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EXPERIMENTAL ANALYSIS OF THE QUADRICEPS MUSCLE FORCE AND PATELLO-FEMORAL JOINT REACTION FORCE FOR VARIOUS ACTIVITIES

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The orthopaedic surgeon is often challenged by derangements of the patello-femoral joint or the so-called anterior compartment of the knee joint.

Chondromalacia patellae, patellar malalignment, osteoarthritis of the patello-femoral joint and fractures of the patella are commonly seen problems interfering with the normal function of this joint.

The patello-femoral joint belongs to the extensor mechanism of the knee where the patella can be considered as a sesamoid bone improving the efficiency by increasing the moment arm of the quadriceps muscle force to the center of rotation of the knee. The patella also allows a better distribution of the reaction force on the femur by increasing the area of contact.

The apposition of two cartilage surfaces represents a better system than a single articular surface opposed to a sliding tendon. Basic biomechanical information with regard to the quadriceps muscle and patello-femoral joint reaction force in locomotion are necessary for a better understanding of the above-mentioned diseases.

This paper is concerned with the quadriceps muscle force and patello-femoral joint reaction force during various activities such as level walking, climbing and descending stairs, knee bending and quadriceps exercises against resistance.

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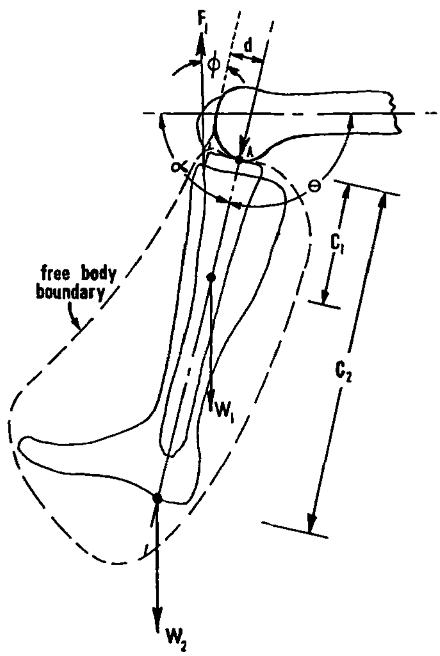

Figure 1 A. A free body diagram is a basic tool in solving a problem in statics. The free body diagram of the shank and foot includes the forces passing through the boundary of the body.

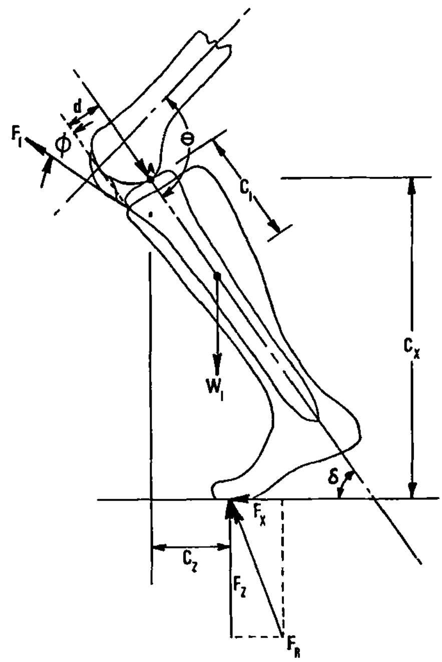

Figure 1 B. Free body diagram for the determination of the patellar tendon force in stair climbing and descending and for deep knee bends. The two components F_Z and F_X of the floor reaction force F_R are found experimentally using a force plate.

METHOD OF ANALYSIS

The patello-femoral joint reaction force and the quadriceps muscle force were studied in leg raising exercises, stair climbing, level walking and deep knee bends. The calculation for the leg raise exercise is a purely mathematical formulation, whereas the other cases are a combination of a mathematical formulation with experimentally determined parameters. In all cases a static situation of equilibrium is analysed which would tend to underestimate the true values for the forces calculated.

