Trochanteric Transfer in Total Hip Replacement: Effects on the Moment Arms and Force-Generating Capacities of the Hip Abductors

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Summary: A three-dimensional computer model of the pelvis, femur, gluteus medius, and gluteus minimus was used to evaluate the changes in muscle moment arms and force-generating capacities caused by alterations in the location of the greater trochanter. In the first part of this study, the hip center and all other aspects of joint geometry remained unaltered, while we examined changes in abduction moment arms that resulted from transfer of the trochanteric fragment to a wide variety of positions on the femur. The largest increase in average abduction moment arm was 11% (0.5 cm), which occurred with an anterolateral transfer. Most transfers resulted in moment arm changes of less than 5%. In the second part of this study, the hip center was displaced 2 cm superiorly, and the effects of a distal trochanteric transfer on the moment arms and force-generating capacities of the abductors were analyzed. The superior displacement caused a 13% decrease in the moment arm of the abductors and a 43% decrease in their force-generating capacity. The moment arm was not restored by distal transfer of the greater trochanter; however, distal transfer had the major advantage of restoring muscle lengths and force-generating capacities. These results suggest that trochanteric transfer should be considered primarily as a means to restore muscle length because it has limited potential to increase the moment arms of the two primary hip abductors.

The success of a total hip replacement depends partially on the preservation or restoration of abduction strength. The patient may limp postoperatively if the hip abductors cannot generate sufficient moment about the hip to counteract the moment from the patient's body weight. Some authors have suggested that a trochanteric transfer can increase the capacity of the muscles to generate an abduction moment by lengthening the muscles or increasing their moment arms (3,8,16). If this were possible, then the trochanteric transfer could potentially compensate for changes in musculoskeletal geometry that decrease muscle lengths and moment arms.

Trochanteric transfer is a controversial procedure, and researchers disagree about its utility. Some have argued that trochanteric transfer provides a better operative exposure, stability against dislocation, and improvement of abduction moment arm (3,8,12,16,17, 20,22). Obrant et al. (20) compared osteotomy and non-osteotomy groups and found that abduction

strength was greater in the osteotomy group. Mallory (17) made a similar comparison and concluded that the osteotomy group had less limp, improved walking endurance, and better abduction against gravity. Other studies, however, reported that trochanteric osteotomy had no significant advantage in terms of abduction strength (15,18). There are also clinical disadvantages of trochanteric transfer, including nonunion, wire breakage, increased blood loss, increased operating time, and trochanteric bursitis (8,10, 12,14,21). Because of these disadvantages and questionable benefits, trochanteric transfer is usually only performed in revision surgeries and complicated primary surgeries that require greater joint exposure or major musculoskeletal alterations (18,19,21-23).

Several groups have attempted to determine the effects of trochanteric transfer on muscle moment arms and force-generating capacities using measurements from planar radiographs (1,18,22,25). However, there are fundamental limitations to this approach. First, since planar radiographs do not characterize three-dimensional changes in musculoskeletal geometry, surgical alterations cannot be measured accurately. Second, because preoperative and postoperative radiographs are taken under different conditions, errors are introduced. Third, measurements

from radiographs do not allow one to estimate the nonlinear changes in the force-generating capacities of the muscles that may result from the trochanteric transfer.

We developed a three-dimensional musculoskeletal model that was used to simulate the geometric changes that result from trochanteric transfer and to estimate the effects of these changes on the moment arms and force-generating capacities of the hip abductors. The first objective of these simulations was to determine if the moment arms of the hip abductors could be increased by trochanteric transfer with the hip center in its anatomical position. The second objective was to evaluate the effects of trochanteric transfer on muscle moment arms and force-generating capacities when the hip center was displaced superiorly, as may occur in revision surgery.

