How Superior Placement of the Joint Center in Hip Arthroplasty Affects the Abductor Muscles

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This study examines the effects of a superiorly placed hip center on the strength of the abductor muscles. A 3-dimensional computer model of the hip and the surrounding musculature was used to calculate the moment arms, forces, and moments generated when the hip abductor muscles are maximally activated. A representation of a hip prosthesis was implanted into the computer model with altered hip center positions and a range of prosthetic neck lengths. Analysis of these simulated hip replacements demonstrated that superolateral placement of the hip center (2 cm superior and 2 cm lateral) decreases the moment arms of the hip abductor muscles by an average of 28%. This decrease in moment arm cannot be restored by increasing prosthetic neck length, resulting in an unrecoverable loss of abduction strength with superolateral displacement. By contrast, a 2-cm superior displacement of the hip center changes the moment arms and force generating capacities of the abductors by less than 10% if prosthetic neck length is increased to compensate for decreased muscle length. The results of this study suggest that superior positioning of the hip center, without lateral placement, does not have major, adverse effects on abduction moment arms or force generating capacities when the neck length is appropriately increased.

It generally is considered desirable to place the acetabular component as close to the anatomic hip center as possible in total hip arthroplasty.[8,19,28] However, there are a number of situations in which loss of bone stock may indicate superior placement of the hip center to provide secure fixation of the acetabular component. In difficult primary hips, often with dysplasia, and in revision arthroplasty, bone grafting may be used to bring the acetabular component down to an anatomic position.[1,5,7,15,31,36] Unfortunately, long term followup studies have shown that this technique may be associated with a collapse of the graft.[18,25] To avoid the problems of bone grafting and to support the prosthesis

with native bone stock, some elevation of the hip center has been advocated.[8,29,30]

Clinical reports provide conflicting evidence regarding superior positioning of the hip center. A number of clinical studies have reported acceptable results with superior placement of the hip center when lateral displacement of the hip was avoided.[29,30] However, other studies have reported poorer results when the acetabular component was left in a superior position.[4,13,14,19,22,23,28] The 2 major concerns with the elevated hip center are higher incidence of component loosening and decreased strength of the abductors. This article addresses the second concern: namely, the influence of hip center elevation on abduction strength.

The moment generating capacity of a muscle is the product of its maximum force and moment arm and is a measure of muscle strength. Maintaining or improving muscle strength is important to the outcome of hip arthroplasty because patients must be able to generate the moments required to perform a variety of activities postoperatively. For instance, if the hip abductors are weak and unable to generate the moments needed to counteract the moment from body weight during single leg stance, a limp is likely to result.[3,16,17,27]

Several studies have evaluated the effects of hip center elevation on abduction moment arms and muscle lengths using measurements from planar radiographs.[13,22,30] However, there are a number of limitations with this approach. First, because planar radiographs do not characterize 3-dimensional changes in geometry, surgical alterations cannot be measured accurately. Second, because preoperative and postoperative radiographs are taken under different conditions, such as altered hip flexion and rotation angles, errors can be introduced into the measurements. Third, measurements from radiographs do not allow determination of the potential changes in muscle force generating capacities that result from alterations in the hip center. The relationships between musculoskeletal geometry and maximum muscle forces are complex, nonlinear, and difficult to evaluate without a quantitative, 3-dimensional representation of the musculoskeletal geometry and muscle force generating characteristics.

Thus, a 3-dimensional biomechanical model was developed that can be used to evaluate the changes in muscle moment arms and force generating capacities that result from alterations in the hip center and changes in femoral component geometry.[9,11] Based on these previous investigations, it was hypothesized that moment generating capacity of the abductors could be maintained after superior displacement of the hip if lateral placement was avoided and the prosthetic neck length was increased to compensate for elevated hip center. To test this hypothesis, this study examined differences between superolateral, superior, and superomedial placement of the hip center along with the effects of increased prosthetic neck length. The effects of these alterations were studied in terms of 5 factors: (1) the moment arms of the abductors; (2) moment generating capacity of the abductors; (3) the active and passive components of the force generating capacity of the abductors; (4) the abductor moments required during single leg stance relative to the moment generating capacity of the abductors; and (5) the ratio of the body weight moment arm to the abductor moment arm, which is directly related to the hip joint reaction force.