A free body diagram of the shank and foot is drawn as shown in Figure 1, and only the forces which traverse the free body boundary are considered. The force conditions have been simplified to the patellar tendon force, the tibio-femoral joint reaction force, the weight of the limb, and the weight of the exercise boot.

Other forces across the joint are not accounted for in this analysis; however, inclusion of other forces (e.g. gastrocnemius) will increase the value calculated for the patellar tendon force and therefore the patello-femoral joint reaction force (PFJR). The analysis yields a lower bound, i.e. a minimum value, for the patello-femoral joint reaction force (PFJR).

Since a static condition is assumed, moments may be summed and set equal to zero for equilibrium. Moments are summed about point A (the point of application of the tibial femoral joint reaction force) as this allows the solution for the patellar tendon force without solving for the tibio-femoral joint reaction force.

The angle between the patellar tendon and the axis of the tibia is designated as Ø, and values for this angle for various positions of flexion were taken from the work of Morrison (1967).

The point of contact between the tibia and the femur, and therefore also the point of application of the knee joint reaction force, is taken to be constant throughout the angles of flexion considered. Steindler (1964) states that this is constant for angles of flexion ranging from 10° to 118°. The center of gravity of the limb is assumed to lie on the axis of the tibia at a distance C_1 from the proximal condyle of the tibia given by Drillis & Contini (1964). The weight of the limb is calculated from body weight by a proportional constant taken from the same publication. Values for the moment arm of the patellar tendon force (d) were measured from roentgenograms of the knee of the subjects. The subjects were three young men, respectively twenty-four (subject C), twenty-six (subject B) and thirty (subject A) years old, who had no complaints at the knee and walked with a normal gait pattern.

For the leg raising exercises, the center of gravity of the exercise boot is assumed to lie on the axis of the tibia at the bottom of the foot (see C_2 Figure 1).

The sum of the moments about point A is given by:

$$\sum M_A = F_1 d \cos |\Phi| - W_1 C_1 \cos \alpha - W_2 C_2 \cos \alpha$$

If this is set equal to zero for equilibrium and if solved for in terms of patellar tendon force (F_1) the result is:

$$F_1 = \frac{1}{d}\left(\frac{\cos \alpha}{\cos |\Phi|}\right)\left(W_1 C_1 + W_2 C_2\right)$$

For the cases of stair climbing and deep knee bends, a different method was used for the determination of the patellar tendon force.

As the diagram of the free body for these cases shows (Figure 2), the floor reaction force must be found experimentally.

This was done with a strain gage instrumented force plate which produced the values for the components of the floor reaction force (F_X and F_Z) as the activity was performed.

This information was recorded continuously and synchronized with stroboscopic photographs of the subject (Figure 3). Thus values for the components of the floor reaction force could be correlated to various positions of flexion during the activity.

The values for the moment arm about point A (C_Z and C_X) and the angle with the horizontal (see Figure 2) were measured from the stroboscopic photographs. All these values were measured with a corresponding range of error, which was carried over into the calculation. All other quantities were determined as in the previous case.

