

# The Pathophysiology of Patellofemoral Pain

## *A Tissue Homeostasis Perspective*

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**Fundamental to rational, safe, and effective treatment for any orthopaedic condition is an accurate understanding of the etiology of the symptoms. The decades-old paradigm of a pure structural and biomechanical explanation for the genesis of patellofemoral pain is giving way to one in which biologic factors are being given more consideration. It is increasingly evident that a variable mosaic of possible pathophysiologic processes, often caused by simple overload, best accounts for the etiology of patellofemoral pain in most patients. Inflamed synovial lining and fat pad tissues, retinacular neuromas, increased intraosseous pressure, and increased osseous metabolic activity of the patella all have been documented as contributing to the perception of anterior knee pain. Considered together, these processes can be characterized as loss of tissue homeostasis and can be seen as providing a new and alternative explanation for the conundrum of anterior knee pain. Certain high loading conditions of the patellofemoral joint can be of sufficient magnitude to induce the symptomatic loss of tissue homeostasis so that, once initiated, they may persist indefinitely. From this new biologic perspective, it clinically matters little what structural factors may be present in a given joint (such as chondromalacia, patellar tilt or a Q angle above a certain value) if the pain free condition of tissue homeostasis is safely achieved and maintained.**

**Level of Evidence: Level V (expert opinion). See the Guidelines for Authors for a complete description of levels of evidence.**

Patients with symptoms of patellofemoral pain present one of the most substantial challenges to the diagnostic and therapeutic abilities of orthopaedic surgeons worldwide.

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The author certifies that he has no commercial associations (eg, consultancies, stock ownership, equity interest, patent/licensing arrangements, etc) that might pose a conflict of interest in connection with the submitted article.

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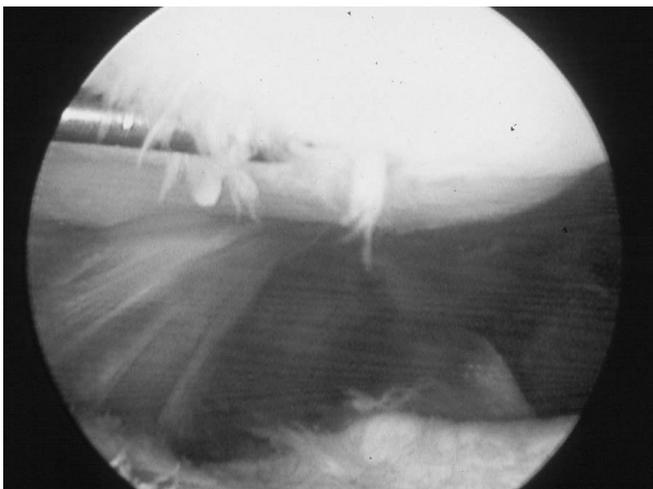
DOI: 10.1097/01.blo.0000172303.74414.7d

The patellofemoral joint often is viewed by physicians and patients as a deceptively simple musculoskeletal system that readily can be understood and that therapeutic decisions can be made by acquisition of data from current imaging techniques such as static (or even dynamic) radiography, computed tomography (CT), or magnetic resonance imaging (MRI). The treatment algorithms that follow from the nearly exclusive consideration of such structural data (including excessive use of the lateral retinacular release, aggressive chondroplasties, and proximal and distal realignments) unfortunately often have resulted in the worsening of the patient's symptoms.<sup>29</sup> The worst cases of patellofemoral pain, in my experience, are in those patients who have been subjected to such well-meaning but incomprehensively considered aggressive surgical procedures for symptoms that were initially only mild or intermittent in nature.<sup>17,18</sup>

At the beginning of the twenty-first century, the concept of the cause for anterior knee pain is shifting away from the long-held view of the supreme importance of certain structural characteristics (such as the presence of chondromalacia or a Q angle greater than a specific threshold number) to the consideration of pathophysiologic factors.<sup>3,9,10,12,22,46</sup> Pathophysiologic processes such as inflamed peripatellar synovial lining and fat pad tissues and increased osseous metabolic activity of patellar bone (similar to the early stages of a stress fracture) have been documented to be of etiologic importance in the genesis of patellofemoral pain,<sup>13,15,17,18</sup> whereas indicators of malalignment have not.<sup>42,51</sup> Furthermore, peripatellar soft tissue neuromas, unable to be clinically imaged by any current technology, have been shown in patients with symptoms of patellofemoral pain.<sup>23,46,47</sup> Considered together, these biologic phenomena can be characterized as loss of tissue homeostasis. A new perspective of the etiology of patellofemoral pain therefore has been developed that emphasizes the loss of tissue homeostasis of innervated musculoskeletal tissues as often being of greater importance than the presence of certain structural characteristics, such as chondromalacia of the patella.<sup>9,17,18</sup> For example, I have patellae that manifested advanced Grade III chondro-

malacic changes at arthroscopic inspection (in the presence of a normal Technetium 99m-MDP bone scan), but they were asymptomatic to direct probing without intra-articular anesthesia (Fig 1).<sup>19</sup> Classifications of chondromalacia are as follows: Grade I, articular cartilage softening; Grade II, fibrillation of less than ½ inch in diameter; Grade III, fibrillation of more than ½ inch in diameter; and Grade IV, erosion to bone.<sup>40</sup> However, even light touch of unanesthetized synovial lining and fat pad tissues resulted in the perception of exquisite and substantial patellofemoral pain (Fig 2). I also had the intraosseous pressure of my right patella measured experimentally through the placement of a 15-gauge Jamshidi needle (Bard, Inc., Murray Hill, NJ) with the use of local anesthetic in the skin and periosteous tissues of the medial facet.<sup>15</sup> With the sudden increase of intraosseous pressure caused by the injection of normal saline, I experienced transient, severe, lancinating patellar pain that resolved fully with decreasing pressures to normal range. Therefore, I have experienced directly the perception of anterior knee pain with the experimental induction of increased intraosseous pressure of the patella—an event that confirms the long-held view that the intraosseous environment is well innervated and that increases in intraosseous pressure can cause the perception of substantial pain.