MATERIALS AND METHODS

Three hip center positions were analyzed: superolateral displacement (2 cm superior and 2 cm lateral from the anatomic hip center), superior displacement (2 cm superior), and superomedial displacement (2 cm superior and 2 cm medial). These 3 hip positions represent extremes of hip center positions that are observed clinically (Fig 1).

A 3-dimensional biomechanical model of the lower extremity was used to evaluate the effects of hip center position and prosthetic neck length on the hip abductors.[10,11] The model represents an adult male with a height of approximately 1.8 m and a mass of 75 kg; the femur has a neck length of
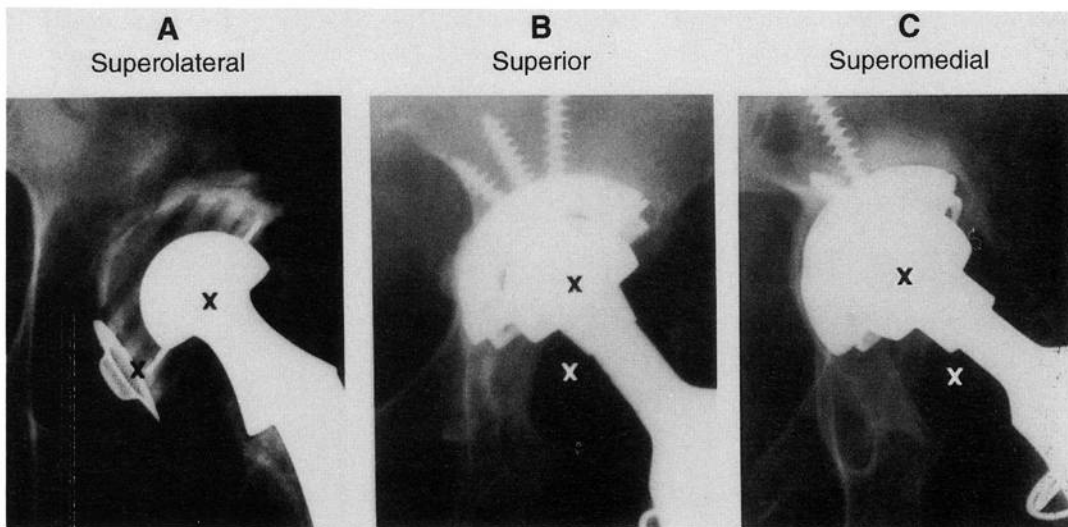
Fig 1A–C. Radiographs showing the hip center located (A) superolaterally, (B) superiorly, and (C) superomedially. The estimated anatomic hip center and the hip center after revision surgery are marked with an x.

4.8 cm, a neck stem angle of 128°, and an anteversion angle of 19°. The computer model of the abductor muscles consists of 10 individual muscle tendon complexes: gluteus medius (anterior, medial, and posterior compartments), gluteus minimus (anterior, medial, and posterior compartments), and gluteus maximus (lateral compartment), tensor fasciae latae, piriformis, and sartorius. Each muscle is described as a line segment, or a series of line segments in cases in which muscle wraps over bone or underlying muscles. The hip can be rotated through a range of hip abduction angles so that the moment arm and origin to insertion length of each muscle tendon complex can be determined for a range of abduction angle.

