All living organisms are limited to a finite life span, and humans are no exception. As with any mechanical system, the cumulative debilitating effects of time, wear, and gravity result in an almost imperceptible gradual degradation in performance. All our tissues are susceptible to these effects, although some are more resistant than others. Skin and bone are perhaps the most resilient tissues, and both have an amazing capacity for healing and regeneration that is the foundation of much of modern reconstructive surgery. Although articular cartilage is subjected to some of the highest mechanical demands, its capacity for repair and regeneration is unfortunately extremely limited and it is often among the first tissues to manifest the effects of aging. Remarkably, this relatively fragile tissue is responsible for transmitting loads exceeding several times our body weight for an estimated billion cycles during the course of an average lifetime. It is not surprising that any disturbance of the normal anatomic and biomechanical relationships can result in an acceleration of this gradual degradation characteristic of aging.

Because the lower extremities are normally weight bearing throughout our lives, axial alignment of the lower extremities is critical with respect to determining the demands to which articular cartilage is repeatedly exposed during gait. Alignment is therefore an important consideration in many clinical situations, whether considering fracture reduction, total knee arthroplasty, or deformity correction. At present, there is general agreement that the cause of degenerative arthropathy is mechanical, not inflammatory (Radin et al. 1991). Commonly called degenerative arthritis, this expression is inappropriate because inflammation is a secondary result and not the principle cause. Arthrosis is the preferred word for describing purely degenerative pathological abnormality of the joint.

Unicompartmental knee arthrosis is often associated with malalignment resulting from deformity (Barrett et al. 1990; Hernborg and Nilsson 1977; Kettelkamp et al. 1988). Although the association between malalignment and arthrosis is acknowledged, the possible pathogenic relationship is less well documented. This may represent the response of abnormal cartilage to normal forces or may reflect the response of normal cartilage to excessive stress. Direct clinical evidence of a cause-and-effect relationship between malalignment and arthrosis has not been possible, but substantial evidence from the orthopaedic literature supports this hypothesis.

Central to this hypothesis is the assumption that malalignment alters stress distribution across the joints in the lower extremity, particularly the knee. The concept of a weight-bearing axis is not new and is usually termed the mechanical axis (Maquet 1984; Pauwels 1980). This is depicted as the line passing from the center of the ankle to the center of the hip and represents the path of transmission of the load-bearing force relative to the lower extremity. Any deformity in the coronal plane that alters the alignment of the joints of the lower extremity, resulting in malalignment, disturbs this load-bearing axis. When the load-bearing axis passes medial or lateral to the center of the knee, this creates a moment arm acting to increase force transmitted across either the medial or lateral tibiofemoral compartment, respectively (Kettelkamp and Chao 1972; Maquet 1984; Pauwels 1980).

Pauwels (1980) pioneered the concept of the mechanical axis and recognized the significance of realignment to restore normal force transmission across the knee. He was one of the first to recognize the importance of biomechanics and its relationship to surgical planning for the correction of deformity by osteotomy. Maquet (1984) later expanded on these ideas and elegantly showed the alteration in stress transmitted across simulated joints using polarized light and photoelastic models (Fig. 13-1). His studies verified the concepts put forth by Pauwels and emphasized the importance of restoring or correcting the mechanical axis to alter load transmission across the knee.

The relationship between malalignment and subsequent degenerative arthropathy may seem intuitively obvious. Because of the slow progression of the disease, its poor tolerance by patients, and readily available treatment alternatives, it is difficult to document the natural history of the process. There is ample evidence to support the contention that persistent malalignment of sufficient magnitude will later result in degenerative arthropathy. This includes both basic science and clinical investigations and can be most conveniently reviewed in

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CHAPTER 13 · Consequences of Malalignment

Fig. 13-1
Photoelastic model in polarized light shows altered stress distribution when axial load is applied eccentrically. (Reprinted with permission [Maquet 1984].)

three sections: animal models, cadaver models, and clinical longitudinal studies. However, before considering malalignment, it is paramount to first establish the limits of normal alignment.