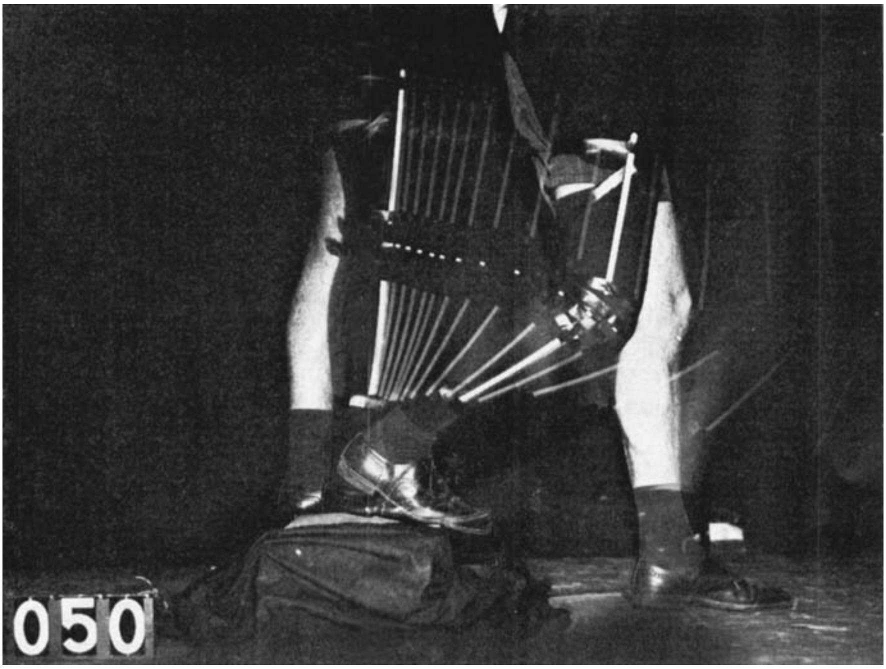

Figure 2. Picture of the stroboscopic photograph of the subject descending a step. The picture with the reflective targets allows scaling of the distances, measurement of the linear and angular displacements and this information is synchronized with the continuous force plate readings of the vertical and forward component of the floor reaction force.

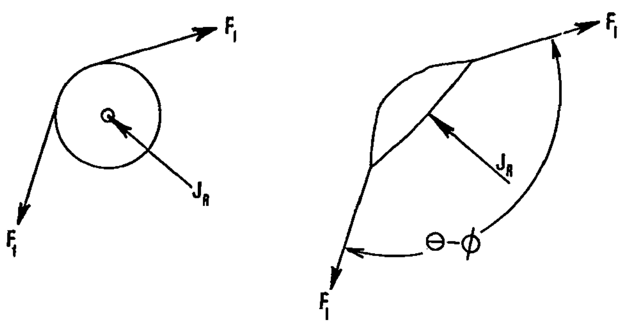

Figure 3. The patello-femoral joint reaction force (PFJR) is the force which must equilibrate the patella and it is equal and opposite to the resultant of the patellar tendon and quadriceps force. The PFJR is changing with the angle of knee flexion and magnitude of the quadriceps force.

The sum of the moments about point A is:

$$\Sigma M_A = F_1 d \cos|\Phi| + W_1 C_1 \sin \delta F R_z C_Z + F_{R_x} C_X$$

Setting this equal to zero and solving for the patellar tendon force, the equation becomes:

$$F_1 = \frac{1}{d \cos|\Phi|}\left(F_{R_z} C_Z - F_{R_x} C_X - W_1 C_1 \sin \delta\right)$$

The values for the QF (quadriceps force) during level walking were taken from Morrison (1967). With the patellar tendon force calculated for all cases, the patello-femoral joint reaction (PFJR) force can be determined in the following manner. Due to the low friction coefficient of cartilage, the patellar tendon force can be assumed to be equal in magnitude to the quadriceps force (QF). If the quadriceps force (QF) is assumed to act parallel to the shaft of the femur, the angle between the patellar tendon force and the quadriceps force (QF) is equal to $(\theta - \Phi)$.

The PFJR force is the force which must equilibrate the patella just as in the case of the frictionless pulley (Figure 4). The resultant of the patellar tendon force and the quadriceps muscle force must be equal and opposite to the PFJR force.