The maximum isometric force generated by each muscle tendon complex was computed as a function of its physiologic cross sectional area, muscle fiber length, and tendon length.[11,12,33] The maximum isometric moment generated by each muscle tendon complex was computed as the product of the muscle's maximum isometric force and moment arm. The maximum isometric moments produced by the 10 abductor muscles were summed to determine the maximum isometric abduction moment generated by the abductor group. Abduction moments calculated with the computer model corresponded closely with isometric strength measurements.[11,26]

The moment generating capacity of the abductors was characterized by averaging the maximum moment generated from 10° adduction to 20° abduction. The moment arm of the abductor group was computed as a weighted average of the moment arms of the individual muscles, with physiologic cross sectional area as the weighting factor.[11] The abductor moment arm was plotted against the hip abduction angle and averaged from 10° adduction to 20° abduction. The force generated by the abductor group when the muscles were maximally activated was calculated by summing the maximum isometric force developed by each of the individual abductor muscles. The force generating capacity of the muscle group was characterized as the average force generated by the muscle group from 10° adduction to 20° abduction. The force contributed by both active and passive components was determined, where passive force was developed when muscle fibers were stretched beyond their optimal length.[38]

The moment generating capacity, the moment arm, and the force generating capacity of the abductor muscle group were computed with the hip center in the anatomic location and with an unaltered neck length. The hip center was displaced, and the percent changes in the moment generating capacity, the moment arm, and the force generating capacity were determined. The neck

length was increased from 0 to 3 cm with hip center in the superolateral, superior, and superomedial positions, and the percent changes in the moment generating capacity, the moment arm, and the force generating capacity were found in each case.

This study also analyzed how hip center location affects the moment generating requirement of the abductor muscles, which was defined as the moment that the abductors must generate to balance the torso during single leg stance. The moment required was calculated using a frontal plane model[21,32] and assuming that the body weight force vector acts through the midline of the body. A body mass of 75 kg was used; approximately 5/6 of this mass generates a moment about the hip in single leg stance (the other 1/6 is the mass of the stance limb). In the computer model, the distance between the hip center and midline of the body is 8.3 cm; this is termed the moment arm of the body weight. With the normal hip center, the abduction moment required to balance the moment from body weight is 51 Nm (51 Nm = 75 kg × 5/6 × 9.8 m/second^2 × 0.083 m). This is within the range of abductor moments others have reported during single leg stance.[35]

The difference between the moment generating capacity and the moment generating requirement was termed the excess moment capacity available for balancing the torso. The excess moment was computed for the normal hip center and each of the 3 displaced hip center positions. When the hip was displaced, the prosthetic neck length was increased to restore the abductor muscles to their lengths with the hip at the anatomic hip center. For instance, with the hip displaced 2 cm superiorly and 2 cm laterally, the prosthetic neck length was increased 7 mm to restore the abductor muscle lengths. With the hip displaced 2 cm superiorly, the neck length was increased 1.9 cm; with the hip displaced 2 cm superiorly and 2 cm medially, the neck length was increased 2.8 cm. For each of these cases, a 2-cm elevation of the hip center would require approximately a 2.8-cm increase in neck length to restore leg length.

Finally, this study examined the ratio of the body weight moment arm to the abductor moment arm with various hip center positions and prosthetic neck lengths. The ratio of the body weight moment arm to the abductor moment arm is important because it is related to the hip joint reaction force during single leg stance. As this ratio increases, joint reaction force increases because the abductors must generate more force to balance the torso. Conversely, as the ratio decreases, joint reaction force decreases.[20,21]
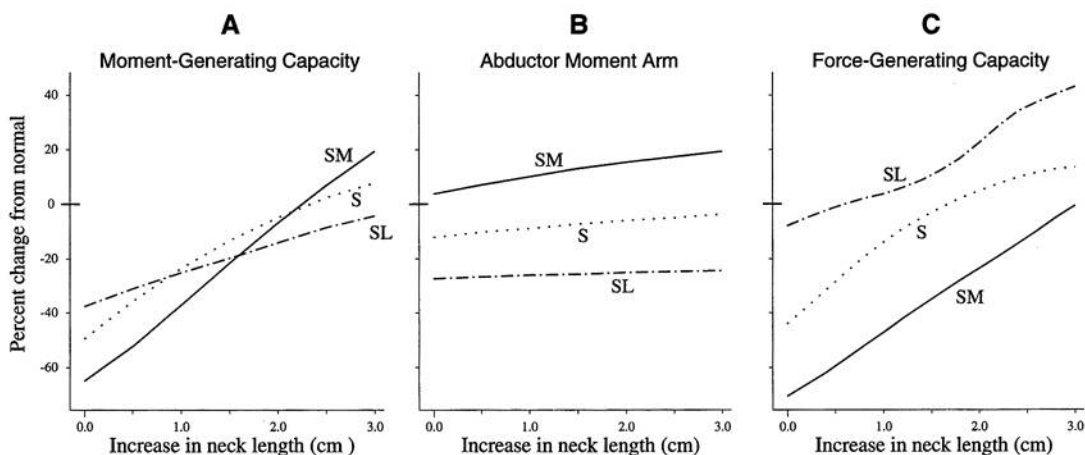
RESULTS

