Early Quadriceps Strength Loss After Total Knee Arthroplasty

The Contributions of Muscle Atrophy and Failure of Voluntary Muscle Activation

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Background: While total knee arthroplasty reduces pain and provides a functional range of motion of the knee, quadriceps weakness and reduced functional capacity typically are still present one year after surgery. The purpose of the present investigation was to determine the role of failure of voluntary muscle activation and muscle atrophy in the early loss of quadriceps strength after surgery.

Methods: Twenty patients with unilateral knee osteoarthritis were tested an average of ten days before and twenty-seven days after primary total knee arthroplasty. Quadriceps strength and voluntary muscle activation were measured with use of a burst-superimposition technique in which a supramaximal burst of electrical stimulation is superimposed on a maximum voluntary isometric contraction. Maximal quadriceps cross-sectional area was assessed with use of magnetic resonance imaging.

Results: Postoperatively, quadriceps strength was decreased by 62%, voluntary activation was decreased by 17%, and maximal cross-sectional area was decreased by 10% in comparison with the preoperative values; these differences were significant ($p < 0.01$). Collectively, failure of voluntary muscle activation and atrophy explained 85% of the loss of quadriceps strength ($p < 0.001$). Multiple linear regression analysis revealed that failure of voluntary activation contributed nearly twice as much as atrophy did to the loss of quadriceps strength. The severity of knee pain with muscle contraction did not change significantly compared with the preoperative level ($p = 0.31$). Changes in knee pain during strength-testing did not account for a significant amount of the change in voluntary activation ($p = 0.14$).

Conclusions: Patients who are managed with total knee arthroplasty have profound impairment of quadriceps strength one month after surgery. This impairment is predominantly due to failure of voluntary muscle activation, and it is also influenced, to a lesser degree, by muscle atrophy. Knee pain with muscle contraction played a surprisingly small role in the reduction of muscle activation.

Level of Evidence: Prognostic Level I. See Instructions to Authors for a complete description of levels of evidence.

Total knee arthroplasty successfully reduces pain and provides a functional range of motion for patients with severe knee osteoarthritis[1-3]. Despite these positive outcomes, walking and stair-climbing speeds have been reported to be as much as 50% below those of age-matched controls at one year after surgery[4]. Quadriceps weakness has been reported at the time of long-term postoperative assessment[3-6] and has been correlated with disability in individuals with knee osteoarthritis[7-9]. Quadriceps weakness may be a factor that propagates continued functional limitations after total knee arthroplasty.

Despite its potential impact on functional outcome, quadriceps strength is not typically assessed in studies of the postoperative results of total knee arthroplasty. Investigations of acute postoperative changes are particularly rare, but the existing evidence suggests that patients lose approximately half of their preoperative quadriceps strength in the first month after surgery[10,11]. Perhaps the most commonly held belief as to why patients are weak early after surgery is that the pain associated with surgical trauma evokes failure of voluntary muscle activation, also known as muscle inhibition. Failure of voluntary muscle activation is a reduction in the maximal force output of a muscle resulting from an inability to recruit all of the muscle's motor units or to attain the maximal discharge rate from the motor units that are recruited[12]. The results of preliminary studies have confirmed that reduction in muscle activation contributes substantially to early postoperative weakness[10,11], but the contribution of a loss in muscle cross-sectional area to a loss in strength is unknown.

Understanding how atrophy and the failure of voluntary muscle activation contribute to quadriceps weakness following total knee arthroplasty is important when directing postoperative care. The purpose of the present study was to determine the role of failure of voluntary muscle activation and muscle atrophy in the early loss of quadriceps strength after surgery. We hypothesized that (1) voluntary activation, maximal cross-sectional area, and strength of the involved quadriceps muscle decrease substantially after surgery, (2) changes in voluntary activation and cross-sectional area account for a majority of the loss of strength, (3) the change in muscle activation accounts for more of the loss of quadriceps strength than does the change in muscular cross-sectional area, and (4) a worsening of knee pain compared with the preoperative level accounts for a considerable portion of the worsening of voluntary activation after surgery.

