving muscle moment generating capacity. With the hip center moved 2 cm superiorly, lateral displacements of up to 1 cm produce increases in adductor, extensor, and flexor moment generating capacities and smaller decreases in abductor moment generating capacities. However, when the hip center is placed 2 cm superiorly and more than 1 cm laterally, no compensation provides a smaller decrease in abductor moment generating capacity.

DISCUSSION

This study showed that compensating for changes in muscle length that arise from alterations of the hip center can have a large effect on the isometric moment generating capacity of the muscles. For some hip center displacements, the moment generating capacity of a muscle group may decrease without compensation and increase with compensation. For example, with superior displacement the moment generating capacity of the flexors increases with compensation, but decreases without compensation. In other cases, compensation can restore normal moment generating capacity to a muscle group when displacement of the hip center without compensation may have caused a large decrease. For instance, moving the hip center 2 cm superiorly and 1 cm medially produces a 60% decrease in abductor moment generating capacity, while compensation restores the moment generating capacity to normal.

It is important to examine several simplifying assumptions that were made in this investigation. First, this study used a very specific definition of the compensated condition. It was assumed that the muscle insertions were restored to exactly the same location, relative to the pelvis, as with the anatomic hip center. For example, when the hip center was displaced superiorly and laterally, muscle insertions had to be displaced medially and inferiorly in the femoral reference frame to return them to their original locations relative to the pelvis. For lateral displacements of the hip center, this definition may result in a large valgus orientation of the femoral neck. For inferior displacements of the hip center, a varus neck may result. It should be noted that changes other than the two conditions studied here (compensated and uncompensated) may be more effective in terms of restoring the moment generating capacity of the muscles. Further study is needed to determine how to best restore muscle strength (*i.e.*, to determine the combinations of neck length, neck-stem angle, and anteversion angle to maximize moment generating capacity).

Second, the authors studied the effects of changes in geometry on the maximum isometric moment generating potential of the muscles. Thus, the moments reported here do not represent the moments generated during movement, when muscles are generally neither isometric nor maximally activated. Rather, the maximum isometric moments represent measures of muscle strength. Because the moment generating capacities calculated with the model correlate well with maximum isometric moments measured by several other investigators,[3,13,15,18–20,23,26] the moments reported here are reasonable estimates of muscle strength.

Third, the results presented here were obtained using a computer model that represents an adult male who is approximately 1.8 m tall. An elderly woman, however, will probably have different body proportions and relationships between strength and body size. Because of these variations, the displacements of the hip center and changes in moment generating capacities presented here should not be accepted as absolute values, but should be scaled to an individual's size. The percent changes in moment generating capacity, nevertheless, indicate the relative effects of compensation or no compensation. For example, the results show that, for superior and medial displacements of any magnitude, abductor moment generating capacity decreases substantially without compensation, but can be restored with compensation.

Fourth, the model does not account for muscle–tendon adaptation, which may accompany musculoskeletal disease and subsequent surgical reconstruction. Changing a muscle's resting length by altering musculoskeletal geometry can affect the muscle force-length relation, similar to the effects of immobilization discussed by Williams and Goldspink.[27] Thus, muscle fiber length may decrease if muscle length is reduced. Additionally, increases or decreases in muscle cross-sectional area may result from rehabilitation or disuse. The current simulations, however, kept constant muscle fiber length and cross-sectional area and analyzed the effects of changing musculoskeletal geometry exclusively.

Finally, this study analyzed only the effects of changing musculoskeletal geometry on the moment generating capacity of the muscles. However, changes in the hip center also change the moment arm of the body centroid about the hip, which affects the muscle forces needed to maintain equilibrium. Alterations in geometry and moment generating capacity can also influence other important factors, such as joint reaction force, stresses in prosthetic components and cement, loosening rates, and leg length, which have been examined in previous studies.[4,10,14,22,24,29]

Comparison With Previous Studies

The results obtained in this study are in agreement with several other studies. Johnston *et al.*[14] used gait analysis and musculoskeletal modelling to estimate the abductor force required for various activities. They assumed that the relative positions of the pelvis, femur, leg, and foot remained constant as the location of the hip center changed, which corresponds to the compensating condition in the current study. Using inverse dynamics, Johnston *et al.* determined that abductor muscle force necessary for walking was reduced by moving the hip center medially, inferiorly, and anteriorly. This result is supported by the current study, because abductor moment arms were found to increase when the hip center was moved medially and inferiorly, meaning that lower muscle force would be required for walking.

Delp and Maloney[8] used the same model of the lower extremity as described here to examine how the force- and moment generating capacities of muscles are affected by changes in the position of the hip center. In their study, displacement of the hip center corresponded to the uncompensated condition in the current study. The changes in the moment generating capacity reported by Delp and Maloney are, therefore, in accord with the uncompensated results presented here.

The results of the current study are also corroborated by retrospective clinical studies. Gore *et al.*[10] correlated radiographic measurements with hip muscle strength and found that, in general, a more superior position of the prosthetic head was associated with decreased abductor and adductor strength and shortening of the limb. However, when superior placement of the femoral head was compensated by an increase in femoral neck length, there was little difference in muscle strength between affected and unaffected limbs. Russotti and Harris[22] concur that superior placement of the acetabular component alone is acceptable when proper tension is restored to muscles.

Clinical Considerations

Although locations of the hip center that maximize the moment generating capacities of the muscles may be known, they are not always practical positions for the acetabular component. The acetabular component is generally not placed too far medially because of the unstable structure of the medial wall of the acetabulum.[14] Inferior placement may be difficult to achieve, and anteroposterior displacement is usually negligible. Thus, the positions of the hip center that maximize moment generating capabilities[8] and minimize joint force[14] (inferior, medial, and anterior) may be impractical in some clinical situations.

Pathologic conditions also influence the possible locations of the hip center. In *protrusio acetabuli* of rheumatoid arthritis, the femoral head may move up to 1.5 cm into the pelvis, in a medial and superior direction.[21,24] With osteoarthritic conditions, the femoral head may move laterally, superiorly, and posteriorly.[14] Congenital acetabular dysplasia can result in a high, laterally subluxated or dislocated femoral head.[9,11,12,17,28] In revision arthroplasty, the acetabular component is usually moved laterally because of medial bone loss, or may be placed superiorly to obtain stable fixation.[4]

Even when pathology does not dictate hip center location, surgical convention may influence technique. In the early history of THA, the acetabular component was often medialized.[29] Excessive reaming can cause the hip center to be placed superiorly, as well. With a Charnley prosthesis, the small inner diameter of the acetabular component leads to a more superior and medial position of the hip center.

Because the hip center can be displaced for a variety of reasons, it is important to understand when to compensate for alterations that result from displacement. The results of the current study show that there can be large differences in muscle moment generating capacities after THA, depending on whether changes in muscle length are compensated by altering femoral geometry. This study presents the condition (compensating or noncompensating) that best preserves the moment generating capacities of muscles crossing the hip when acetabular placement is dictated by pathologic conditions or surgical technique. Given the specific definition of compensation used here, the authors' results indicate that, in general, when the hip center is displaced superiorly and medially, compensation is indicated. When the hip center is located inferiorly, within normal anatomic ranges, muscles have greater moment generating capacity when femoral geometry is unaltered.

Acknowledgments

The authors thank Peter Loan and Abraham Komattu for help with computer programming and data analysis.

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