The moment generating capacity of the abductor muscles decreased substantially for the 3 hip center displacements with no increase in neck length (Fig 2A). The moment generating capacity of the abductors decreased 38% with superolateral displacement, 49% with superior displacement, and 65% with superomedial displacement. Although the decrease is greatest with superomedial displacement, the moment generating capacity of the abductors can be fully restored by increasing prosthetic neck length. However, with a superolaterally displaced hip center, the moment generating capacity of the abductors cannot be fully restored, even with a large increase in neck length.

With superolateral displacement of the hip, the moment arm of the abductors decreased 28% and is not restored by increasing neck length (Fig 2B). For a superiorly displaced hip center, the abduction moment arm also decreased, but only by approximately 12%. In contrast, the moment arm of the abductor muscles is greater than normal with a superomedially displaced hip center. Increasing the neck length 2 cm increases the moment arm to 15% above normal with a superomedially displaced hip center.

The force generating capacity of the abductors decreases least with superolateral displacement of the hip (Fig 2C). The decrease in the force generating capacity with superolateral displacement is small (9%) because of the small decrease in muscle length. With a 2-cm increase in neck length, the force developed by the abductors is 22% greater than normal, but this increase primarily is attributable to an increase in the passive muscle force (Fig 3). As the neck length is increased beyond 1 cm with superolateral

Figs 2A–C. Percent change from normal in (A) moment generating capacity, (B) moment arm, and (C) force generating capacity of the abductor muscles versus increase in neck length. Three hip center positions are compared: 2 cm superior and 2 cm lateral (dot-dash curve; SL), 2 cm superior (dotted curve; S), and 2 cm superior and 2 cm medial (solid curve; SM). (A) Although the moment generating capacity of the abductors decreases most with superomedial displacement, it can be restored by increasing neck length; whereas, the moment generating capacity cannot be restored after superolateral displacement. (B) This occurs because the abductor moment arm is less than normal for a superolaterally displaced hip center and does not increase with neck length. (C) The force generated by the abductors is greatest with superolateral displacement, but this is caused primarily by an increase in passive muscle force.

displacement of the hip, the active component of force decreases and the passive component increases. For a 2-cm increase in neck length, the passive component is 33% of the maximum active force generating capacity; such large passive muscle forces may limit range of motion. By comparison, the force generating capacity of the abductors decreases dramatically with the superomedially displaced hip because of the large decrease in the abductor muscle length. However, this decrease can be compensated by increasing the femoral neck length. With a 3-cm increase in neck length, the force generated by the abductors is restored. With superior and superomedial displacement, the increase in force primarily is attributable to an increase in the active force generating capacity of the muscles (Fig 3).