Materials and Methods

Subjects

This prospective study included a total of twenty subjects (eight women and twelve men) who were scheduled to undergo primary unilateral total knee arthroplasty for the treatment of knee osteoarthritis. All subjects underwent tricompartmental total knee arthroplasty with cement fixation through a medial parapatellar surgical approach. All of the operations were performed by experienced surgeons who extended the proximal incision into the quadriceps tendon. Potential subjects were excluded from the study if they were considered to be morbidly obese (that is, if they had a body-mass index [calculated as the weight in kg divided by the height in meters squared] of >40) or if they had been diagnosed with uncontrolled blood pressure, diabetes mellitus, neoplasms, or neurological disorders (e.g., Parkinson disease or stroke). Subjects who had substantial impairment in any of the other lower-extremity joints were also excluded. The average age was 62 ± 8 years (range, fifty-two to eighty-two years), and the average body-mass index was 31 ± 5 kg/m^2 (range, 22 to 40 kg/m^2).

Postoperatively, all subjects underwent standardized inpatient and home-therapy protocols before testing and were functioning clinically as expected. The average maximal active knee flexion was 119° ± 13° (range, 95° to 141°) before surgery and 95° ± 14° (range, 75° to 121°) at the time of the follow-up test. The study was approved by the Human Subjects Review Board at the University of Delaware, and all subjects signed an informed consent form before participation.

Measurement of Quadriceps Strength and Voluntary Activation

Knee extensor strength and voluntary activation were assessed in all patients at an average of 10 ± 4 days (range, three to sixteen days) before and 27 ± 2 days (range, twenty-three to thirty-two days) after surgery. Measurement of maximal voluntary isometric contraction of the quadriceps muscle was assessed with use of a burst-superimposition technique, which was described in detail in a previous publication[11]. Subjects were seated in a dynamometer with the knee flexed to 75°. All

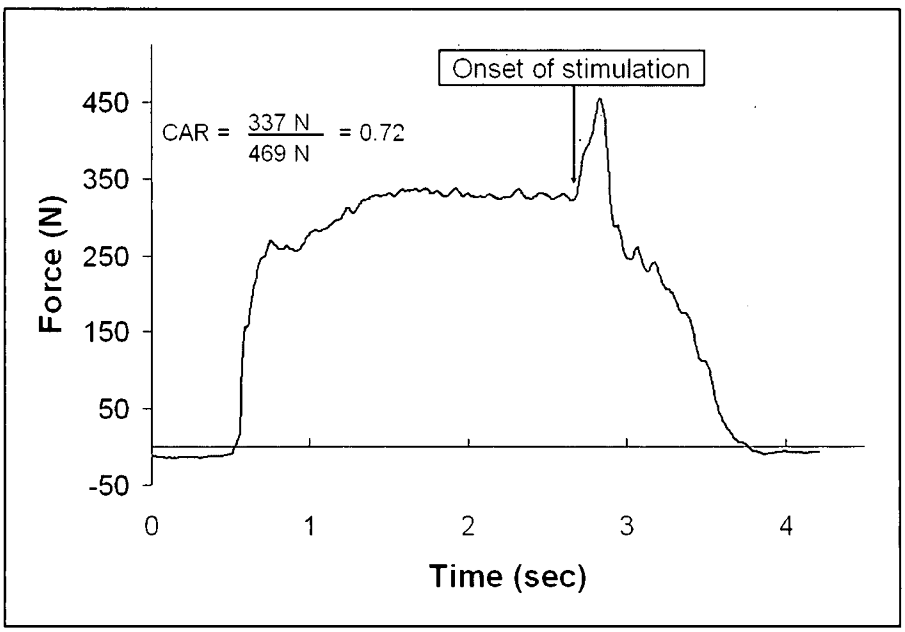

Fig. 1

A sample of quadriceps force production during a burst-superimposition test of a subject who was tested four weeks after total knee arthroplasty. CAR = central activation ratio.

subjects were able to achieve 75° of knee flexion without additional discomfort. Seat adjustments and transducer settings were recorded to allow for an identical setup for subsequent postoperative testing.

Each subject performed two submaximal contractions (perceived to be 50% to 75% of maximal effort) and one maximal voluntary contraction lasting two to three seconds each in order to warm-up the muscle and to gain familiarity with the testing procedure. After three minutes of rest, the subject was instructed to contract the quadriceps muscle maximally for approximately three seconds. Approximately two seconds into the contraction, a stimulator delivered a supramaximal burst of electrical stimulation through two electrodes that had been placed on the motor points of the quadriceps.

If maximal voluntary force output was achieved and no augmentation of force was observed in association with the stimulation (that is, there was optimal muscle recruitment), then the testing session was concluded for that limb. If force augmentation was present during the application of the electrical stimulus, the test was repeated. Three minutes of rest were provided between contractions in an effort to minimize fatigue. A maximum of three trials was recorded. The trial with the highest volitional force achieved during the three attempts was used for analysis.