**Static Considerations**

The normal relationship of the joints of the lower extremity has been the focus of several recent studies (Chao et al. 1994; Cooke et al. 1994; Hsu et al. 1990; Moreland et al. 1987; Paley et al. 1994). There are two considerations when evaluating the coronal plane axis of the lower extremity: joint alignment and joint orientation (Paley et al. 1990; Paley and Tetsworth 1992b) (see Fig. 1-8). Alignment refers to the collinearity of the hip, knee, and ankle. Orientation refers to the position of each articular surface relative to the axes of the individual limb segments (tibia and femur). Alignment and orientation are best judged using standing long AP view radiographs of the entire lower extremity on a single cassette. Proper rotation of the limb is critical and requires the patella be centered between the femoral condyles and directed forward. A standardized technique is useful to assure that the radiographs are reproducible (Cooke et al. 1987, 1994; Paley et al. 1994).

Alignment is determined by the line extending from the center of the hip to the center of the ankle, the mechanical axis of the limb. By definition, malalignment occurs when the center of the knee does not lie close to this line. The mechanical axes of the individual limb segments (tibia and femur) are also important. In the tibia, the mechanical and anatomic axes are almost the same (Moreland et al. 1987), but in the femur, they are very different. The mechanical axis of the tibia is defined by the line from the center of the knee to the center of the ankle. The mechanical axis of the femur is defined by the line from the center of the hip to the center of the knee. This typically subtends a 6° angle to the anatomic axis of the femur (Hsu et al. 1990; Moreland et al. 1987; Yoshioka et al. 1987), which runs from the piriformis fossa to the center of the knee joint.

Although normal alignment is often depicted with the mechanical axis passing through the center of the knee, a line drawn from the center of the femoral head to the center of the ankle typically passes immediately medial to the center of the knee. Moreland et al. (1987) reviewed standing long AP view radiographs of both lower extremities of 25 normal male volunteers and documented that the hip, knee, and ankle are nearly colinear. Using several radiographic landmarks to define the center of each joint, the intersection of the femoral and tibial mechanical axes measured 1.3° varus (± 2°). Hsu et al. (1990) reviewed standing long AP view radiographs of the lower extremities of 120 normal participants and confirmed that the mechanical axis generally passes immediately medial to the center of the knee. In their study population, the intersection of the femoral and tibial mechanical axes measured 1.2° varus (± 2.2°).
Based on these observations, the joints of the lower extremity are considered normally aligned in a nearly collinear fashion. Any distortion of this relationship is considered malalignment and predictably affects the transmission of load across the joint surfaces. The hip is approximately spherical and is best able to accommodate an alteration in its normal position. The proximity of the subtalar joint allows the ankle to better tolerate deformity, although subtalar stiffness is common in posttraumatic situations and may be a clinically significant factor (McMaster 1976). However, the knee is most vulnerable to changes in the normal coronal plane relationship of the joints of the lower extremity.

When coronal plane deformity results in axial malalignment, the load-bearing axis passes medial or lateral to the center of the knee (Maquet 1984). This creates a moment arm acting to increase force transmission across either the medial or lateral tibiofemoral compartment, and that moment arm can be depicted by measuring the MAD (Paley and Tetsworth 1992a, 1992b). The mechanical axis is drawn from hip to ankle, and a perpendicular segment is added, extending from the axis to the center of the knee (see Fig. 1-8). The magnitude of this additional segment, measured in millimeters, reflects the magnitude of alteration in stress transmission across the knee. Determining MAD accounts for deformity of any type, including rotation, translation, and angulation. It also takes into consideration the level of the deformity. The effect on the mechanical axis increases as the apex of deformity approaches the knee (Fig. 13-2) (McKellop et al. 1991, 1994; Puno et al. 1987). This method has been useful for both preoperative planning (Paley and Tetsworth 1992a, 1992b; Paley et al. 1990, 1994) and postoperative evaluation of the results of deformity correction (Tetsworth and Paley 1994).

After determining the alignment of the joints of the lower extremity, the second consideration is the orientation of the joints to the mechanical axis. Each joint has a normal inclination to the mechanical and anatomic axes of both limb segments (Chao et al. 1994; Cooke et al. 1994; Moreland et al. 1987; Paley et al. 1994). These form reference lines and angles that are useful in preoperative planning to determine the deformity present in each bone segment (Paley and Tetsworth 1992a, 1992b; Paley et al. 1990, 1994). The goal of deformity correction is to not only restore normal alignment but also maintain or restore the normal orientation of each joint to the mechanical axis. Cooke et al. (1987, 1989, 1994) showed the clinical significance of malorientation at the knee by documenting an association with osteoarthritis.