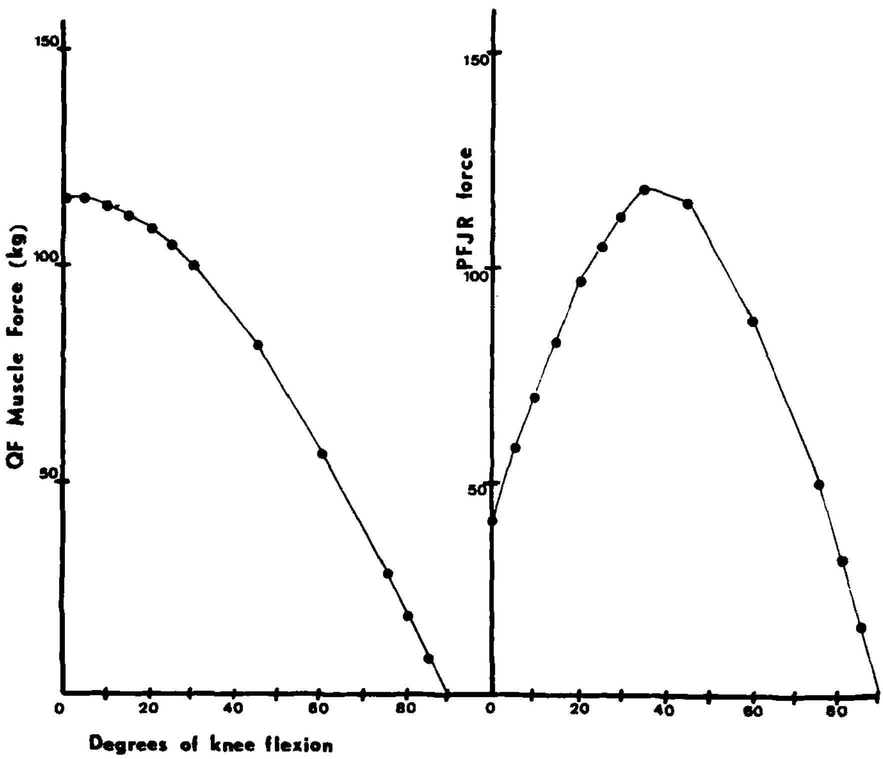

Figure 4. Quadriceps exercise against resistance (9 kg boof).

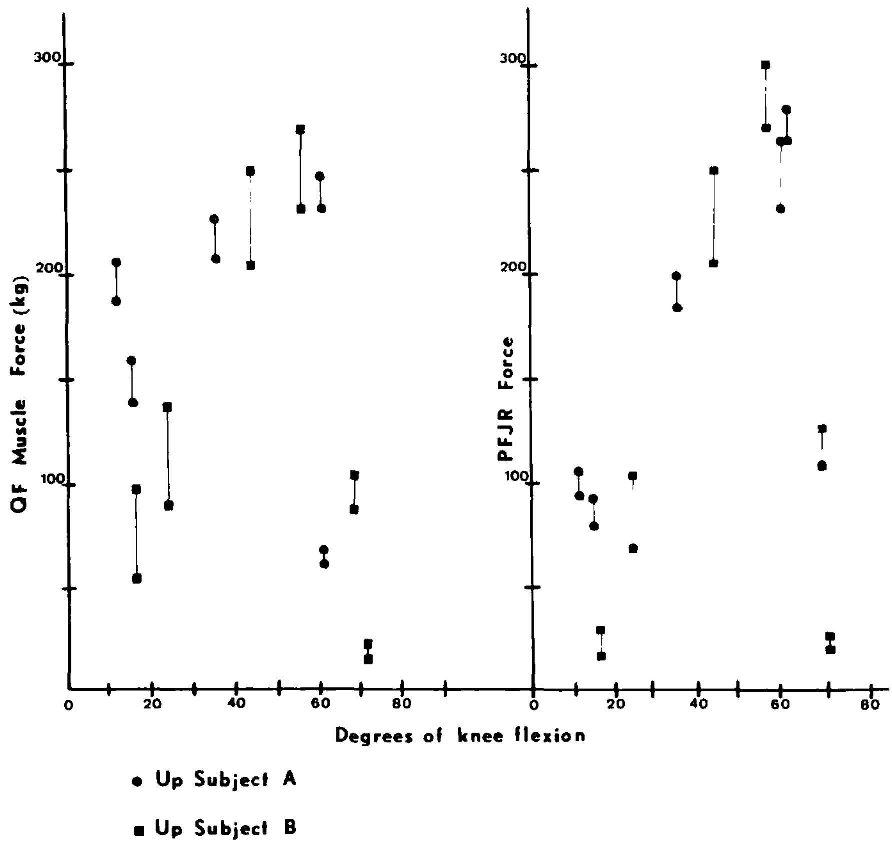

Figure 5 A. Climbing a step (height 20 cm).