I will offer for consideration an alternative biologically oriented perspective of the genesis of patellofemoral pain as arising from the loss of tissue homeostasis of innervated components of the knee. Information will be provided that indicates this new perspective results in a more rational explanation for the etiology of anterior knee pain and also leads to therapeutic approaches that are inherently safer



**Fig 1.** Palpation of my right patella without intra-articular anesthesia is shown. Despite the documented presence of advanced chondromalacia, I had no pain.



**Fig 2.** Palpation of the anterior peripatellar synovial lining of my right knee without intra-articular anesthesia is shown. I had excruciating pain with even light touch of the synovial tissues.

than those which follow from the more traditional structural view.

### Tissue Homeostasis

The concept of tissue homeostasis may be new to the reader. Homeostasis is a term used by physiologists to mean active maintenance of constant conditions in the internal environment.<sup>26</sup> The more familiar concept of humeral homeostasis reflects the maintenance of a constant level of chemical factors in fluids such as serum ionic calcium or blood glucose within a certain range and certain biochemical markers in synovial fluid. Tissue homeostasis encompasses the more complex biologic phenomenon of normal physiologic processes of volumes of living cells. All living musculoskeletal structures are composed of cells that normally are metabolically active, with continuous physiologic maintenance of tissues at the molecular level. A single loading event of sufficient magnitude or a series of repetitive loading events of a lesser magnitude can cause an injury inducing a cascade of reparative biochemical processes which reflect a loss, at least temporarily, of normal tissue homeostasis.<sup>18</sup> Currently, the tissue whose property of homeostasis is most readily imaged is that of living bone. The technique of Technetium-99m-MDP scintigraphy allows one sensitively to manifest the metabolic and geographic characteristics of bone homeostasis, and therefore currently represents a window into the overall metabolic status of a living joint.<sup>15</sup> Unlike the structural imaging modalities of radiographs, CT, and even MRI (which at present cannot readily distinguish between dead and living joints),<sup>38</sup> technetium scintigraphy requires a liv-

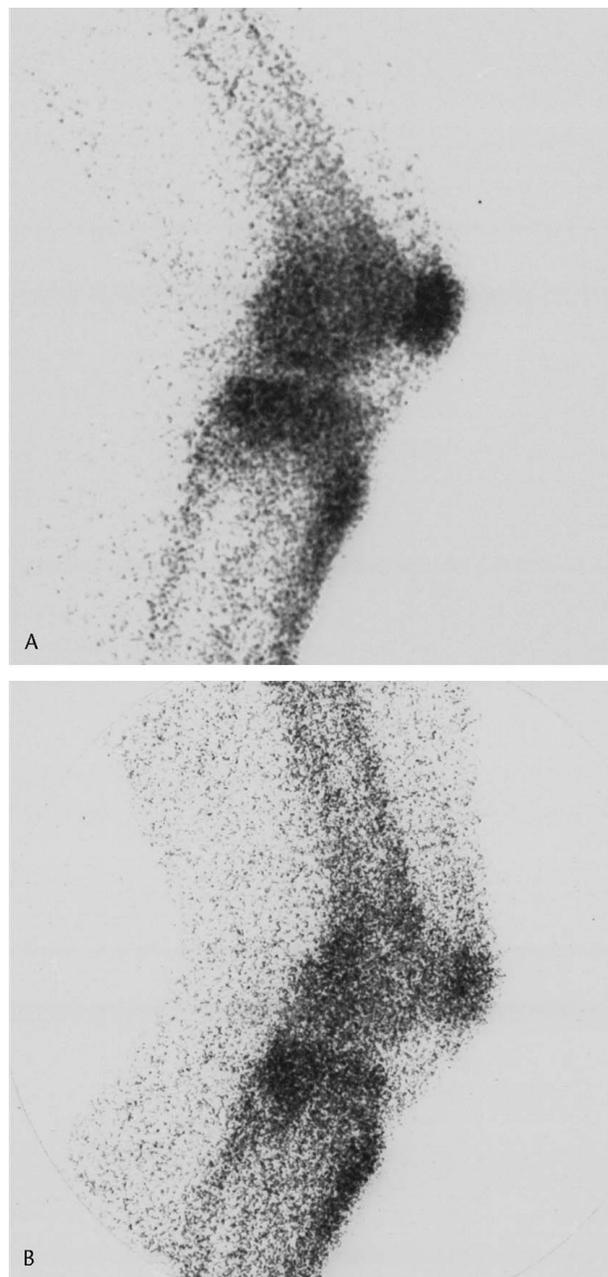
ing, metabolically active system. Currently, there is no easily obtainable soft tissue equivalent scan (short of positron emission tomography) that can provide similar geographical metabolic data.

The relationship of an abnormally increased technetium bone scan of the patellofemoral joint to anterior knee pain and the association of restoration to normalcy of the bone scan with resolution of patellofemoral pain symptoms, often after nonoperative treatment measures, have been documented (Fig 3).<sup>13,16</sup> The dynamic character of osseous homeostasis as manifested by sequential technetium bone scintigraphy provides a more rational explanation for the presence or absence of patellofemoral pain than do the often stated and overemphasized structural characteristics such as chondromalacia of the patella and Q angle—characteristics that remain unchanged after a successful nonoperative treatment program.