MATERIALS AND METHODS

The computer model of the hip used in this study was described in detail and compared with experimental measurements of muscle strength in previous publications (4-7). The femur had a neck length of 4.8 cm, a neck-shaft angle of 128°, and an anteversion

muscle forces included active force generated when the muscle fibers were assumed to be maximally excited and passive force developed when the muscle fibers were stretched beyond their rest lengths (27). The maximum isometric moment-generating capacity of each muscle compartment was calculated as the product of the muscle's maximum isometric force and moment arm. Comparisons between the model and experimentally measured hip abduction moments demonstrated that the model represents normal moment-generating characteristics (6).

The total force-generating and moment-generating capacities of the gluteus medius and minimus were calculated by summing these capacities of the constituent muscle compartments. The moment arms of the constituent muscle compartments were also summed and then divided by the number of muscle compartments, to calculate an average abductor moment arm. Finally, the total force-generating capacity, moment-generating capacity, and moment arm were averaged over a range of abduction angles. The range from 20° of abduction to 10° of adduction was used because it includes abduction angles necessary for activities such as walking, stair climbing, exiting from a car, and stepping to one side. All simulations were performed with the hip in 0° of flexion, which is the upright standing position.

Six cutting planes were used in the analysis of trochanteric transfers with the hip center in its anatomical location (Fig. 1). These planes were chosen to represent a wide range of feasible trochanteric transfers. For each cutting plane, a set of left-handed axes was defined with the origin on the cutting plane surface, the
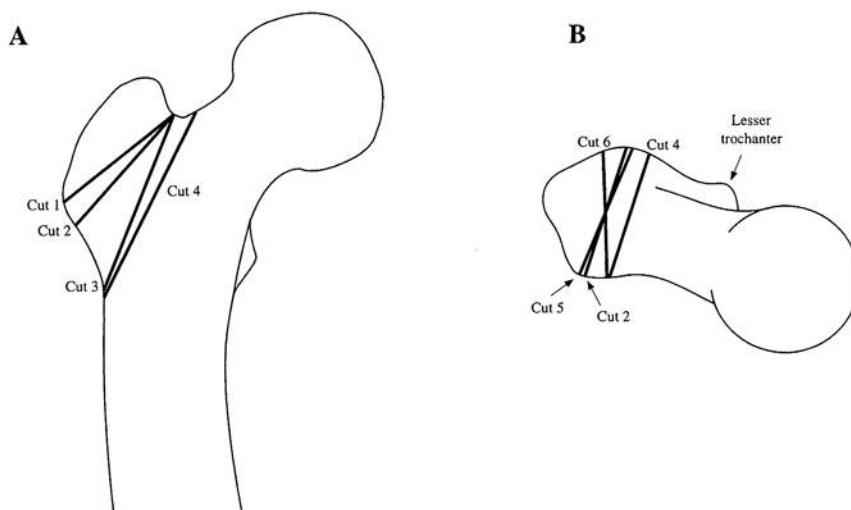

FIG. 1. Six trochanteric osteotomy cutting planes were examined in this study and are shown in both an anterior (**A**) and a superior (**B**) view. Cuts 5 and 6 are not shown in **A** because their differences from Cut 2 are evident in the transverse plane (**B**). Cuts 1 and 3 are not shown in **B** because their differences from Cut 2 are evident in the frontal plane (**A**).

angle of 19°. The gluteus medius and minimus were the only muscles examined in the current study because they account for a large percentage of the total moment-generating capacity of the hip abductors and are the muscles that are most affected by alteration of the trochanter position. Each muscle was represented as three compartments to characterize its anterior, medial, and posterior aspects. The moment arm and origin-to-insertion length of each compartment were calculated for a range of hip abduction angles and a variety of trochanter positions. The maximum isometric force generated by each muscle compartment was calculated by scaling a generic model of muscle and tendon on the basis of the compartment's physiologic cross-sectional area, optimal muscle fiber length, tendon slack length, and pennation angle (the angle between tendon and muscle fibers at optimal fiber length), which were derived from anatomical studies (2,11,24). The calculated