The extent of voluntary activation of the quadriceps muscle was quantified with use of the central activation ratio described by Kent-Braun and Le Blanc[12]. The central activation ratio is calculated by dividing the maximal volitional force by the maximal force produced by the combination of volitional effort and the superimposed burst (Fig. 1). A central activation ratio of 1.0 indicates complete activation of the muscle, with no augmentation of the maximal volitional force being observed during the electrical stimulation.

Measurement of Knee Pain

A numeric rating scale was used to quantify knee pain during burst-superimposition testing. Subjects were asked to verbally rate the pain in and around the knee during the burst-superimposition test on a scale from 0 to 10, with 0 representing no pain and 10 representing the worst pain imaginable. The knee pain rating that was assigned during the attempt that produced the greatest force was used for analysis.

Health-Status Questionnaires

Health-status questionnaires were completed by all subjects at the time of the strength assessment and included the Medical Outcomes Survey Short Form 36 (SF-36)[13] and the Activities of Daily Living Scale of the Knee Outcome Survey[14]. The Activities of Daily Living Scale of the Knee Outcome Survey is a fourteen-item scale designed to assess how knee symptoms and knee condition affect the ability to perform daily functions. Scores are presented as a percentage of the maximal

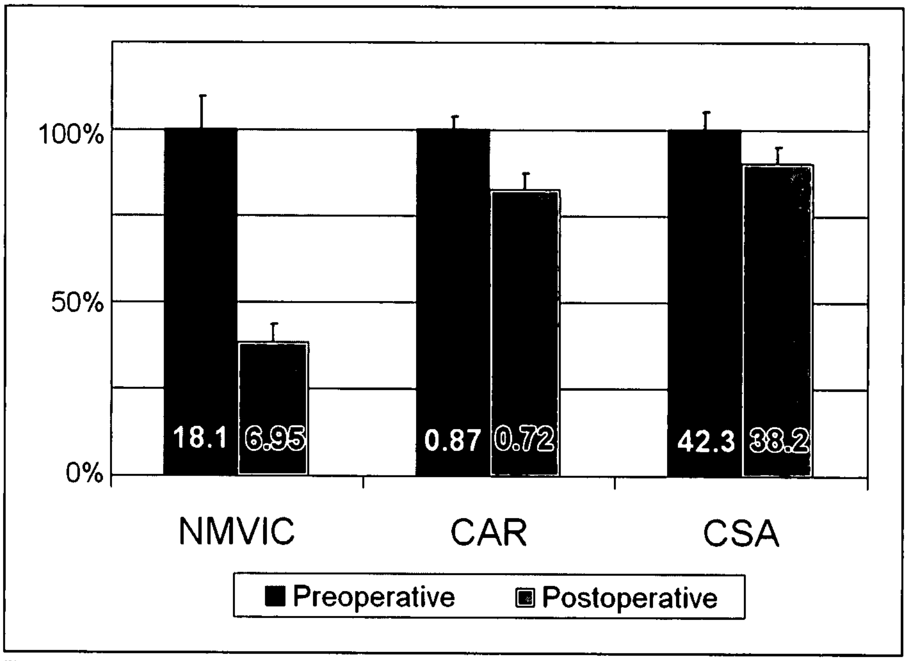

Fig. 2

Illustration showing the mean percent changes (and standard errors) in quadriceps strength, voluntary muscle activation, and maximal cross-sectional area, normalized to the initial condition. NMVIC = normalized force of maximal voluntary isometric contraction (calculated as the units of force, in Newtons, divided by body-mass index [weight in kg divided by the height in meters squared]). CAR = central activation ratio (with a value of 1.0 representing complete activation). CSA = maximal cross-sectional area (in centimeters squared).

score, with 100% representing full perceived knee function during activities of daily living.