As noted previously, loss of tissue homeostasis that can account for the symptoms of anterior knee pain is not limited to osseous components. The peripatellar soft tissues also potentially contribute to the genesis of patellofemoral pain, particularly the peripatellar synovial lining and fat pad structures.<sup>2,17,18</sup> These tissues are in intimate contact with the patellofemoral joint and are highly innervated.<sup>55</sup> Any patellofemoral structure that possesses a sensory nerve supply (essentially all, with the exception of articular cartilage) can be a potential source of nociceptive output, and therefore can result in a patient's subjective perception of anterior knee pain.<sup>1</sup> Any combination of innervated tissues can be involved concurrently in the genesis of patellofemoral pain at any given moment. Therefore a variable and changeable mosaic of patellar and peripatellar tissue pathophysiology (loss of tissue homeostasis) not necessarily able to be imaged by any current modality, may contribute to the perception of anterior knee pain on a given day.<sup>17</sup> Because the perception of pain ultimately and fundamentally is a function of complex central nervous system events, factors other than direct nociceptive output of innervated patellofemoral structures also can result in the perception of pain in the anterior aspect of the knee including pain referred from a hip with ipsilateral arthritis, saphenous nerve irritation, or even the dysesthetic "phantom limb" sensations of an individual with an above-the-knee amputation (see list of factors that induce patellofemoral nociceptive output; Table 1).<sup>9,12,18</sup>

### Role of Loading in Patellofemoral Pain

Despite the differing perspectives of the genesis of patellofemoral pain, from the more traditional structural view and the newer tissue homeostasis theory, both theories include the role of differential loading as an important factor. If one sustains a sufficiently great and sudden external loading event—such as a direct blow to the patella



**Fig 3A–B.** (A) A technetium bone scan of a 28-year-old man with anterior knee pain shows a diffusely positive bone scan. (B) A repeat technetium bone scan of the same patient 4 months later after resolution of symptoms with a conservative treatment program involving rest, a nonsteroidal anti-inflammatory medication, and gentle rehabilitation, manifesting restoration of osseous homeostasis is shown.

associated with a fall onto the pavement—an overt structural failure of patellar bone (fracture) may result, which can be the source of substantial pain. Similarly, a direct external blow of a lesser magnitude, such as sustained with

**TABLE 1. Factors Inducing Patellofemoral Nociceptive Output**

Mechanical environment
Direct patello femoral trauma
Excessive intrinsic compressive and tensile forces
Normal alignment
Malalignment (load shifting)
Impingement of intra-articular structures
Increased intraosseous pressure
Barometric pressure changes
Chemical environment
Presence of cytokines
Altered pH of damaged tissues
Localized peripheral neuropathy
Painful neuroma
Nonpatellofemoral sources
Referred pain (such as hip arthrosis)
Phantom limb pain in above-the-knee amputee

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a dashboard injury—without an overt radiographically identifiable fracture—also can cause the sudden onset of pain that may persist for an extended time. Certain activities that highly load the patellofemoral joint also are well recognized as being associated with the initiation and persistence of anterior knee pain, such as climbing up or down stairs, hills or inclines, sitting in and rising from chairs, and with kneeling or squatting. Furthermore, the phenomenon of deep aching pain associated with prolonged flexion of the knee—the so-called movie or theater sign<sup>35</sup>—is recognized as a clinical complaint in many patients. Often these symptoms of aching of the anterior aspect of the knee resolve rather quickly by merely straightening the joint or walking.

A wide range of patellofemoral loading activities (eg, climbing up or down stairs, squatting, kneeling, prolonged flexion) are well recognized as potential factors in the genesis of pain. How are these well-known phenomena explained by the tissue homeostasis perspective? The patellofemoral joint is considered to be the one of the highest loaded musculoskeletal components in the human body<sup>7</sup> and therefore is one of the most difficult musculoskeletal systems in which to restore functionality after injury and subsequent loss of tissue homeostasis.<sup>11</sup> The actual stress experienced by any given patellofemoral joint at any given moment is caused by the load applied and the surface area of the area of the patella and femur that are in contact. Estimates of the joint reaction forces that are created within the patellofemoral joint, in compression and tension with normal activities of daily living, are on the order of multiples of body weight.<sup>31</sup> These high loads have been estimated from 3.3 times body weight with activities such as climbing up or down stairs, to 7.6<sup>45</sup> times body weight

with squatting, and up to 20 times or more body weight with jumping activities.<sup>49</sup> As noted above, the actual stresses generated within living patellofemoral joints depends also on the surface areas of the patella and femur that may be in contact at any given moment, as well as the load applied. Such high forces readily can result in loads that may exceed the safe load acceptance capacity of musculoskeletal tissues, leading to symptomatic damage and the induction of a mosaic of pathophysiologic processes causing patellofemoral pain. A new method of conceptualizing the loading conditions across the knee and the relationship of loading to tissue homeostasis developed by this author is termed the envelope of function,<sup>8</sup> a concept that will be discussed further in the next section.