The orientation of the hip on the AP view can be characterized by the NSA, and the radiographic projection of the NSA ranges from 125°-131°. In an anatomic study of isolated cadaver femora, Yoshioka et al. (1987) determined that the NSA in adult men normally measures 129°. Alternatively, Paley et al. (1990) defined a line from the tip of the trochanter to the center of the femoral head, which can be used to define a joint orientation axis of the proximal femur. Chao et al. (1994) measured the LPFA on the standing long radiographs of 127 normal volunteers and stratified the study group according to age and gender. There was no significant change noted with age in women, and the relationship of this line to the mechanical axis of the femur measured 91.5° varus (±4.6°) in younger women and 92.7° varus (±4.9°) in older women. In men, the LPFA showed an age-related tendency toward increasing varus, measuring 89.2° (±5.0°) in younger men and 94.6° (±5.5°) in older men. Data from our institution (Paley et al. 1994), based on a smaller group of 25 asymptomatic adults, indicate that this proximal femoral joint orientation line measures 89.9° (±5.2°). Based on these observations, we have advocated 90° for the LPFA (Paley et al. 1990, 1994; Paley and Tetsworth 1992b).

Chao et al. (1994) also measured the mLDFA and stratified the data according to age and gender. The average mLDFA was 88.1°±3.2° and was independent of age and gender. These results have been confirmed by our own data (Paley et al. 1990), which indicate that the average mLDFA is 87.8°±1.6°. Cooke et al. (1994) obtained standing long radiographs after positioning the patient in a frame to enhance precision, and in 79 asymptomatic young adults, the distal femoral orientation line mea-

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sured 86° valgus (± 2.1°). Based on these data, the normal relationship of the distal femoral joint orientation line and the mechanical axis of the femur is considered to be 87° (Paley et al. 1990, 1994; Paley and Tetsworth 1992b). Chao et al. (1994) again stratified their data according to age and gender for the medial proximal tibial angle and found a significant difference when comparing older with younger men. In all groups, the MTPA measured slightly varus relative to the mechanical axis of the tibia, and in women, it measured 87.2° (± 2.1°). Interestingly, the subgroup of asymptomatic young men had slightly more varus (85.5±2.9°) compared with asymptomatic older men (87.5±2.6°). Perhaps some of the young men with more varus later develop symptomatic degenerative arthritis and "drop out" of the asymptomatic group of older men. However, this is largely speculative and there currently are few data to support this conjecture.

One study (Glimet et al. 1979) of 50 elderly asymptomatic French women does document that the mechanical tibiofemoral angle in this select group measures zero degrees, which is consistent with this hypothesis. Cooke et al. (1994) reviewed radiographs obtained using a frame to position patients precisely and found the proximal tibia in 86.7° varus (± 2.3°). These results were confirmed by our data (Paley et al. 1994), with the proximal tibia in 87.2° varus (± 1.9°), and by Moreland et al. (1987), who measured 87.2° varus (± 1.5°). Based on these observations, the normal relationship of the proximal tibial joint orientation line and the mechanical axis of the tibia is considered to be 87° varus (Paley et al. 1990, 1994; Paley and Tetsworth 1992b).

The transverse axis of the knee measures approximately 3° off the perpendicular, such that the distal femur is in slight valgus and the proximal tibia is in slight varus (Krackow 1983; Moreland et al. 1987; Paley et al. 1990; Paley and Tetsworth 1992b). When walking, the feet progress along the same line, with the leg inclined to the vertical approximately 3°. This 3° varus position of the lower limb allows the knee to maintain a parallel orientation to the ground during gait (Fig. 13-3) (Krackow 1983). In bipedal stance with the feet apart the width of the pelvis and the tibia perpendicular to level ground, the knee transverse axis would be oriented in 3° varus relative to vertical.

Moreland et al. (1987) measured the ankle joint orientation. The lateral distal tibial angle measured 89.8±2.7°. Data from our institution (Paley et al. 1994) also showed slight valgus (LDTA = 88.6±3.8°), as did data presented by Chao et al. (1994) (LDTA = 87.1±3.3°). This relationship is variable, and up to 8° of valgus may be normal (Moreland et al. 1987). Based on these measurements, the normal relationship of the distal tibial joint orientation line and the mechanical axis of the tibia is considered perpendicular (Paley et al. 1990, 1994; Paley and Tetsworth 1992b).