The PFJR force (J_R) is calculated by:

$$J_R = 2F_1 \left(\cos \frac{\theta - \Phi}{2} \right)$$

The actual PFJR force is distributed over the contact surfaces of the patello-femoral joint. The force calculated above represents the component of the resultant PFJR force in the plane of the tibial and femoral axes.

RESULTS AND CONCLUSIONS

The obtained results of this study give basic information with regard to the clinical symptoms where patients with derangements of the patello-femoral knee compartment are more disabled for climbing and descending stairs than in level walking. The difference in PFJR force for those activities is significant.

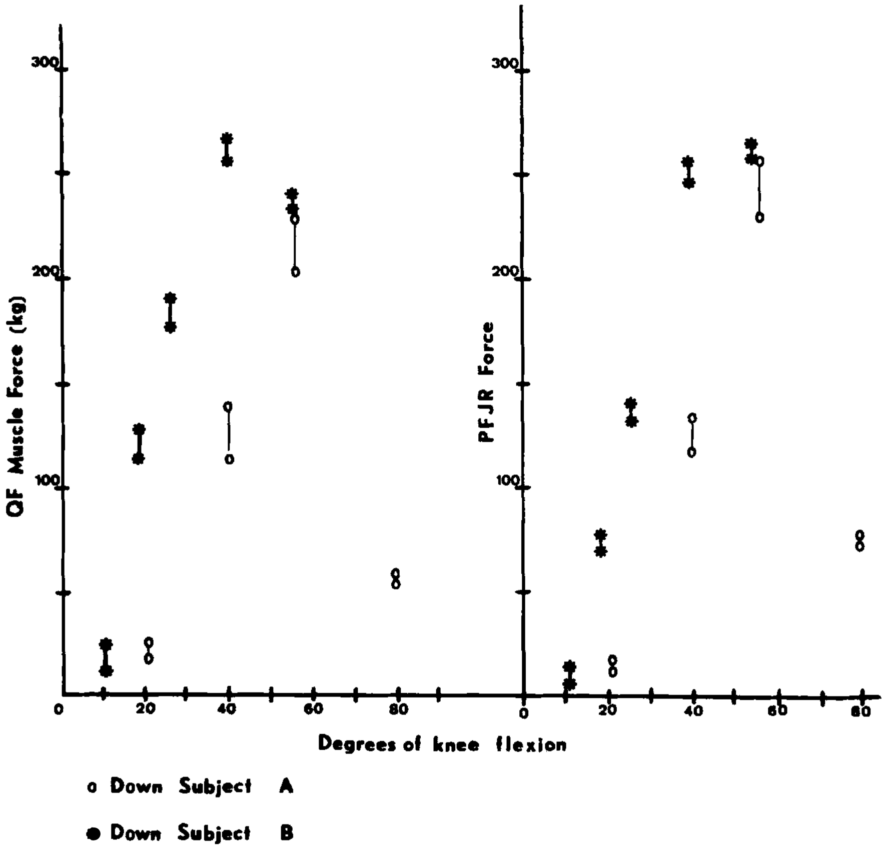

Figure 5 B. Descending a step (height 20 cm).

Figures 4 through 8 show the quadriceps muscle force and the patello-femoral joint reaction force plotted against angle of flexion for the various activities investigated. The ranges shown for the forces represent the influence that the errors in measurements (made from the stroboscopic photographs) have on the calculated values. No range is shown in Figure 4 for the leg raising exercise, since these results were obtained from the purely mathematical analysis explained earlier.

The lowest values for the QF force and the PFJR forces were obtained for level walking. This is to be expected since an efficient mechanism for walking would be developed so as to minimize energy expenditure and the forces that the skeletal structure would have to bear.