z axis normal to the cutting plane, the x axis pointing anterolaterally, and the y axis pointing inferiorly, laterally, and posteriorly along the plane (Fig. 2A). Trochanteric displacements were made by changing the location of the trochanteric fragment with respect to this reference frame. One-centimeter displacements in each direction along the cutting planes were used to represent the extreme trochanter positions (Fig. 2B). To ensure that these displacements were anatomically feasible, we performed a trochanteric osteotomy on a plastic femur model that was similar in size to the computer model of the femur. Analysis of the physical model and the computer model demonstrated that all trochanter displacements within the 1 cm radius circle allowed more than half of the trochanteric fragment surface to remain in contact with the femur (Fig. 2C). Distal trochanteric transfer to the femoral shaft was deemed infeasible when hip center and joint geometry were
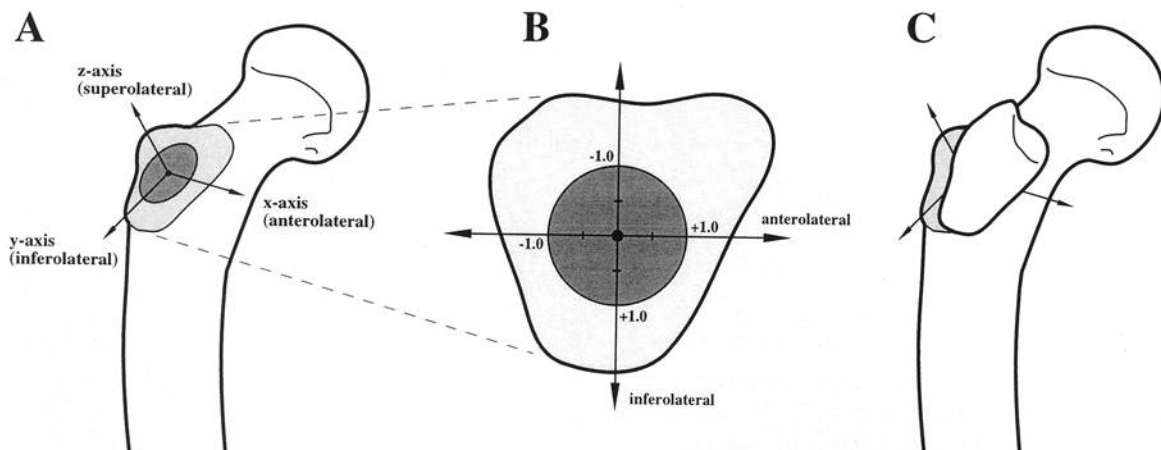
FIG. 2. The range of feasible trochanteric displacements was within the darkly shaded region on the plane of the trochanteric cut. **A:** The x and y axes are in the plane of the cut, and the z axis is normal to the cutting plane. **B:** Movement of the trochanter origin (dot) was limited to 1 cm in any direction. **C:** An example of anterolateral trochanteric displacement.

not altered because it stretched the abductors excessively, resulting in a large increase in passive force. Therefore, distal transfers were only simulated in conjunction with superior displacement of the hip.

With the hip center in its anatomical location, the trochanter was transferred to 63 discrete points within the feasible region. Sixteen points around the perimeter were selected to represent the extreme trochanter positions, and 47 additional points representing smaller trochanteric displacements were used to determine the trends within the feasible region. The average abduction moment arm for the gluteus medius and minimus was calculated for each position of the trochanteric fragment, and the percentage change from normal average moment arm was determined. This procedure was performed for each of the six cutting planes. The results for all trochanter positions and cutting planes were combined on one plot to demonstrate the range of possible changes in abduction moment arms.