### Dynamic Considerations

Although static malalignment is readily documented on standing long radiographs, this has not been a reliable means of predicting outcome after corrective osteotomy (Adriacchi 1994; Prodromos et al. 1985; Wang et al. 1990). The clinical situation is far more complex, and the simple activities of daily living create dynamic loading conditions that reflect additional considerations (Adriacchi 1994; Harrington 1983; Johnson et al. 1980), including joint instability, muscle contractions, and individual idiosyncrasies of gait. Gait analysis is being used more frequently to assess dynamic aspects of malalignment, but this technology has not been widely available and most of the literature to date concerns static assessment of malalignment.

Stress transmission across the knee can be calculated using a rigid body spring model, if certain assumptions are made (Hsu et al. 1990; Kettlekamp and Chao 1972). The distribution of force transmitted across the knee is normally shared unequally between the medial and lateral compartments (Harrington 1983; Hsu et al. 1990; Johnson et al. 1980). Even in the absence of malalignment, calculations indicate that approximately 70% of the load across the knee in single-leg stance is transmitted through the medial compartment. When 4°–6° of varus deformity is present, almost 90% of the knee joint force during single-leg stance passes through the medial compartment (Fig. 13-3) (Hsu et al. 1990).

The dynamic loads that occur during walking and other weight-bearing activities of daily living are probably more important but have been difficult to determine accurately. Important issues regarding the dynamics of knee malalignment have been reviewed in detail by Adriacchi (1994). The normal forces that act on the lower extremity during gait produce moments tending to flex, extend, abduct, and adduct the knee. These are the primary factors influencing the distribution of medial and lateral forces across the knee. The ground reaction force acting at the foot during the stance phase of gait passes medial to the center of the knee. The perpendicular distance from the line of action of this force to the center of the knee is the length of the lever arm for this force. The product of the magnitude of the force and the length of the lever arm results in an adduction moment acting on the knee. This adduction moment during gait is an external load tending to thrust the knee into varus; it is also known as lateral thrust (Prodromos et al. 1985; Wang et al. 1990).

The external forces and moments acting on the lower extremity can be measured directly in a gait laboratory. The internal forces acting through muscles, through ligaments, and on the joint surfaces are of greater interest but can only be estimated based on the external forces and moments measured (Adriacchi 1994; Harrington...
Graphical representation of force distribution across the knee and changes that occur as deformity is introduced. With normal alignment, approximately 70% of the force passes through the medial compartment. When varus malalignment of the limb is greater than 5°, approximately 90% of the force passes through the medial compartment. (Reprinted with permission from Hsu et al. 1990).

Fig. 13-3

Graphical representation of force distribution across the knee and changes that occur as deformity is introduced. With normal alignment, approximately 70% of the force passes through the medial compartment. When varus malalignment of the limb is greater than 5°, approximately 90% of the force passes through the medial compartment. (Reprinted with permission from Hsu et al. 1990).

1983; Johnson et al. 1980). Mechanical equilibrium mandates that external forces acting on the limb must be balanced by internal forces generated by muscle and ligaments. Prediction of internal forces is extremely complicated because of the many combinations of muscle and soft tissue forces that can balance the external forces and moments acting on the limb. Solving this problem requires several simplifying assumptions, the most basic being to group internal structures together. Analysis of the relationship between external loads and internal forces under these assumptions allows estimation of the magnitude of the joint reaction force acting across either the medial or lateral compartment independently. The distribution of the medial and lateral joint reaction forces shows that the adduction moment is the primary factor producing the higher medial joint reaction force during normal function. For a group of normal participants, the maximum joint reaction force across the knee is approximately 3.2 times body weight, with 70% of this load passing through the medial compartment. The average maximum magnitude of the adduction moment during normal gait for this population has been calculated as approximately 3.3% of the product of body weight and height (Andriacchi 1994). This adduction moment is greater than the moments calculated for either flexion or extension of the knee in this same study group.

Some patients modify their gait, effectively reducing the load on the medial compartment of the knee. The adaptive mechanism used reduces the adduction moment and has been related to a shorter stride length and an increase in external rotation of the foot (toe-out position) during stance phase (Andriacchi 1994; Prodromos et al. 1985; Wang et al. 1990). The toe-out position places the hindfoot closer to the midline, beneath the center of gravity. This simply moves the ground reaction vector toward the center of the knee, effectively reducing the lever arm of the external ground reaction force and therefore the resulting adduction moment. Patients are considered to have high adduction moments if the calculated moment exceeds 4% of the product of body weight and height when walking at speeds of approximately 1 m/s. All other patients are considered to have low adduction moments.