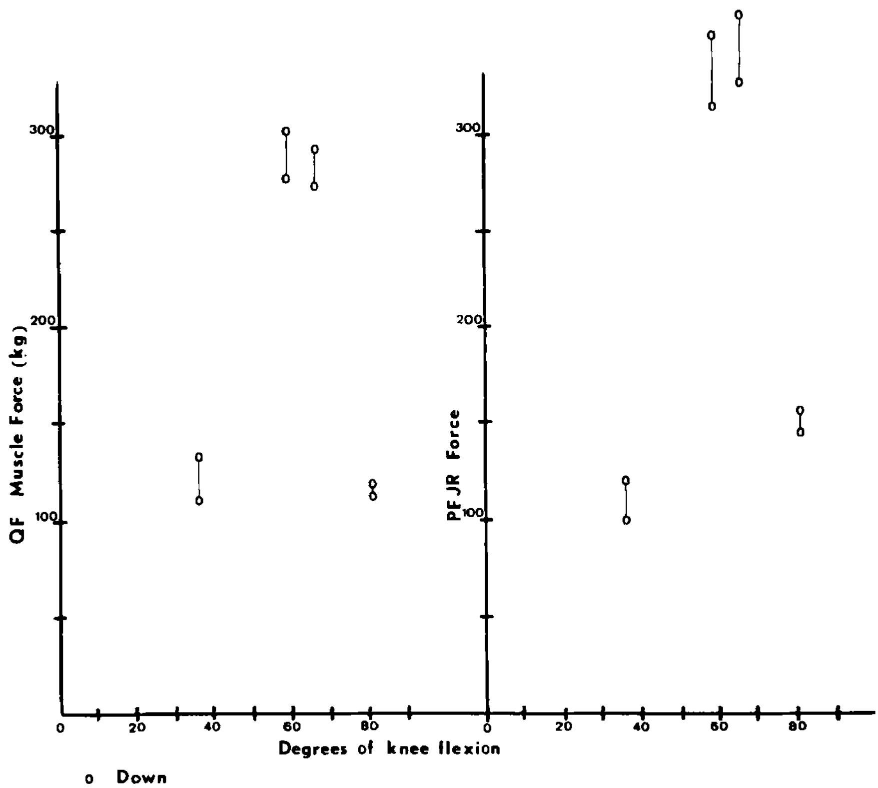

Figure 6. Descending a step (height 40 cm).

The patello-femoral joint reaction force has a different pattern and different values during level walking than the tibio-femoral joint reaction force.

Morrison (1967) obtained in his experiments a mean peak value of 3.4 body weight for the tibio-femoral joint reaction force during level walking.

We calculated as the highest value for the PFJR force 35 kg or 0.5 body weight. The patello-femoral joint reaction force is not only dependent upon the quadriceps muscle force, but also upon the angle of knee flexion (Figure 3). Since the angles of flexion are kept quite low during the activity, the PFJR force is always smaller than the QF muscle force.

The opposite is true for an activity during which the knee is flexed to larger angles, such as deep knee bends.