Magnetic Resonance Imaging

Each subject underwent magnetic resonance imaging of the quadriceps muscle an average of 2 ± 2 days after both the preoperative and postoperative strength assessments. Three-dimensional images were acquired with a spoiled gradient-echo sequence (flip angle, 30°) with use of a body coil in a 1.5-T magnet (General Electric Medical Systems, Milwaukee, Wisconsin). Images were acquired with an encoding matrix of 256 × 256 × 28, a field of view of 24 cm, a pulse-repetition time of 31 ms, and an echo time of 10 ms. Seven-millimeter slices were acquired along the entire length of the thigh with use of chemically selective fat suppression to enhance the definition between muscles. The cross-sectional area of each individual knee extensor muscle was determined with use of a validated, custom-designed, interactive computer program that allows for correction of partial volume-filling effects[15]. Nonmuscular regions, such as subcutaneous fat, were excluded from these measurements. The sum total of each of the four muscles of the quadriceps provided an anatomical maximal cross-sectional area for each slice. The slice with the largest combined cross-sectional area was used for analysis. All cross-sectional area measurements were performed by one person who had a high intratester reliability for determining the maximum cross-sectional area, with an intraclass correlation coefficient (ICC [2,1]) of 0.97 (95% confidence interval, 0.94 to 0.99).

Data Management and Statistical Methods

All statistical analyses were performed with SPSS for Windows (Version 11.5.1; SPSS, Chicago, Illinois). The contribution of changes in voluntary activation and atrophy to the change in quadriceps strength was analyzed with use of multiple linear regression analysis. The influence of knee pain during strength-testing on voluntary activation of the quadriceps was analyzed with use of linear regression analysis. The level of alpha was set at 0.05 for all regression analyses. Differences in the mean values between the preoperative and postoperative conditions were compared with use of paired t tests, with a Bonferroni correction for multiple corrections. An adjusted alpha level of 0.007 (determined by dividing the original alpha by the number of comparisons [i.e., 0.05/7]) was used to determine significance for all statistical tests performed to compare means.

Results

The average score on the Activities of Daily Living Scale of the Knee Outcome Survey was 50% ± 20% before surgery and 54% ± 17% one month after surgery (p = 0.33). Preoperatively, the average physical component and mental com-

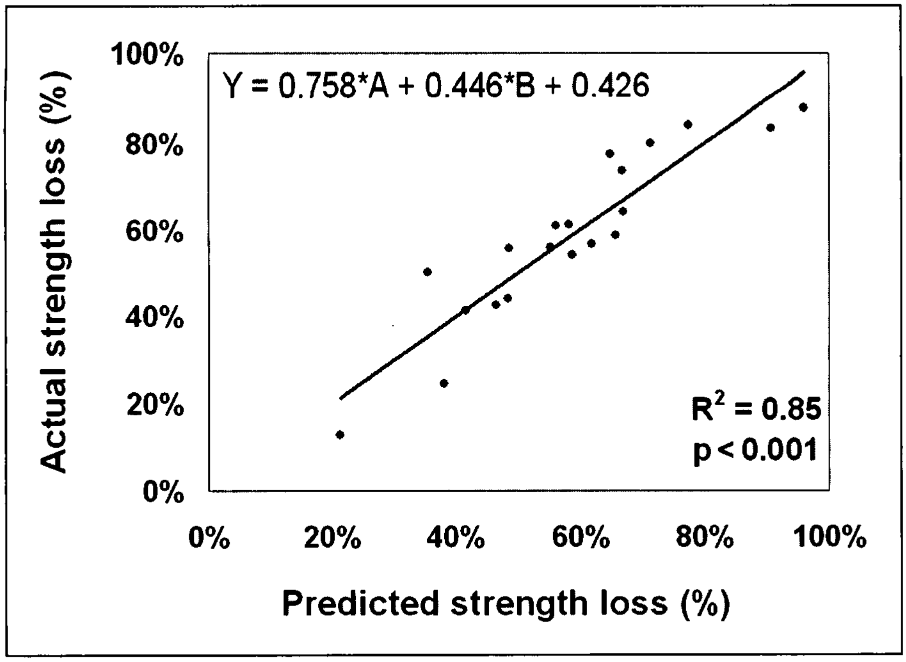

Fig. 3

Illustration depicting the results of multiple regression analysis of the relative contributions of loss of cross-sectional area and voluntary muscle activation to the change in strength. The relative change from the preoperative value to the postoperative value was quantified as a percentage of the preoperative value ([preoperative value – postoperative value]/preoperative value). Y = Predicted percent loss of quadriceps strength, A = percent loss in central activation ratio, and B = percent loss in cross-sectional area.