The clinical outcome after treatment of patients with varus gonarthrosis by valgus high tibial realignment osteotomy has been closely related to the magnitude of the adduction moment measured during preoperative gait analysis (Andriacchi 1994; Prodromos et al. 1985; Wang et al. 1990). Patients in the low preoperative adduction moment group had a better clinical result initially, and this result was sustained over an average follow-up period of 6 years. The valgus correction was maintained with follow-up in 79% of the low adduction moment group compared with only 20% of the high adduction moment group (Andriacchi 1994; Wang et al. 1990).

Load transmission across the knee can be effectively altered by adjusting the location of the center of gravity. This dynamic compensation involves either use of an external support or gait modification. Shifting the upper body center of mass to a position directly over the involved limb can decrease the medial compartment force by 50% compared with its value when the center of gravity is positioned in the midline (Hsu et al. 1990). Clinical evidence has already established the importance of gait alteration and its relationship to results after corrective high tibial osteotomy (Andriacchi 1994; Prodromos et al. 1985; Wang et al. 1990). Patients with the best clinical outcomes are able to modify their gait, externally rotating the limb and developing a lower adduction moment at the knee (Fig. 13-4). This is contrary to observations presented by Krackow et al. (1990) regarding malrotation during gait. During the stance phase, when load transmitted through the limb is greatest, the knee is maintained in a position of slight flexion. Internal rotation of a slightly flexed limb then creates apparent valgus. External rotation creates apparent varus and would be expected to be associated with a poorer prognosis after a valgus osteotomy. This contradiction confirms the discrepancies that may result when attempting to correlate static and dynamic analyses of malalignment.

Static considerations may not accurately reflect the clinical condition, and the contribution of muscles and ligaments acting across the knee can markedly influence the joint reaction forces. Although the medial compartment may sustain higher average loads based on static analysis, recent publications suggest that the loads are more evenly balanced across the entire femorotibial articulation. In a biostatic cadaver laboratory model, Inaba et al. (1990) measured forces across the femorotib-
Gait modifications observed clinically that alter adduction moment arm (modified from Andriacchi 1994).

a. Toe-out gait by use of excessive external rotation of the lower limb places the ground reaction force vector closer to the center of the knee joint. This reduces adductor moment arm.

b. Toe-in gait with internal rotation of the lower limb places the ground reaction force vector away from the center of the knee joint. This increases adductor moment arm.

Using cadaver and magnetic resonance imaging measurements, investigators at the Oxford Orthopaedic Engineering Center (Huss et al. 2000; Lu and O’Connor 1996) developed an anatomy-based mathematical model to predict loads transmitted across the knee. This model incorporates the lines of action and moment arms of the major force-bearing structures crossing the human knee joint, including both muscles and ligaments. Theoretical values derived from this model replicate the previously published experimental measurements presented by Herzog and Read (1993), validating the model. Including contributions from muscles and ligaments, both experimentally measured and theoretically calculated forces across the knee are more evenly distributed than published results have suggested. The difference between the static single-leg standing simulations and those that factor in the surrounding muscle forces is mostly attributable to the tensor fascia lata muscle. In a well-conditioned person, this muscle counters the adduction moment arm on the knee, unloading the overloaded medial side and transferring that load to the lateral side. As one gets older and naturally loses muscle mass and strength, the protection afforded the medial compartment by the tensor fascia lata is diminished and lost. This may precipitate the progressive de-
torporation of the medial compartment that most commonly occurs in people older than 40 years.

Joint laxity is a further confounding variable to consider when determining the risk of developing osteoarthritis secondary to malalignment. Sharma et al. (1999) reported that ligament laxity may precede the development of osteoarthritis. Ligament laxity can result in dynamic malalignment during gait, with associated changes in loading patterns across the knee. Collateral ligament laxity may increase the risk of gonarthrosis and cyclically contribute to progression of the disease. LCL laxity is typically associated with varus malalignment and, when superimposed, may have a synergistic effect. The tensor fascia lata may protect the knee from overload due to lateral collateral laxity. Again, this protection is gradually lost or overwhelmed with increasing age, deconditioning, and deformity.