Balancing the Torso

The simulations indicate that the abductor muscles cannot generate enough moment

about the hip to balance the torso in single leg stance when the hip is displaced to the superolateral position, even with an increase in neck length. With superolateral displacement, the abductor moment required increases because of the increase in the body weight moment arm (the distance from the hip center to the midline of the body increases with superolateral displacement). Superolateral displacement also decreases the abductor moment generating capacity by decreasing the abductor moment arm. Thus, the moment required exceeds the moment generating capacity with superolateral displacement (Table 1). For the model used here, the moment required to balance the torso with the normal hip center is approximately 51 Nm (see Methods). Normally, the abductors are capable of producing an average of 88 Nm throughout a 30° range of abduction, yielding an excess moment capacity of 37 Nm (73% more than the required moment). In the model, with superolateral dis-
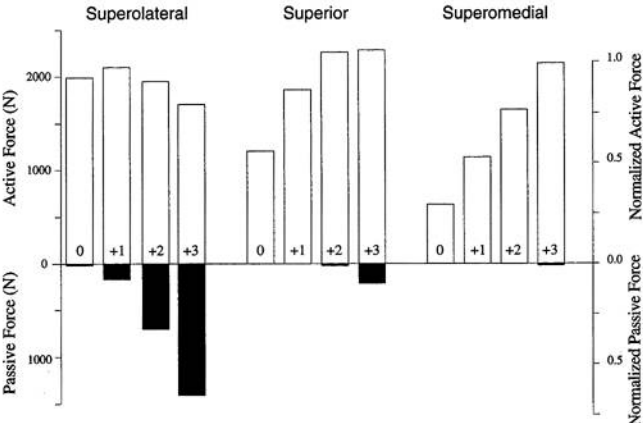
Fig 3. Active and passive forces generated by the abductor muscles for the three hip center positions: superolateral, superior, superomedial. For each position, forces are shown for neck length increases of 0, 1, 2, and 3 cm (indicated by 0, +1, +2, +3). The active force generating capacity of the abductors (open bars) decreases when the neck length is increased more than 1 cm for superolateral displacement, whereas the passive force (filled bars) increases. In contrast, the active force increases with neck length for superior and superomedial displacement, and the passive force remains small. The normalized forces, indicated on the right vertical axis, are based on the force generating capacity of the muscles with the anatomic hip center and normal neck length.

placement of the hip and a neck length that restores muscle length, the abductor moment required increases to 63 Nm and the moment capacity decreases to 62 Nm. When the requirement exceeds the capacity, a limp may result. In contrast, superomedial placement of the hip improves the abductor's ability to balance the torso when the neck length is increased to restore the length of the abductor muscles.

Ratio of the Body Weight Moment Arm to Abductor Moment Arm

The ratio of the body weight moment arm to the abduction moment arm is much greater with superolateral displacement of the hip

center than with superior or superomedial displacement (Fig 4). The results show that the superolaterally displaced hip has a body weight moment arm to abductor moment arm ratio that is 65% greater than that seen with the normal hip. This ratio decreases as the hip center is moved medially. With a superomedially displaced hip, the body weight to abductor moment arm ratio is 34% less than that seen with the normal hip center, indicating that the joint reaction force is less with superomedial displacement than with superolateral displacement.

Increasing prosthetic neck length decreases the ratio of the body weight moment arm to abduction moment arm (see upper and

TABLE 1. Moment Required to Balance Torso During Single Leg Stance Compared With Moment Generating Capacity of Abductors for 4 Hip Center Positions

Hip Center Position	Moment Required* (Nm)	Moment Capacity (Nm)	Excess Moment Capacity (Nm)**	Excess Moment (%)
Normal	51	88	+37	+73%
Superolateral†	63	62	−1	−2%
Superior†	51	82	+31	+61%
Superomedial†	39	102	+63	+162%

*Moment Required = (Body weight of the model × body weight moment arm).

**Excess Moment = (Moment Capacity − Moment Required)

†Prosthetic neck length was increased such that the muscle was restored to its normal anatomic length.
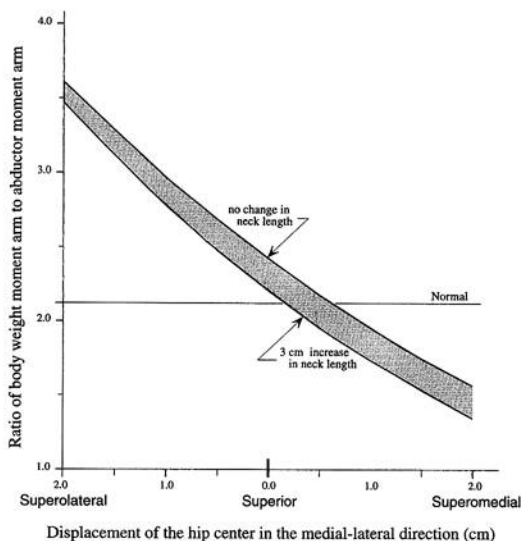
Fig 4. The ratio of body weight moment arm to abductor moment arm for a range of hip center positions and prosthetic neck lengths. The hip center was displaced 2 cm superiorly, and its position was varied in the medial lateral direction. The shaded region defines all possible values for neck length increases from 0 to 3 cm. The ratio of body weight moment arm to abductor moment arm with the normal hip center is approximately 2.1. The ratio increases with lateral displacement and decreases with medial displacement, demonstrating that a higher joint reaction force is associated with a superolaterally displaced hip center.