Here, the larger angles of flexion yield a higher value for the vector

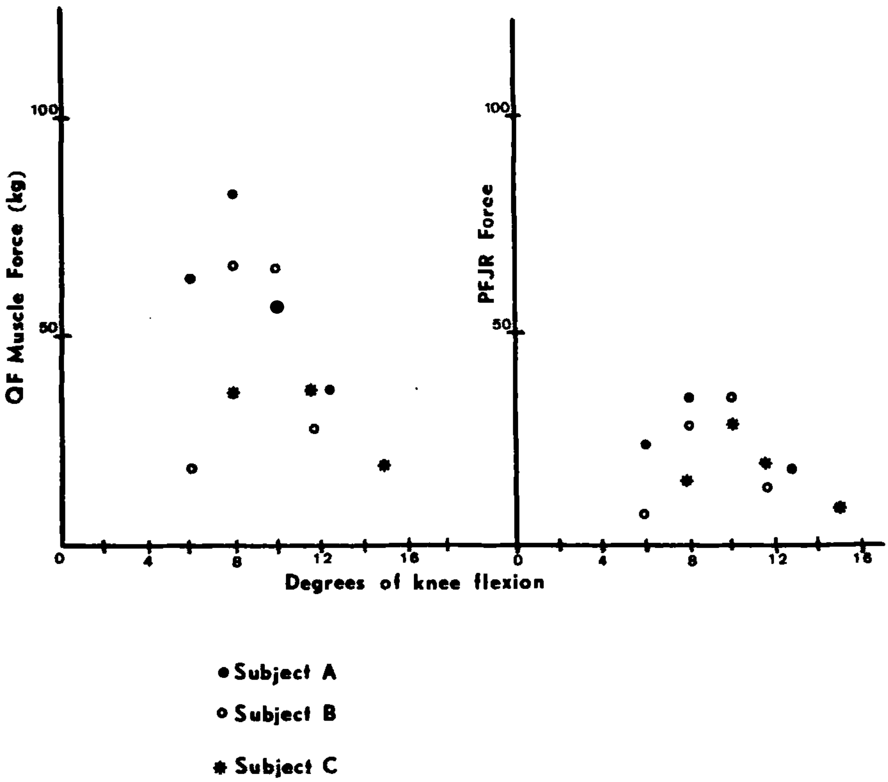

Figure 7. Level walking.

sum of the QF force and the patellar tendon force, which the PFJR force must equilibrate. The maximum value calculated for the PFJR force during this activity was 650 kg. The subject's body weight was 85 kg and this joint reaction force represents a force which is 7.6 times body weight.

For the stair climbing and descending activities the PF reaction force attained a level of 3.3 body weight. This value is almost seven times the PF joint reaction force obtained during level walking. This figure gives the explanation why the patients with patello-femoral joint derangements experience more pain while climbing and descending stairs. Patients with PF joint derangements adapt their gait pattern in stair walking by assisting with the uninvolved side in order to decrease the muscle force. The push-off with the unaffected leg helps considerably in decreasing the muscle force when climbing stairs.

