Difference in Effect of Muscle Weakness versus Obesity on Stability of Knee Joint

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Abstract. This research examines a question about which is worse to the knee joint: increasing body weight or decreasing muscle force. We simulated unilateral weight bearing and analyzed the extent to which each had a deleterious effect on the knee joint. We used a rigid body model in which body weight was increased and quadriceps muscle force decreased. Also, to account for differences between men and women, the model reflected difference in pelvic width. In this simulation, decreasing muscle strength by 30% of its initial normal value had a stronger unfavorable effect than that of increasing body weight to the same relative degree. The effect of differences in body proportion between men and women did not appreciably influence the results, as long as masses and linear dimensions were average values of the respective sexes. Our results suggest that a patient with osteoarthritis in the knee should pay particular attention to problems of muscle weakness.

Key words: quadriceps muscle weakness, increasing body weight, biomechanical simulation

Muscle weakness and obesity are considered factors that can hasten the progression of osteoarthritis in the knee. They are seen in osteoarthritic patients, so muscle strengthening exercises or weight reduction is often a part of such a patient’s treatment program. Many investigators have shown that muscle strengthening exercises can be effective in reducing pain and increasing functional activities in osteoarthritic patients. Obesity was shown, in a study by Kohatsu et al., to be 3.5–5.3 times more likely in patients with osteoarthritis than in a comparable control group. Felson et al. showed that weight loss in women lowered the risk of future development of knee osteoarthritis in about 50% of cases in the Framingham Knee Osteoarthritis Study.

Although the effects of excessive body weight and of inadequate muscle strength have been established as risk factors for knee osteoarthritis, their comparative biomechanical effects on the knee are unknown. If the effect on progression of osteoarthritis can be quantitatively compared between changes in muscle strength and changes in body weight, the physical therapist can more precisely set up an appropriate treatment program for the patient with osteoarthritis of the knee.

The purpose of this study was to clarify which has a mechanically more deleterious effect on the knee joint, muscle weakness or obesity. We analyzed this by a biomechanical simulation using a rigid body model. Burstein and Wright have described a mechanism of stability in the frontal plane whereby a point in the knee joint is determined to balance muscle forces against the ground reaction force. They state that this point of balance is located in the medial compartment of the knee. If the point of balance shifts medially, beyond the confines of the knee joint itself, the knee will tend to go into varus and thus must be equilibrated by adding tension from the lateral collateral ligament.

In accordance with this idea, we compared the extents to which lowering muscle tension and raising body weight caused the balance point in the knee to shift medially. Also, to account for differences between men and women, the model reflected difference in pelvic width.
Methods

Analytical model

To calculate the reaction force at the knee joint in standing, we imported pictures into a personal computer (Power Macintosh) that were views in the frontal and sagittal planes. The image was converted to a rigid body model consisting of four segments: head, trunk including arms, thigh, and shank including foot (Fig. 1). Link boundaries and such body parameters as weight of segment and center of mass were based on information from a textbook. For the analytical model in the frontal plane, pelvic width (D in Fig. 2) was not clear, so we had to derive that value ourselves, to be explained in the next section. For purposes of this study, we assumed that the pelvic width was horizontal. The analytical model included various angular relationships, as shown in Figs. 1A and 2, that would be appropriate for both long and short segments. Since we were focusing on ordinary functions requiring activity of the quadriceps, the posture analyzed did not look like stable one-leg standing.

Proportions of the simulation model were based on data of proportions in 50 year old Japanese people. For men the height was 166 cm and the weight 65 kg; for women the height was 154 cm and the weight 53 kg. Using this information, the center of mass of the body excluding the weight-bearing foot and shank was calculated.

Pelvic width

Pelvic width was assigned values on the basis of normal pelvic radiographs. Length between the centers of the femoral heads was measured in radiographs of 7 men and 15 women. Mean age and standard deviation were 41.6 ± 23.0 for men and 49.7 ± 26.6 for women. Simple regression between height and pelvic width based on these data was then used to obtain an equation for estimating pelvic width. Male and female pelvic widths were both estimated to reflect differences in proportion between the sexes.

Numerical procedure

Moment about the knee joint due to body weight was calculated under static conditions. Equilibrium in the sagittal plane (Fig. 4) could then be expressed as

\[ a \times F_q - b \times F_h = W \times L_1 \]  

Equation 1

where \( a \) is moment arm for the quadriceps and \( b \) is moment arm for the hamstrings. Moment arms \( a \) and \( b \) were determined by measurement on one skeletal specimen. For accuracy of measurement, the muscle line was marked by colored tape. The joint center was derived from the convexity of the lateral condyle of the femur in the region of the joint center. \( a \) is length of a perpendicular line from the joint center to the quadriceps muscle force line. \( b \) is length of a perpendicular line from the joint center to the hamstrings muscle force line.
In the frontal plane, the point of reaction force in the knee was determined as a mechanical fulcrum (Fig. 3). Equilibrium in the frontal plane could then be expressed as:

\[ BP = \frac{W \times L_2}{\cos 25^\circ + \cos 5^\circ + W} \]  