### Knee as Biologic Transmission

The knee functions as a type of biologic transmission whose purpose is to accept, to redirect, and ultimately to dissipate loads between its various components.<sup>8</sup> The ligaments in this analogy can be seen as nonrigid, sensate, adaptive linkages and the menisci can be seen as mobile sensate bearings within this living, self-maintaining, self-repairing, transmission. The patellofemoral joint can be viewed as a large slide bearing within the transmission that often is exposed to high forces. The muscles in this analogy act in concentric contraction as cellular engines that provide motive forces across the knee, and in eccentric contraction, as brakes and dampening systems absorbing shock loads. It has been estimated that nearly four times the energy is absorbed in eccentric contraction and deceleration than are created in motive forces with concentric contraction across the knee.<sup>54</sup>

### Envelope of Function

The function of a mechanical transmission is defined by the torque (a rotational force usually expressed in foot pounds) that can be safely withstood and transmitted by that system without damage. This range of torque can be described as the torque envelope for that system. The human knee, of course, is evolutionarily an ancient biomechanical design<sup>6</sup> with no direct morphologic similarity to transmissions of modern motor vehicles. However, both can be observed as systems designed to accept, transfer and dissipate a range of (mechanical) energy in the case of a vehicular transmission and (biomechanical) energy in the case of a living human knee. The capacity of the knee in a live person (and by extension, all diarthrodial joints) to safely accept and transfer a range of loads can be described by the envelope of function—or that range of loading applied across the joint that is compatible with and probably inductive of maintenance of tissue homeostasis (Fig 4A).<sup>8</sup> If a sufficiently diminished load is placed across a joint for

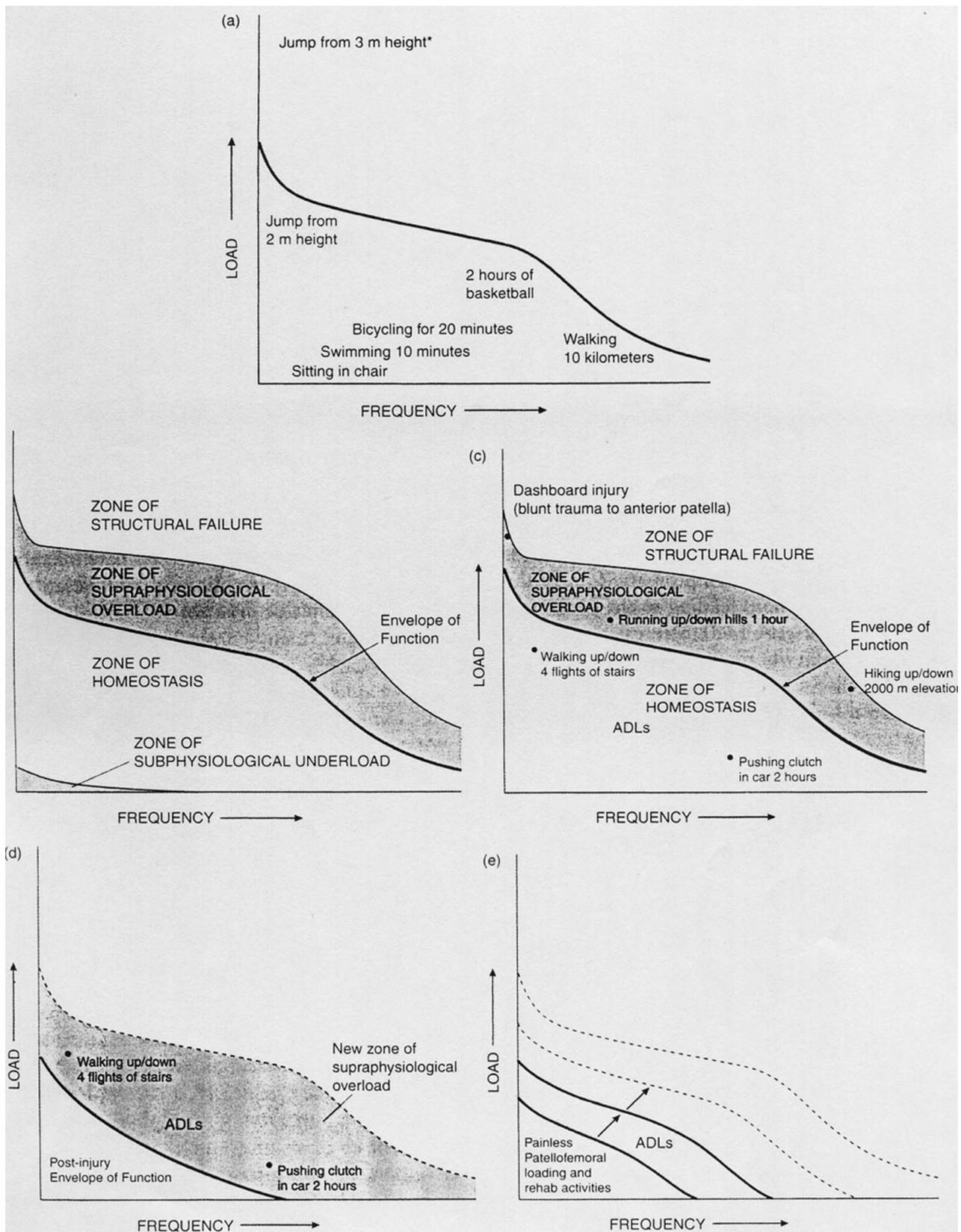


Fig 4A-E. Legend on following page.

a lengthy period of time (such as with prolonged bed rest or extended space travel in a microgravity environment), loss of tissue homeostasis manifested by muscle atrophy and calcium loss from bone secondary to disuse can ensue. This region of diminished loading is termed the zone of subphysiologic underload (Fig 4B).