For analysis of the distal trochanteric transfer with superior hip displacement, only a single cutting plane (Cut 2 in Fig. 1) was used because there were only small differences among the cutting planes with the hip center in the natural location (see Results section). We examined positions of the trochanteric fragment that allowed for adequate bone contact and that did not create excessive passive forces in the muscles (Fig. 3). Trochanteric transfers were regarded as feasible only if passive force did not exceed half of the maximum active force with the hip in 10° of adduction. This feasibility range allowed a variety of trochanter positions but excluded transfers that resulted in rapidly rising passive muscle forces. For this analysis, the effects of 2 cm superior hip displacement on abduction moment-generating capacity, force-generating capacity, and moment arm were calculated. The trochanter was then transferred distally to determine if the force-generating capacity and moment arm could be restored to normal. Moments, forces, and moment arms were compared by calculating percentage changes from the original anatomical values.

RESULTS

Abduction moment arm changed less than 12% for the range of trochanter positions studied here (Fig. 4). The greatest increase in abduction moment arm was 11%; this resulted from a 1.0 cm anterolateral displacement of the trochanteric fragment along Cut 5. This transfer maximized moment arm because it provided a relatively large lateral displacement, which

was the primary reason moment arm increased. Anterior and superior displacements of the trochanter also increased moment arm but less than lateral displacement. Moment arm was minimized, decreasing by
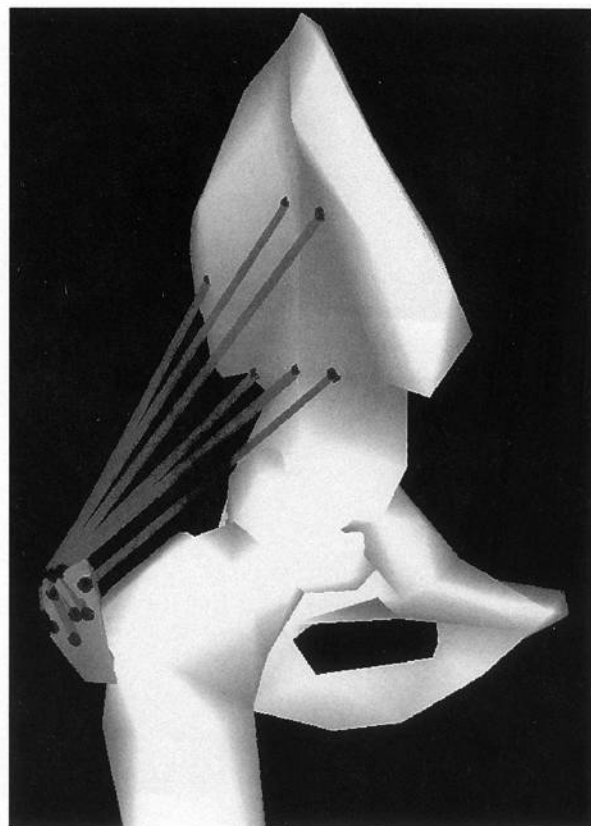

FIG. 3. Computer simulation of a distal trochanteric transfer with the hip center displaced 2 cm superiorly and the greater trochanter transferred with the gluteus medius and minimus. Each muscle was represented by three compartments. To accurately represent the muscle geometry, each compartment was designed to wrap around the trochanteric fragment when it was transferred and rotated. In this example, the trochanteric fragment was transferred 0.5 cm laterally, 1.1 cm inferiorly, and 0.5 cm posteriorly with 60° of rotation about the x axis (see Fig 2).

TABLE 1. *Moment-generating capacities, force-generating capacities, and moment arms*

Condition	Moment-generating capacity (Nm)[a]	Force-generating capacity (N)[b]	Average moment arm (cm)
Normal	71	1,660	4.3
2 cm superior displacement of the hip center	34 (−52%)	940 (−43%)	3.7 (−13%)
2 cm superior displacement of the hip center with distal trochanteric transfer	71 (0%)	1,810 (+10%)	3.8 (−12%)

[a] Moment-generating capacity of the gluteus medius and minimus.
[b] Force-generating capacity of the gluteus medius and minimus.