Equation 2

We thus had three unknown parameters \((F_q, F_h, BP)\), but only two equations. Since this was a statically indeterminate problem, we had to reduce the number of unknown parameters, so we set the \(BP\) parameter as an initial normal condition. We decided to set it to 15 mm as a reasonable value after trying various values. With this value for \(BP\), we could calculate the quadriceps force \((F_q)\) and hamstrings force \((F_h)\). We first did the calculations under normal conditions. Then we simulated a situation with decreased quadriceps muscle force as well as a situation with increased body weight. When quadriceps muscle force or body weight was altered, the hamstrings force was calculated by equation 1, and the balance point \((BP)\) was determined by equation 2.

The balance point represented the point at which the compressive reaction force (the vertical joint reaction force) acted in the knee joint. The magnitude of this compressive force was the sum of the vertical component of the quadriceps force \((F_q \cos 25^\circ)\), the hamstring force \((F_h \cos 5^\circ)\), and body weight \((W)\).

**Results**

Decreasing quadriceps force appeared to be more potent in disrupting stability of the knee joint than increasing body weight. This is based on the following analysis.

Figure 5 shows pelvic width (mm). Regression analysis yielded 0.166 \times (height in mm) – 80.55 for men and 0.185 \times (height in mm) – 84.3 for women. Related correlation coefficients were 0.70 for men and 0.78 for women.

The moment arms that we measured on the skeletal specimen were 5 cm for the quadriceps \((a)\) and 3 cm for the hamstrings \((b)\).
Figure 6 illustrates how the balance point of reaction force moved medially as the quadriceps force decreased. When muscle force in the simulation decreased 30% from the initial normal condition, the balance point moved 2.6 cm medially (Fig. 6-C).

When body weight was increased in the simulation, the reaction force point again moved medially, but its effect was smaller than when the muscle force decreased an equivalent amount from the initial condition (Fig. 7). If, for example, body weight was increased 30%, the balance point moved 2.0 cm. To achieve the same effect on migration of the balance point as the 30% decrease in muscle strength, body weight would have to increase 75%.

Figure 7 shows that men and women exhibited no apparent differences in the effect of decreasing quadriceps strength or increasing body weight. The balance point would shift about 3.2 mm medially, however, if the normal value of quadriceps for a man were used in combination with the regression equation for the pelvis of a woman (data not shown).

Discussion

In this simulation, decreasing muscle strength had a stronger unfavorable effect on stability of the knee joint than did increasing body weight. When muscle strength decreased 30% from the initial normal condition, the balance point shifted almost to the edge of the medial compartment. A 30% decrease in muscle strength is clinically realistic. Murray et al.\textsuperscript{15, 16} showed that knee muscle strength was 30% lower in elderly subjects than in young subjects. To achieve the same effect on the knee by increasing body weight, an increase of 75% would be necessary. For example, a person weighing 60 kg would need to increase body weight to 105 kg. Clearly patients with osteoarthritis of the knee should be more concerned about maintaining muscle strength than about reducing body weight as far as the knee is concerned.

This simulation is corroborated by findings reported by Miller et al.\textsuperscript{17}, who evaluated the relationship between clinical and roentgenographic findings in patients with degenerative arthritis of the knee. They reported that medial instability of the knee joint was related to decreased quadriceps tension, but that body weight was not significantly related to severity of roentgenographic changes. These findings suggest that our simple simulation model may be practical.
Our simulation model does not reflect the real condition of osteoarthritic patients in very much detail. The model was kept simple to compare the apparent effects of decreasing muscle strength versus increasing body weight. One implication of our results is that the balance point in the knee might not move medially very far by changing position of a body segment, such as the head or the pelvis. This contrasts sharply with the effect of a loss in quadriceps strength. The patient with osteoarthritis in the knee should thus pay serious attention to problems of muscle weakness.

The effect of differences in body proportion between men and women did not appreciably influence the results, as long as masses and linear dimensions were average values of the respective sexes. However, if the regression for a female were used with a man, the balance point would shift to make the knee less stable. This naturally indicates that an excessively wide pelvis may be a risk factor for knee stability. That a wider pelvis did not unfavorably influence knee stability in women may be attributable to their smaller dimensions in height and weight.

**Conclusion**

We compared the effect of muscle weakness versus increasing body weight, using simulation with a rigid body model, on static stability of the weight-bearing knee during unilateral standing. In this simulation, decreasing muscle strength had a stronger unfavorable effect on stability of the knee joint than did increasing body weight. Not only patients with osteoarthritis of the knee, but also their physical therapists should be more concerned about maintaining muscle strength than about reducing body weight.

**References**