lower curves in Fig 4). The decrease in the ratio is small with the hip in the superolateral position because increasing neck length has little effect on abduction moment arm. Increased neck length decreases the ratio more with the hip in the superomedial position. However, the variation in the ratio with increases in neck length is much smaller than the variation with changes in hip center.

DISCUSSION

The computer simulations indicate that it is possible to preserve the moment generating capacity of the abductor muscles after superior and superomedial displacement of the hip center by increasing prosthetic neck length. In contrast, the simulations revealed that superolateral displacement adversely affects the function of the abductor muscles by decreasing their moment arms and their capacity to generate hip abduction moments. Before discussing the implications of these results, the effects of several limitations of the computer modeling approach used here should be considered.

First, the results presented here represent values obtained using a computer model that represents an average size adult male. However, there are wide variations in musculoskeletal geometry, muscle force generating capacity, and body weight among individuals. Because of these variations, the absolute values presented here should not be applied to a particular individual, who may be greatly different from the model. Rather, the results should be used to understand the relationships between the changes in musculoskeletal geometry and muscle function. For this reason, many results are presented in a normalized form, such as a percent change or a ratio of moment arms, to emphasize trends, rather than absolute values.

Second, the simulations kept constant each muscle's peak isometric force, muscle fiber length, and tendon length. However, these parameters may change 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 fiber length, as a muscle tendon complex adapts to altered conditions.[34] Muscle atrophy may produce changes in physiologic cross sectional area and decrease the force generating capacity of muscle. By keeping properties of each muscle tendon complex constant, the simulations demonstrate the effects of changing musculoskeletal geometry exclusively.

Third, this study reports the effects of medial lateral positioning of a superiorly displaced hip center, together with compensatory changes in neck length, on the abductor muscles only. Other muscle groups about the hip,

such as the hip flexor group, also could be affected. Delp and Maloney[11] analyzed the effects of hip center displacement on the flexor, extensor, adductor, and abductor muscle groups, without altering femoral neck length. The abductor muscles were analyzed in detail in the current study because of their significant influence on the gait of arthroplasty patients and their sensitivity to the positioning and geometry of the hip prosthetic components.

It is helpful to put the results reported here into context by comparing them with the results of previous studies. Charnley[6] and Muller[24] first advocated moving the acetabulum medially to decrease joint reaction force. The results of Gore et al[13] also support the idea that medial placement of the acetabular component is advantageous. Johnston et al[20] reported that medial positioning of the hip center reduces hip joint force and advocated inferior medial positioning of the hip center to maximally reduce the joint contact force and the moment generating requirements of the muscles. Three-dimensional computer simulations have suggested that inferior medial positioning of the hip center is desirable in terms of maintaining or improving the moment generating capacity of the muscles.[11]

However, in some instances, particularly in revision surgery, a superiorly displaced hip center may be difficult to avoid. The results show that a 2-cm elevation of the hip center, without lateral displacement, changes the moment arm and force generating capacity of the abductors by less than 10% if the neck length is increased to compensate for decreased muscle length. This suggests that superior positioning, without lateral placement, does not have major, adverse effects on abductor moment arms or force generating capacities when the neck length is appropriately increased. This is consistent with the results of a number of clinical studies in which superior placement of the hip center, without lateral placement, provided good abduction moment arms.[22,30]

As discussed by others,[2,20] superolateral displacement of the hip center increases the distance between the hip joint center and the body weight force vector (it increases the moment arm of the body weight). Equally important is the observation reported here that superolateral displacement of the hip decreases the moment arms of the abductors by moving the hip center closer to the muscle line of force. Thus, the ratio of the body weight moment arm to the abductor moment arm increases dramatically with superolateral displacement. This has 2 detrimental effects. First, it increases the force that must be generated by the hip abductors during single leg stance, thereby increasing joint reaction force. It also decreases the moment generating capacity of the hip abductors. If the moment generating capacity of the abductors falls below the moment generating required to balance the torso, a limp is likely to result.