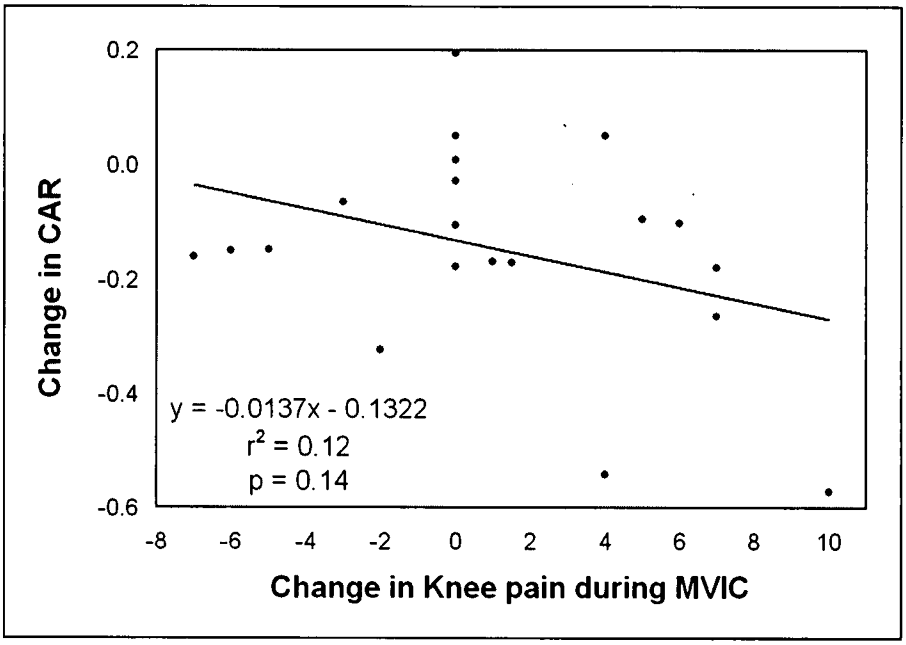

Fig. 4

Illustration depicting the results of linear regression analysis of the contribution of the change in knee pain during strength-testing to the change in voluntary activation of the quadriceps muscle. CAR = central activation ratio. MVIC = maximal voluntary isometric contraction. Change was determined by subtracting the preoperative value from the postoperative value. Negative values for the central activation ratio represent a reduction in voluntary activation of the muscle compared with the preoperative value. Negative values for knee pain represent a reduction in the knee pain associated with maximal voluntary isometric contraction compared with the preoperative value.

ponent summary scores of the SF-36 were 34 ± 11 and 58 ± 8, respectively. The postoperative physical component summary score (31 ± 9) was not significantly different from the preoperative score ($p = 0.42$), whereas the postoperative mental component summary score (52 ± 11) approached a significant decrease compared with the preoperative score ($p = 0.03$).

The quadriceps muscle of the involved limb was significantly weaker after surgery than it had been before surgery; specifically, the average normalized strength of the involved quadriceps muscle was decreased by 62% compared with the preoperative value ($p < 0.001$) (Fig. 2). In addition, the average voluntary muscle activation of the involved quadriceps was decreased by 17% compared with the preoperative value ($p = 0.002$) and the maximal cross-sectional area of the involved quadriceps was decreased by 10% compared with the preoperative value ($p = 0.004$).

Multiple regression analysis revealed that the percent change in voluntary muscle activation and the percent change in maximal cross-sectional area explained 85% of the relative change in quadriceps strength ($r^2 = 0.85$, $p < 0.001$) (Fig. 3). The relative contribution of the percent change in the central activation ratio was nearly twice the relative contribution of the percent change in maximal cross-sectional area in the regression equation that was used to predict the loss of quadriceps strength after total knee arthroplasty.

The postoperative score for knee pain with muscle contraction was not significantly different from the preoperative score (average, 3.6 ± 3.9 compared with 2.4 ± 3.0; $p = 0.31$). Knee pain with muscle contraction explained a small but significant portion of the variance in voluntary activation of the quadriceps at the time of the preoperative assessment ($r^2 = 0.29$, $p = 0.015$), but it did not have a significant effect at the time of the postoperative assessment ($r^2 = 0.20$, $p = 0.05$). The change in knee pain during muscle contraction between the preoperative and postoperative tests did not account for a significant amount of the change in voluntary muscle activation ($r^2 = 0.12$, $p = 0.14$) (Fig. 4). Half of the subjects reported no knee pain during the quadriceps strength test preoperatively, and the same proportion reported no knee pain during the same test postoperatively.

Discussion

We found that patients who had undergone total knee arthroplasty experienced a profound loss of quadriceps strength, marked failure of voluntary muscle activation, and a decrease in quadriceps cross-sectional area when evaluated one month after surgery. The loss of strength was largely explained by a combination of failure of voluntary muscle activation and atrophy. Failure of voluntary muscle activation explained much more of the strength loss than atrophy did;

however, the increased activation failure after total knee arthroplasty was not explained by increased pain.