12%, with a transfer directed 0.87 cm posteromedially and 0.5 cm superomedially along Cut 1. The medial displacement component of this transfer was the major factor contributing to the decrease in moment arm. It should be noted that the trochanteric transfers that maximized and minimized moment arms represented extreme displacements of the greater trochanter; most trochanteric transfers resulted in changes in moment arm of less than 5%.

Although lateral trochanteric displacement had the greatest effect on moment arm, it was difficult to obtain much lateral displacement because of cutting plane constraints. The trochanteric fragment had to remain in contact with the femur, so it could not be displaced laterally alone. Lateral displacement was achieved by sliding the trochanter anterolaterally and inferolaterally along the cutting plane. Combining lateral displacement with an inferior component caused very little change in moment arm, however, because the increase from the lateral displacement was offset by the decrease from the inferior displacement. In

FIG. 4. Percentage change in abduction moment arm plotted against anterolateral displacement of the greater trochanter. The shaded region represents the range of changes resulting from differences among the six cutting planes (Fig. 1) and combined displacements along the inferolateral axis.

contrast, lateral and anterior displacements complemented each other and caused greater increases in moment arm when performed together.

Moving the hip center 2 cm superiorly decreased abduction moment-generating capacity by 52%, force-generating capacity by 43%, and moment arm by 13% compared with the normal condition (Table 1). However, a simulated transfer of the greater trochanter to the position shown in Fig. 3 restored the moment-generating capacities of the gluteus medius and minimus. This was due to an increase in muscle force-generating capacity to 10% greater than normal. The increase above normal was due to increased passive force developed by the muscles when stretched beyond their rest lengths. The abduction moment arm remained 12% below normal because the distal transfer extended the muscles along their lines of action, which did not increase moment arm.

DISCUSSION

Several limitations of this study should be considered when interpreting the results. First, the simulations did not include alterations in the neck length, neck-stem angle, and anteversion angle of the femur so that the effects of the trochanteric transfer could be examined in isolation. Alterations in implant geometry may allow for a wider range of trochanter positions, and thus larger changes in abduction moment arms, as reported in our previous publications (7). However, these changes in moment arms result from alterations in the implant geometry and not from the effects of the trochanteric transfer.

Second, our analysis did not include all conceivable trochanteric transfers. Smaller or larger trochanteric fragments may be removed and transferred to new sites on the femur. Moment arm changes in these cases would most likely fall within our range of results because trochanteric displacements are still limited by bone contact constraints. In other instances, it may be possible to achieve more lateral displacement if a bone graft were inserted between the trochanteric fragment and the femur (9), resulting in a larger increase in abduction moment arm.

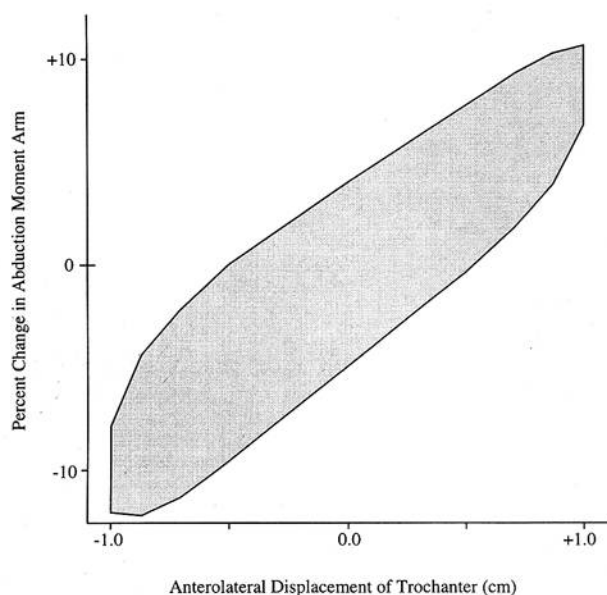Third, our maximum and minimum moment arm values result from extreme trochanteric displace-

ments. In most cases, such extreme trochanteric displacements may not be desirable due to the risk of trochanteric detachment. In general, changes in moment arm were less than 10% for situations in which displacements were less than 1.0 cm. At most, an increase of approximately 1% in the moment arm can be expected for each millimeter of trochanteric displacement in the anterolateral direction.