**Rotational Considerations**

Recognizing the role of limb rotation in gait modification and its effects on load transmission, it is clear that fixed rotational deformities can also have a potential role in the development of degenerative arthropathy. This has been investigated by many authors with conflicting results, usually focusing on either the hip or knee independently. Several studies have attempted to establish a correlation between anteversion of the femur and arthrosis of the hip. In two published studies (Kitaoka et al. 1989; Wedge et al. 1989), the attempt to correlate increased anteversion with hip arthritis was unsuccessful. The relative sphericity of the hip itself may render it less susceptible to both angular and rotational deformities of lesser magnitude. However, two other studies did establish a relationship between hip arthrosis and abnormal femoral anteversion. In a Scandinavian population, Reikeras and Hoiseth (1982) showed a positive correlation between increased femoral anteversion and an increased incidence of hip osteoarthritis. Conversely, Tonnis and Heinecke (1991) later reported a positive correlation between decreased femoral anteversion and an increased incidence of hip arthrosis. These results suggest that there is a limit to the tolerance of the hip for both internal and external malrotation.

Investigations into the possible pathogenetic role of rotation and arthrosis of the knee have examined either femoral or tibial torsion independently. Takai et al. (1985) reported a relationship between patellofemoral arthropathy and increased femoral anteversion. Eckhoff et al. (1994b) subsequently established a positive correlation between medial compartment degenerative arthritis and decreased femoral anteversion. Eckhoff (1994) suggested that the impact of femoral version varies in the knee, with the patellofemoral compartment being most affected by increased femoral anteversion and the medial compartment being most affected by decreased femoral anteversion. This again suggests, as with the hip, that there is a limit to the tolerance of the knee for both internal and external femoral torsion. Three published studies (Tonnis and Heinecke 1991; Turner and Smillie 1981; Yagi and Sasaki 1986) have also shown a relationship between tibial malrotation and knee arthrosis. All three indicated that decreased version of the tibia results in increased incidence of arthropathic changes, principally in the medial compartment.

An additional consideration is the rotational alignment of the tibia relative to the femur itself, discussed in at least two studies (Eckhoff et al. 1994a; Takai et al. 1985) as knee version. This refers to a static rotation in alignment between the femur and tibia across the extended knee and should not be confused with the automatic and dynamic rotation of the knee observed with flexion and extension, which is typically called the screw home mechanism. The static external rotation of the tibia relative to the femur in the fully extended knee measures greater in the arthritic knee than in the non-arthritic knee (Eckhoff et al. 1994a).

Although the literature reviewed above indicates that malrotation is clinically associated with degenerative arthropathy, few of these studies discuss the presence or absence of coexisting axial malalignment. Simultaneous axial and rotational malalignment is documented in two studies (Cooke et al. 1990; Said and Hafez 1975) in which genu varum was associated with external tibial version in patients with osteoarthritis of the knee.

Eckhoff (1994) discussed many of the issues regarding the effect of limb rotation on malalignment in his review article. Human limbs are three-dimensional objects, and any limb deformity is more likely to be three-dimensional than two-dimensional (Eckhoff 1994; Green and Gibbs 1994). Axial malalignment is recognized and documented more frequently than is rotational malalignment, but both elements of deformity can occur simultaneously. Radiography is perhaps the most common method used to assess deformity; unfortunately, however, this technique reduces the three-dimensional deformity to a two-dimensional image. Restricted to two dimensions, an internally rotated limb with the knee flexed would appear as a valgus deformity in the coronal plane and the rotational component would be difficult to determine. Conversely, the opposite is also true, and an externally rotated limb with the knee flexed would appear as a varus deformity in the coronal plane. The common perception of limb malalignment as an isolated varus or valgus axial malalignment is reinforced clinically by two-dimensional radiographs that fail to accurately portray the third dimension and the coexisting rotational deformity. Considering these limitations, it is not surprising that rotational contributions to malalignment are often inadvertently underestimated or ignored.