Most uninjured joints can accept a broad range of loading (from less than 1 to nearly 8 times body weight)<sup>45,49</sup> and still maintain tissue homeostasis. This range of load acceptance is called the zone of homeostatic loading, the outer limits of which are defined by the envelope of function. If one places an increased load across the knee through, for example, the repetitive loading involved in distance running—loss of osseous and periosseous soft tissue homeostasis can result, characterized by the early stages of a stress fracture or stress reaction. This region of increased loading, insufficient to cause immediate overt structural damage, is termed the zone of supraphysiologic overload. A dashboard injury to a flexed knee insufficient to cause an overt fracture also would be considered as representing a load within the zone of supraphysiologic overload. If even greater energy is placed across a knee (load and frequency are equivalent energy imparted to a joint) overt macrostructural damage, such as acute fracture of bone or rupture of a ligament can occur, and is termed the zone of macrostructural failure.

The perception of musculoskeletal pain is an evolutionarily designed phenomenon that functions as a type of negative feedback-loop system alerting the central processor (central nervous system) of conditions, which if left unchanged, would result in damage.<sup>19</sup> The perception of patellofemoral pain with certain loading activities can therefore be viewed as an overt biologic indicator that the joint is being loaded out of its envelope of function. Degradation of the normal protective sensory mechanisms of the knee can lead to structural failure of intra-articular components with inadvertent excessive loading, as is seen

in neuropathic joints associated with various diseases<sup>4,37</sup> or in people born with congenital insensitivity to pain.<sup>5,30</sup>

The recognized phenomenon of anterior knee pain with prolonged flexion—the movie sign—deserves special comment. Although a relatively short period of apparent nonfunctional loading would seem to be a benign biomechanical event—and therefore at odds with the envelope of function theory—at least two possible factors may provide a rational explanation. Swollen, inflamed peripatellar soft tissues may be mechanically impinged and irritated by the relative position of the patella and femur with high degrees of increasing flexion causing anterior knee discomfort in some patients. Furthermore, transient increases in intraosseous pressure may occur with increasing degrees of flexion and decrease with extension, resulting in the perceived anterior knee discomfort of the movie sign. A possible mechanism for the transient increased patellar intraosseous pressure may arise from force directed onto the anterior vascular ring sufficient to impede venous outflow, but not arterial inflow. A stiff sheet of fibrous tissue anatomically located just anterior to this vascular ring (the recently described intermediate oblique prepatellar aponeurosis)<sup>14,33</sup> may provide sufficient force in some individuals in high degrees of flexion to cause at least a partial venous outflow obstruction resulting in such transient, reversible increased intraosseous pressure.

The envelope of function represents the load acceptance capacity of the joint as a whole system and summarizes all the extant anatomic, kinematic, physiologic, and treatment factors that may be present for a given joint. Using the envelope of function, patients, physicians, and therapists easily can conceptualize the loading environment that may have induced the pathophysiology present in a given patient with patellofemoral pain and also better understand the types of loading that may allow for healing of the symptomatic joint (Figs 4C, D).<sup>9,10</sup> In my opinion, it is unreasonable to expect the restoration of tis-

**Fig 4A–E.** (A) A graph representing the envelope of function for an athletically active young adult is shown. The letters represent loads associated with different activities. All of the loading examples except B are within the envelope of function for this particular knee. The shape of the envelope of function represented here is an idealized theoretical model. The actual loads transmitted across an individual knee in these different conditions are variable and are caused by many complex factors, including the dynamic center of gravity, the rate of load application, and the angles of flexion and rotation. The limits of the envelope of function for the joint of an actual patient probably are more complex. (B) A graph shows the four different zones of loading across a joint. The area within the envelope of function is the zone of homeostasis. The region of loading greater than that within the envelope of function but insufficient to cause macrostructural damage is the zone of supraphysiologic overload. The region of loading great enough to cause macrostructural damage is the zone of structural failure. The region of decreased loading over time resulting in a loss of tissue homeostasis is the zone of subphysiologic underload. (C) Supraphysiologic loads outside the envelope are shown: a dashboard injury, running up hill for one hour, and hiking downhill 2000 meters. (D) Diminished envelope of function after supraphysiologic patellofemoral loading showing that activities of daily living and activities such as climbing four flights of stairs and pushing a clutch in a vehicle for 2 hours have become supraphysiologic loads, leading to recurrent loss of tissue homeostasis and continuance of peripatellar symptoms. (E) An incremental expansion of the diminished envelope of function by restricting patellofemoral loading to within the envelope is shown. Figure 4 is adapted with permission from Dye SF: The knee as a biologic transmission with an envelope of function. Clin Orthop 325:10-18, 1996.

sue homeostasis (healing) of a symptomatic patellofemoral joint with the associated resolution of pain, while the joint is being loaded out of its current envelope of function.

Often the simple but potent insight offered by the envelope of function is sufficient for patients to gain control of their symptoms. Very often, the mere act of decreasing loading to within a joint's current diminished envelope of function after a supraphysiologic loading event (either singly or repetitively) leads to resolution of pain and restoration of function and restoration of tissue homeostasis (Fig 4E). Such decreased loading can be as straightforward as decreasing the number of stairs a patient climbs in a day to that which is painless. Painlessness with a given loading activity followed by a second day without pain is a clinical definition of loading one's joint within its envelope of function. It is insufficient to be painless merely during a given activity, for often there is a lag time of 6 to 24 hours in the production of a post-traumatic cytokine flare<sup>34</sup> that can result in the induction of symptoms of pain later on in that same day or the next.