The loss of >62% of the preoperative quadriceps strength was dramatic and closely matched the 60% loss of strength that we reported previously in a similar study involving a different group of patients[11]. Not only was the change in strength after surgery pronounced, but the preoperative quadriceps strength also appears to have been below normal. The preoperative force production reported in the present study (18.1 N of force/body-mass index) was 25% less than the force production reported for healthy older adults who were tested previously in our laboratory (24.2 N of force/body-mass index)[16,17].

Failure of voluntary muscle activation is likely to have contributed to the low preoperative quadriceps force production. The subjects in the present study had an average central activation ratio of 0.867 at the time of preoperative testing, whereas healthy older adults with no known knee abnormalities have been reported to have an average central activation ratio of 0.955[16,17]. Two recent studies involving the use of electrical burst-superimposition strength-testing showed that patients with less advanced knee osteoarthritis (grade-2 or 3 according to the scale of Kellgren and Lawrence[18]) did not have such a low level of voluntary muscle activation (as indicated by central activation ratios of 0.928[19] and 0.964[8]). Individuals who undergo total knee arthroplasty represent a population of patients who clearly have substantial deficits in voluntary muscle activation.

Not only was there considerable failure of voluntary muscle activation before surgery, but the degree to which it worsened was remarkable. In contrast, it has been previously reported that patients who had undergone anterior cruciate ligament reconstruction did not exhibit abnormal voluntary activation of the quadriceps muscle eight weeks after surgery[20]. Suter et al. reported an unexpected lack of worsening of voluntary muscle activation at six weeks in patients who had undergone arthroscopic surgery for the treatment of anterior knee pain[21]. A large reduction in voluntary activation following total knee arthroplasty bodes poorly for the recovery of strength as patients with large activation deficits have been reported to have negligible improvement in strength even after intensive rehabilitation[22].

Some improvement in voluntary muscle activation is expected during the subsequent recovery period, a point that was not addressed in this investigation. In fact, Berth et al., in a long-term follow-up study of patients managed with total knee arthroplasty, demonstrated that voluntary activation of the quadriceps improves over time[5]. Specifically, the level of voluntary activation of the quadriceps improved from 76% preoperatively to 85% at the time of the thirty-three month follow-up. While this improvement was substantial, the intervention of total knee arthroplasty did not result in resolution of activation impairments as the level of voluntary activation of the quadriceps remained much less than that in healthy controls at both testing times.

A relatively small cross-sectional area of the quadriceps at the time of the preoperative assessment also appears to have contributed to the overall reduction in knee extensor strength. The preoperative maximal cross-sectional area in the present study was much lower than the typical cross-sectional areas found in healthy older adults[23,24] and was slightly lower than the value found in individuals with less advanced osteoarthritis[25]. The change in maximal cross-sectional area was smaller than expected as the average knee extensor strength decreased to less than half of preoperative strength. To our knowledge, the only other investigation that has assessed acute changes in quadriceps cross-sectional area associated with total knee arthroplasty also demonstrated only a small amount of atrophy (a 5% reduction) compared with the preoperative assessment[10].

Unexpectedly, the change in knee pain did not account for a significant amount of the large reduction in voluntary activation of the quadriceps muscle. A similar moderate relationship between knee pain and muscle activation has been reported in previous investigations of patients managed with total knee arthroplasty[11,26]. Most of the activation failure does not appear to be due to knee pain during muscle contraction in this patient population. Assuming that muscle activation will improve as perioperative knee pain subsides, therefore, may not be valid.

In the present study, patients who had been managed with total knee arthroplasty had profound impairment in terms of quadriceps force-producing ability one month after surgery. Both failure of voluntary muscle activation and atrophy contributed to the strength loss; however, the major factor appeared to be failure of voluntary activation. Since activation failure was not strongly related to knee pain after surgery, pain control alone may be insufficient to prevent loss of strength. It appears that efforts that are taken specifically to address deficits in voluntary muscle activation in the early postoperative period may improve the outcome in terms of quadriceps strength. Exploring the use of exercise programs that encourage high-intensity muscle contractions and interventions that facilitate activation (e.g., biofeedback and neuromuscular electrical stimulation) appears to be warranted to counter the large deficit in quadriceps strength following total knee arthroplasty. ■

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