Fourth, because each muscle's physiologic cross-sectional area, fiber length, and tendon slack length were kept constant for our simulations, our analysis of muscle forces neglected any changes in these parameters that may occur before and after surgery. For instance, physiologic cross-sectional area may be altered by muscle atrophy, thus decreasing peak isometric force. Similarly, muscle fiber lengths may be changed by the addition of sarcomeres (26). This can create new optimal fiber lengths that are longer and more closely match the new muscle lengths after distal trochanteric transfer. This would potentially reduce the passive forces observed in this study and allow the muscles to generate active forces that are closer to their peak isometric forces.

Our finding that trochanteric transfer only slightly changes the moment arms of the gluteus medius and minimus is inconsistent with Lazansky (16), who suggested that the trochanteric transfer can increase abduction moment arms substantially. There are two possible explanations for this inconsistency. First, the methods used to determine moment arms by Lazansky (16) and others (18,22) overestimated the change in moment arm with trochanteric transfer. Moment arms were estimated as the distance from the hip center to the lateral aspect of the greater trochanter rather than as the shortest distance from the hip center to the muscle line of action. Second, Lazansky (16) described a hip replacement that included alterations in femoral neck length and offset, whereas the current study examined effects of trochanteric transfer without altering femoral geometry. Our previous analysis showed that abduction moment arm increased with femoral neck length (7). This suggests that reported increases in abduction moment arm may have resulted from alterations in implant geometry rather than from the trochanteric transfer.

Our finding that trochanteric transfer provided little increase in moment arm is consistent with several previous studies. Using a correct method to estimate abduction moment arms, Borja et al. found no significant difference in moment arms between hip replacements done with and without trochanteric transfers (1). Similarly, Wiesman et al. reported that abduction moment arms were not significantly greater with trochanteric transfer (25). Given the small potential to increase the moment arm, the great variability among patients, and the confounding effects of experimental

error, it is not surprising that no significant increases in abduction moment arms after trochanteric transfer were reported in these studies.

The conclusion that trochanteric transfer has little biomechanical advantage when the hip center is in its natural location and femoral geometry is restored has important implications. The small increase in moment arm that can be achieved seems insignificant when compared with the additional risk of complications associated with this procedure. This supports studies suggesting that trochanteric transfer should not be performed in primary hip replacement unless major alterations in musculoskeletal geometry are necessary (18,21,25).

Distal transfer of the greater trochanter, by contrast, has a significant biomechanical benefit when the hip center has been placed superiorly, because the transfer can restore the lengths and force-generating capacities of the gluteus medius and minimus. This is consistent with the findings of Gore et al. (13), who reported that distal positions of the greater trochanter could increase abductor strength by elongating the muscles. It should be emphasized, however, that the abduction moment arm is not restored with distal trochanteric transfer because this transfer essentially extends the muscles along their lines of action.

This study suggests that trochanteric transfer should be considered primarily as a means to restore muscle lengths because it has limited potential to increase the moment arms of the two primary hip abductors. Although trochanteric transfer can restore the lengths of the abductors after superior placement of the hip center, it should be noted that other muscle groups, such as the hip flexors, may be adversely affected by the superior hip displacement if femoral neck length is not increased to compensate (7). Nonetheless, distal transfer of the greater trochanter provides an effective method to maintain the lengths and the force-generating capacities of the primary hip abductors, which is especially important in joint reconstructions that require superior displacement of the hip.

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