### Clinical Application of a Tissue Homeostasis Perspective

My approach to the initial treatment of patients with patellofemoral pain, including those with established patellofemoral arthritis (in addition to a complete physical examination), is to assess thoroughly the history of the activity that may have led to the genesis of the symptoms of patellofemoral pain, and to document which of the patient's current activities cause pain (are out of the envelope of function) so that they can be rigorously restricted.<sup>10,17,18</sup> It is not unusual, however, for patients with anterior knee pain not to recall a specific incident that may have initiated the symptoms, but merely to report that certain activities associated with high patellofemoral loading have now become symptomatic. By suggesting that a patient decrease loading to within his or her joint's current diminished envelope of function, I am not advocating a sedentary existence or treatment approach. On the contrary, it is desirable that the patient remain as active as possible within the upper threshold limits of their joint's envelope (ie, that which is painless).<sup>8</sup> Even joints that are substantially compromised functionally may safely withstand activities such as swimming or light bicycling, which can effectively maintain muscle strength, tone, joint range of motion, and even endorphin production without supraphysiologic overload of the system as a whole. In addition, a safe, but deliberate anti-inflammatory program including multiple episodes of brief (15–20 minutes) tissue cooling daily and nonsteroidal anti-inflammatory medications of the physician's choice is recommended. Furthermore, a safe, painless physical therapy program of leg and

trunk muscle strengthening, balancing, patellar taping, and alternative exercises such as Pilates, and safe activities of daily living instruction often is considered beneficial.

The success of patellofemoral taping, frequently referred to as McConnell taping,<sup>25</sup> after the Australian physical therapist who developed it, often substantially decreases patellofemoral pain—sometimes instantaneously—by taping the skin over a symptomatic patella in typically a medial direction, is said to support the malalignment theory because the taping supposedly works by correcting the malalignment. However, recent work by Powers et al<sup>43</sup> and Watson et al<sup>53</sup> refutes this notion. I think that it is more likely that the pain relieving effect of McConnell taping is achieved by temporarily unloading (unpinching) inflamed and sensitive innervated peripatellar tissues rather than permanently changing any malalignment parameter. The inflamed peripatellar tissues have not, of course instantly healed but the restoration of homeostasis is possible if they are protected from further perturbing events (eg, mechanical impingement) for a sufficient length of time. I liken patellofemoral synovitis from impingement as similar to repetitively biting the inside of one's cheek tissues. If one then uses a finger to pull away the sensitive and swollen cheek tissues from the teeth, instant pain relief can be experienced, even though the inflamed tissues have not suddenly healed.

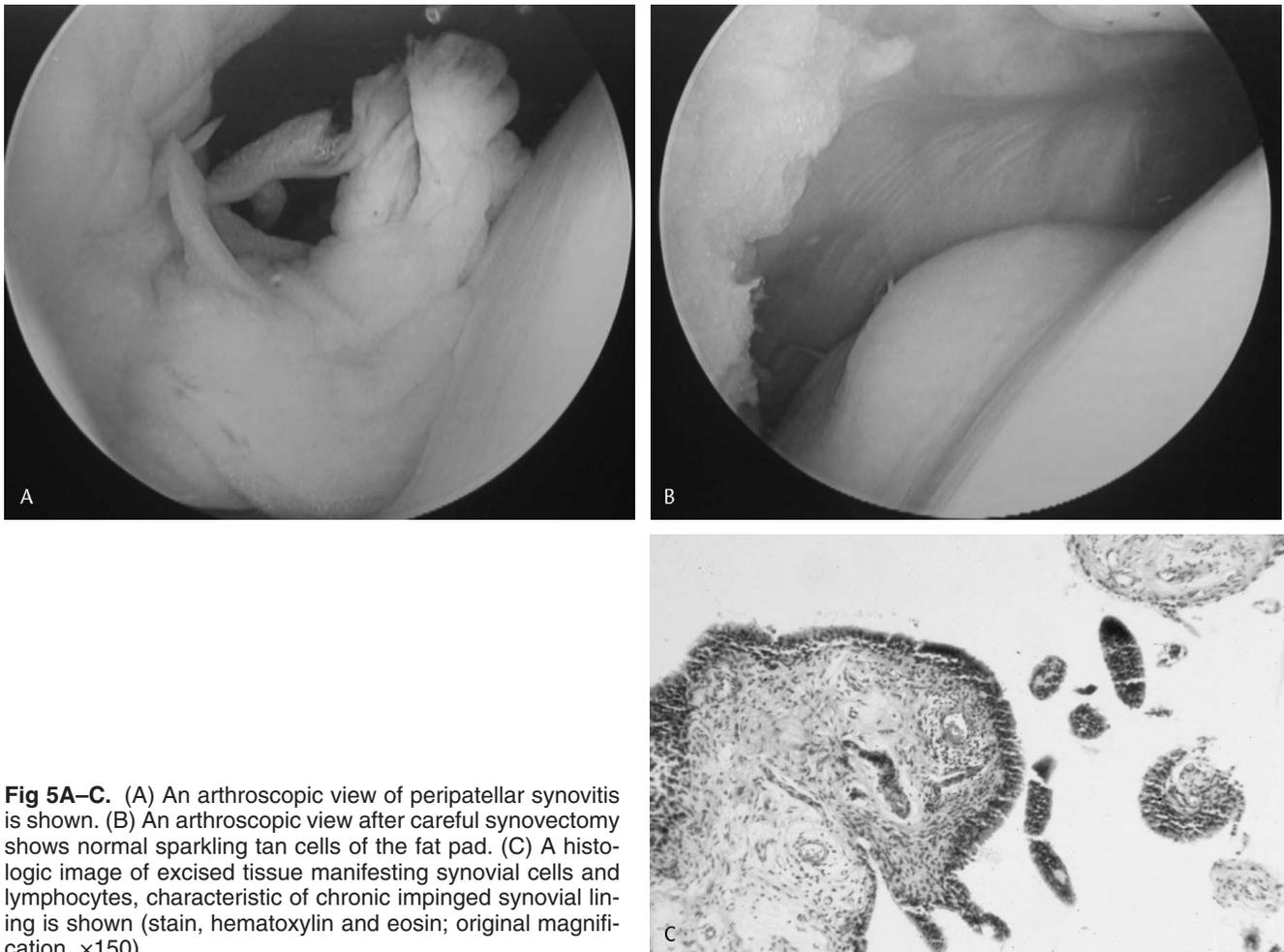
The aphorism of “no pain no gain” applied vigorously and inappropriately to a symptomatic patellofemoral joint by well-meaning, but ill-informed therapists has caused many patients' knees to become symptomatically worse. Any activity-induced pain perceived within the patellofemoral joint is an indication of a supraphysiologic loading event that will only subvert normal healing mechanisms, similar to putting flammable liquid on a fire one is wishing to extinguish. The perception of mild aching in the muscles about the knee after exercise, however, is acceptable and often necessary to result in increased strength and function of the tissues that are, in essence, cellular engines. If all of the above nonoperative measures fail to alleviate pain, consideration of surgical intervention may be warranted.