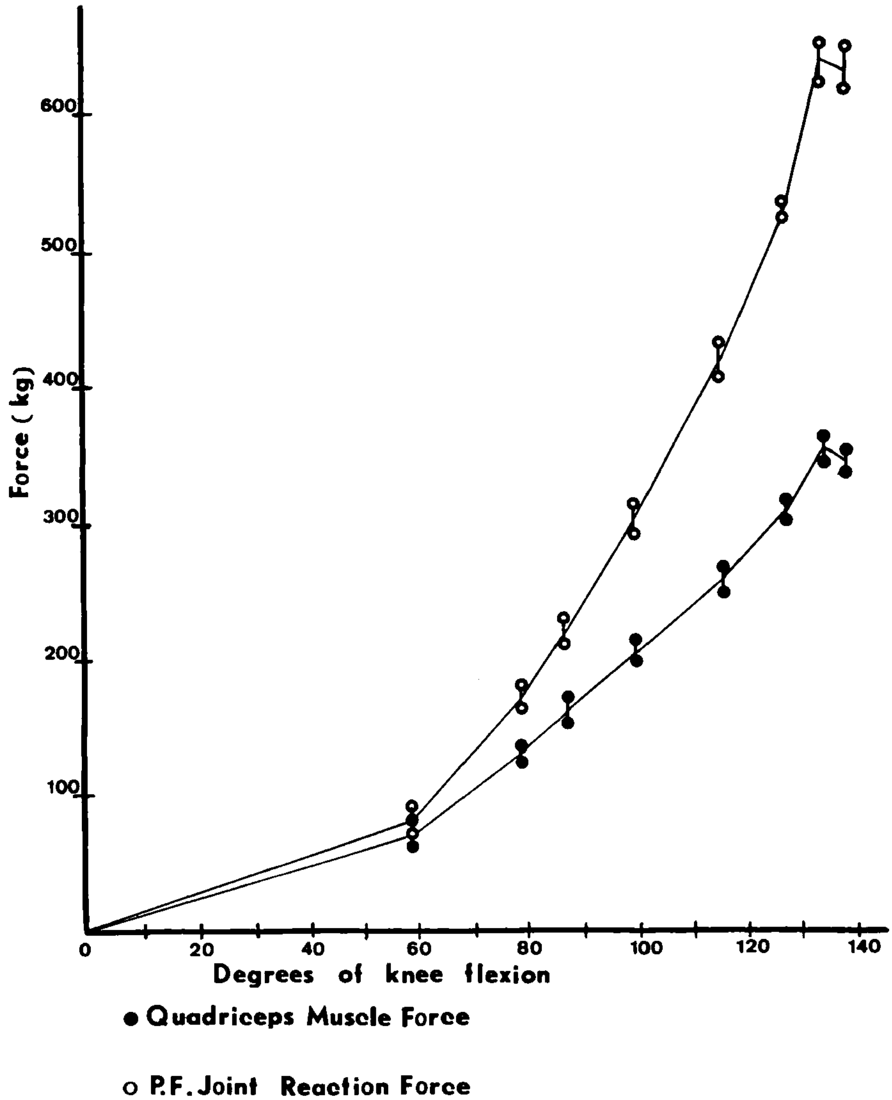

Figure 8. Deep knee bending.

The patients with derangements of the patello-femoral joint have most difficulties while descending stairs, because the only effective adaptation in order to prevent high PFJR forces is a lowering of the body with a controlled knee flexion at the unaffected side while keeping the involved knee straight.

When these patients are treated conservatively with quadriceps exercises against resistance, by extending the knee from 90° to full extension with a lead boot, most of them are unable to accomplish this exercise because of retropatellar pain. They are able, however, to do straight leg raising against the same resistance.

The explanation is given in Figure 4 where a maximum PFJR force of 1.4 body weight is found at 36 degrees of knee flexion when using a 9 kg boot.

If a heavier boot is used, the general shape of the curve obtained remains the same, while the force dimension is proportionally scaled upwards.

Figure 4 also illustrates that the PFJR can be kept at a significantly lower level by doing the straight leg raising exercise.

When the knee is extended, the line of action of the patellar ligament and quadriceps muscle forces are almost parallel, and because of the small angle between those two forces their vector sum represents a lower value.

SUMMARY

The quadriceps muscle force and patello-femoral joint reaction force were investigated for different activities.

A static situation of equilibrium was analysed, and the calculation was based upon a combination of a mathematical formulation with experimentally determined parameters, except in the leg raise exercise where a purely mathematical formulation was used.

The results demonstrate that:

1. The patello-femoral joint reaction force, depending not only upon the quadriceps muscle force but also upon the angle of knee flexion, is always smaller than the quadriceps muscle force during level walking, since the angle of flexion is kept low during this activity.

   The highest value calculated for the quadriceps force during level walking was 82 kg, and the highest value for the patello-femoral joint reaction force was 35 kg, or 0.5 body weight.
2. During stair walking the patello-femoral joint reaction force attained a level of 3.3 body weight or seven times the value of the PFJR force during level walking.

   Comparison of the values for PFJR force during level and stair walking explains why a patient with patello-femoral joint derangement is more disabled for stair walking.

3. Quadriceps exercises by extending the knee from 90° flexion against resistance with a 9 kg lead boot yield a PFJR force of 1.4 body weight at 36° of knee flexion. This explains why some patients with PF derangements complain of retropatellar pain during this exercise.

   The straight leg raising exercise against the same resistance results in a PFJR force at only 0.5 body weight so that they are able to accomplish this exercise.

REFERENCES

Drillis, R. & Contini, R. (1964) Body segment parameters. Technical Report No. 1166.03, New York University, N. Y.

Morrison, J. B. (1967) The forces transmitted by the human knee joint during activity. Thesis, University of Strathclyde, Scotland.

Shinno, N. (1968) Statico-dynamic analysis of movement of the knee. *Biomechanics, first international seminar,* Zurich, pp. 228–237. Krager, Basel.

Steindler, A. (1964) *Kineseology of the human body.* Charles C. Thomas, Springfield.

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