Another important result of this study is the observation that increases in prosthetic neck length do not counteract the adverse effects of superolateral displacement of the hip center. Increasing neck length does not increase the moment arm of the abductors after superolateral displacement of the hip center because increasing neck length moves the insertion point of the primary abductors along the line of force of the abductor muscles. Thus, increasing neck length increases muscle length but changes the moment arm very little after superolateral displacement. In addition, increasing neck length more than 1 cm after superolateral displacement has the potential to increase the passive forces generated by the hip abductors, which may limit joint range of motion. Consequently, normal moment generating characteristics of the abductors are not restored after superolateral placement, even with neck length compensation. In contrast, after superomedial placement of the hip center, increasing prosthetic neck length increases abduction moment arm and active muscle force generating capacity.

Although the results presented here and in other studies[6,13,20,24] show theoretical advantages to superomedial placement of the hip center, it is important to point out 2 potential

problems. First, although improving abduction moment arm is important, assuring adequate bone stock to establish secure fixation of the acetabular component is essential. Excessive medial displacement of a superiorly placed hip center may leave the component in a position where there is insufficient bone for secure fixation. Thus, although superolateral placement should be avoided, pure superior positioning is a better choice than destruction of medial bone stock to obtain a superomedial position.

Second, to restore muscle lengths and force generating capacities after superior and superomedial displacement, the prosthetic neck length had to be increased substantially. This may require a neck length that is not available in standard implant sizes. In addition, in walking, a longer prosthetic neck increases the bending moment supported by the prosthetic neck during single leg stance,[20] which could lead to implant failure. When rising from a chair or climbing stairs, the torsional loads that tend to rotate the femoral stem in the medullary canal may increase with a longer prosthetic neck. Depending on the quality and type of the fixation, this could result in a higher incidence of loosening of the femoral component. Studies by Yoder et al[37] and Kelley[22] have suggested a higher incidence of loosening when cemented femoral fixation was used with a high hip center. Certainly, future clinical, experimental, and theoretical studies of implant bone systems are needed to address this important issue.

For the acetabular component, a number of clinical studies have reported a higher incidence of failure from loosening and increased radiolucencies with cemented fixation in a superior position.[4,8,23,28] In contrast, Russotti and Harris[29] and Yoder et al[37] reported no adverse effect when cemented acetabular components were placed superiorly without lateral displacement. With ingrowth acetabular components, Schutzer and Harris[30] reported no adverse effects on fixation, no migration, and no complete radiolucent lines. With the same prosthesis, Kelley[22] found a 5% incidence of radiographic loosening. Additional long term studies are needed to determine if there is an adverse effect of superior positioning of the hip center on acetabular loosening.

The results of this study suggest that when superior placement of the hip center is necessitated in total hip arthroplasty, the hip should not be left in a lateral position because doing so decreases the moment arm of the abductor muscles, reduces the moment generating capacity of the abductor muscles, and increases the hip joint reaction force. Increasing neck length does not correct these problems but potentially increases the passive force generated by the abductor muscles, which may limit range of motion.

This study also suggests that, with the hip center in the superior or superomedial position, the prosthetic neck length should be increased to restore the length and force generating capacity of the abductor muscles. Superior or superomedial placement of the hip center, without compensatory increases in neck length, are likely to produce a large decrease in the moment generating capacity of the muscles. With a compensatory increase in neck length, a 2-cm elevation of the hip center changes the moment arms and force generating capacities of the abductors by less than 10%. Thus, it is important to compensate for changes in muscle length that arise from superior displacement.

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