The patellofemoral joint is notoriously unforgiving and intolerant of surgical procedures that do not respect its special biologic and biomechanical characteristics. The novice or inexperienced orthopaedic surgeon is urged to be extremely cautious in the choice of operative procedure. I recommend a gentle, minimalist surgical approach in most cases. The principle is to maximize the envelope of function for a given joint as safely and predictably as possible. Furthermore, once that maximum has been achieved, one should encourage the patient to load the affected joint within its envelope. I have noted that the careful application of this principle in one's surgical approach to patients

with patellofemoral pain by a substantial degree of gentleness of technique often yields results, which if not always resulting in a pain-free joint, at least does not cause the severe worsening of symptoms of anterior knee pain that have frequently resulted from more aggressive procedures.<sup>10,29</sup> In other words, an approach based on respect for the biology and special biomechanical nature of the patellofemoral joint is inherently safer. Such a surgical approach would include a careful peripatellar synovectomy, (Fig 5) clearing out the inflamed and impinged intra-articular soft tissues about the patella to the point where normal glistening fat cells can be seen. At the same time, a gentle chondroplasty to stabilize a region of chondromalacia may be done, removing just the loose cartilage tissue that otherwise might separate off in the near future absent arthroscopic intervention. If one is to do this type of procedure, it is crucial that the development of a postoperative hemarthrosis be avoided. In my experience, the following approach usually is successful in preventing a postoperative hemarthrosis. Meticulous intraoperative he-

mostasis must be achieved by use of an arthroscopic cautery or similar device. It is recommended to inject up to 40 cc of 1% lidocaine with 1:100,000 epinephrine sub-synovially before the end of the procedure. The placement of a small drain through one of the portals also is recommended. If the output is low for the first 3 to 4 hours after the procedure, the drain may be removed. Otherwise, the drain should remain overnight before being removed. A modest compression dressing, including the use of a thigh-high antithrombotic stocking also is recommended. The knee should be kept free from supraphysiologic loading and should be intermittently cooled for several days post-operatively. Then a safe, painless rehabilitation program within the envelope of function should be instituted.

If, despite one's best efforts, substantial anterior knee pain persists in the presence of for example, advanced degenerative arthrosis, more involved procedures such as anterior medialization of the tibial tubercle or patellofemoral joint replacement then can be considered as rational treatment options. Neither of these procedures, however,



**Fig 5A–C.** (A) An arthroscopic view of peripatellar synovitis is shown. (B) An arthroscopic view after careful synovectomy shows normal sparkling tan cells of the fat pad. (C) A histologic image of excised tissue manifesting synovial cells and lymphocytes, characteristic of chronic impinged synovial lining is shown (stain, hematoxylin and eosin; original magnification,  $\times 150$ ).

should be viewed as a panacea for patients with symptomatic degenerative disease of the patellofemoral joint. Substantial postoperative complications such as early and late stress fractures,<sup>20,24,50</sup> and displacement of components can and do occur, leaving the patient (at least temporarily) worse off. The surgeon and patient and the patient's family should understand the magnitude and potential pitfalls inherent in such a therapeutic choice. In my opinion, the minimum criteria for patellofemoral joint replacement surgery would include failure of lesser therapeutic methods of pain control and the presence of a positive Technetium 99m-MDP bone scan limited to the patellofemoral joint. If a preoperative bone scan manifests substantial increases in one or more femorotibial compartments, then one should contemplate the use of total joint replacement surgery. The use of unicompartmental patellofemoral replacement surgery in such a circumstance may not result in satisfactory pain relief because of the continued nociceptive output from pathophysiologic processes remaining in the unreplaced femorotibial compartment(s).

## DISCUSSION

For decades the genesis of patellofemoral pain has represented a classic orthopaedic enigma with treatments based on the traditional structural factors of chondromalacia and malalignment. Unfortunately, such treatments have often resulted in iatrogenic worsening of the patient's symptoms. The fundamental issue at the core of the patellofemoral pain problem, in this author's view, has been the limited conceptualization of the genesis of anterior knee pain to that of a pure structural and biomechanical perspective. Such an intellectually constrained view does not include the complex pathophysiologic factors that may be of etiologic significance in living, symptomatic joints. The limitation inherent in this traditional view was well summarized by the late John Insall in 1995, when he noted that "Curiously, neither the widespread use of arthroscopy nor the advent of new diagnostic tests such as CT scanning and magnetic resonance imaging have cast much light" on the enigma of patellofemoral pain.<sup>32</sup> The fact that the metabolic characteristic of loss of tissue homeostasis cannot be reliably imaged by structurally oriented studies such as CT or MRI, and therefore often are covert processes, provides an explanation for a profoundly confusing aspect of the patellofemoral pain enigma, and the puzzlement implicit in Dr. Insall's observation. In order to manifest metabolic characteristics geographically, one must use a metabolically oriented modality such as Tc99m scintigraphy or histologic examination of tissues.

With the traditional structural view of patellofemoral pain, it is as if an astronomer were trying to understand the complexity of the cosmos solely with data obtained from

optical telescopes that collect only visible wavelength photons. The use of scintigraphic imaging, such as the technetium bone scan, can be seen as analogous to the addition of radiotelescopic data to the field of astronomy in the last century which manifested the presence of phenomena that were unexpected based on information obtained only from traditional optical telescopes. Based on the new information obtained from radio telescopes (and others, such as xray and infrared telescopes), a fundamental change resulted in the understanding of cosmology. Similarly, the data from scintigraphic imaging not only has provided a new insight into the genesis of patellofemoral pain, but it also forces one to conceptualize living joints in a fundamentally different way. No longer should one view joints as mere assemblages of macrostructural musculoskeletal anatomy, but as volumes of billions of living cells that are going through constant metabolic activity in an attempt to maintain homeostasis under normal loading conditions or to restore homeostasis after injury.

In an effort to solve the patellofemoral pain enigma, the principle of tissue homeostasis independently was discovered and then was developed into a practical concept by means of the envelope of function. The envelope of function was developed as a simple method to incorporate and connect the concepts of load transference and tissue homeostasis in order to represent the functional capacity of the knee visually. The envelope of function in its simplest form is naturally intuitive and therefore easy for patients to understand and provides a rationale for the presence (or absence) of anterior knee pain caused by different levels of patellofemoral loading.

The versions of the envelope of function as presented in this work and elsewhere are simplified versions representing the four responses of musculoskeletal tissues to differential loading homeostasis, loss of homeostasis caused by disuse or overuse, and structural failure. The interfaces between the four zones are represented as lines and therefore if interpreted literally imply clear, definable indicators of zone change. Although this may be true for sudden, high-loading events that result in overt structural failure, it probably is not true for the interfaces between the other regions. It is likely that the actual loading events that would define the interfaces between the other regions are not exact but are gradual and are better represented by shaded overlapping. The zones likely blend from one to another rather than change abruptly.

The term and the concept of homeostasis pertaining to tissues and joints as a whole are now becoming increasingly accepted in the musculoskeletal literature.<sup>21,28,36,48,52</sup> Examination of the intricate details of the metabolic events within living cells using techniques such as confocal laser microscopy and near-infrared fluorescence are beginning to manifest these biochemical processes with preci-

sion.<sup>1,27,39</sup> One can envision a day when the homeostasis characteristics of all musculoskeletal tissues will be able to be detected and perhaps displayed geographically in a 3-dimensional hologram, with the degree of tissue homeostasis represented by different colors and intensities. When such data easily can be manifested and tracked with time, then many current and future concepts regarding the etiology and treatment of patellofemoral pain (including the relationship between the presence of various structural factors and loss of tissue homeostasis) and other musculoskeletal conditions of orthopaedic significance, will be able to be better assessed and evaluated than is possible with present technology. For example, new methods of treatment designed directly to address the loss of tissue homeostasis biochemically that may seem unorthodox from today's perspective, such as the use of the hormone calcitonin in patients with anterior knee pain and intensely increased osseous metabolic activity could in time prove to be safe and efficacious whereas the indiscriminate use of the lateral release may not. I would suggest that the principle of treatment for all orthopaedic conditions from a tissue homeostasis perspective is to maximize the envelope of function as safely and predictably as possible. Many current surgical approaches to patients with patellofemoral pain such as aggressive chondroplasties and extensive proximal and distal realignments are neither inherently safe nor predictable, and thus fail to achieve this basic treatment principle.

By the presentation of a tissue homeostasis perspective one is not asserting that the enigma of patellofemoral pain has now been solved in its entirety. However, paradigms in many intellectual endeavors, including medicine sometimes change (eg, *H. pylori* and duodenal ulcers) which lead to fundamental changes in understanding and treatments,<sup>41</sup> which may be the case with the concept of tissue homeostasis and patellofemoral pain. Still, much remains to be discovered in patients with patellofemoral pain in order to better understand and gain control of this phenomenon. Direct *in vivo* measurements of patellofemoral joint reaction forces in dynamically loaded joints in symptomatic patients and in asymptomatic control patients have yet to be measured. There may be other subtle factors contributing to the mosaic of pathophysiology resulting in the perception of patellofemoral pain that are undetectable by any current technology that have not yet been discovered. There also may be undiscovered factors that result in suppression of nociceptive output or central nervous system processing that results in decreased pain perception in some patients, which would account for the observation that certain individuals essentially are symptom free despite the presence of overt, radiographically, and scintigraphically identifiable advanced degenerative changes of the patellofemoral joint.

When the complex details of the etiology of patellofemoral pain eventually are known in greater depth, the data discovered also may prove to be valuable in assessing and treating other orthopaedic problems. The tissue homeostasis theory provides a sufficiently broad conceptual framework to help educate patients in the subtle but intellectually accessible principles of musculoskeletal tissue overuse and healing. Above all, the tissue homeostasis perspective has led to therapeutic principles that are rational, gentle, and inherently safer than those encouraged by the current structural paradigm and therefore better respect the ancient Hippocratic dictum of *primum non nocere*.

### Acknowledgments

The author thanks the following individuals for their help and guidance in the preparation of this work: Hans Ulrich Stäubli, MD; Roland M. Biedert MD; Ann M. Dye, RN; Ira Dye, Captain USN (Retired); and Rebecca M. Larsen.

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