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Animal Laboratory Models

Several experimental models have been used successfully to create gradually progressive arthropathy in laboratory animals (Adams and Billingham 1982). Among the first to do so were Hulth et al. (1970), who excised the cruciate ligaments, the medial meniscus, and the medial collateral ligaments (MCLs) in rabbit knees. The resulting instability and altered joint mechanics mimic the response observed clinically after medial meniscectomy. The direct deleterious effect of abnormal contact pressure on articular cartilage has been documented repeatedly in animal models. Thompson and Bassett (1970) investigated the morphological changes in articular cartilage secondary to mechanical derangement. Elastic bands were used to apply continuous compression across an adult rabbit knee while allowing physiological motion. In addition to cartilage degradation, hypertrophic changes in the subchondral bone were noted, consistent with the observations presented by Truea (1963) based on the study of the histology and morphology of human osteoarthritic hip specimens. Pathological changes were observed in the deep chondral layer and subchondral bone, presumably in response to abnormal mechanical demands.

Springs applied across rabbit elbows were used by Gritzka et al. (1973) to provide continuous compression while allowing physiological motion. The springs exerted estimated contact pressures between 11 and 27 kg/cm². In that range, the severity of cartilage damage correlated with the duration rather than the magnitude of the compression. The cartilage matrix initially underwent fibrillation, ultimately resulting in complete erosion. Alternatively, a unilateral spring can be applied to eccentrically load the articular surface, indirectly simulating the conditions common in malaligned limbs. Ogata et al. (1977) used this method in the rabbit knee, altering stress transmitted across the joint less dramatically. Steinmann pins placed in the medial femoral and tibial condyles were connected with a spring to apply a continuous force of 700–900 g, simulating a constant varus stress. This experimental model closely mimicked the clinical situation and created gradually progressive lesions. Even when this small increase in varus stress was applied, the duration of mechanical derangement seemed to be more important than the magnitude of the derangement in determining the severity of cartilage damage. Although this model effectively simulates malalignment, it does not specifically duplicate the mechanical derangement resulting from angular deformity.

Reimann (1973) was one of the first to directly document the detrimental effects of malalignment in a laboratory animal model by creating a 30° varus osteotomy in the proximal tibia of adult rabbits. She concluded that one can induce degenerative changes in articular cartilage by disturbing the mechanical axis and altering the load bearing to create clear initial histological changes analogous to human osteoarthrosis.

Johnson and Poole (1988) successfully induced degenerative arthropathy in a canine model using a unilateral proximal tibial varus osteotomy. Wu et al. (1990) investigated the effects of malalignment in a rabbit model similar to that used by Riemann (1973) with either a valgus or varus proximal tibial osteotomy of 30°. They found degenerative changes in the articular cartilage, increased subchondral bone thickness, and reduced trabecular porosity, reflecting the alteration in mechanical stress transmission secondary to the malalignment produced by the osteotomies.

Repetitive impulse loading is the laboratory model that may best simulate the histological and morphological changes observed in human osteoarthrosis specimens (Radin 1978). Subcritical loads applied to articular cartilage in a pulsed fashion on an intermittent basis during a period of weeks leads to stiffening of the deep chondral layer (calcified cartilage and subchondral plate). Increases in shear stress in the overlying articular cartilage then create local concentrations that lead to degeneration of the cartilage base, with subsequent changes characteristic of degenerative arthropathy. Radin et al. (1991) recently summarized the evidence to support the concept that altered loading affects the stiffness of the deep chondral layer. High shear in the overlying cartilage results in splitting and degeneration at the cartilage base without disruption of the tangential layer at the articular surface. Cartilage thickness gradually diminishes as the tidemark and then advances into the deep chondral substance. Based on observations of laboratory animals, increased density and stiffness in the deep chondral layer seems to be an important component of the final common pathway for articular cartilage degradation and degenerative arthropathy resulting from malalignment.

Cadaver Laboratory Models

Pressure-sensitive film can be used to assay the alteration in stress transmitted across cadaver joints under simulated clinical conditions, and this technique has been applied extensively (Mckellop et al. 1994; Tarr et al. 1985; Ting et al. 1987; Wagner et al. 1984) to investigate the effect of tibial angular deformity on contact pressures in the ankle. Laboratory studies conducted at the Kerlan Jobe Orthopaedic Clinic in Southern California (Tarr et al. 1985; Wagner et al. 1984) showed changes in contact area, contact shape, and contact location across the tibiotalar articulation after simulated angular malunions of the tibia. The results suggested that changes at the tibiotalar joint were greater with distal third tibial
deformities compared with deformities at more proximal levels. Contrary to conventional teaching, contact area across the tibiotalar joint was altered more dramatically with deformities in the sagittal plane than in the coronal plane. Distal third deformities with recurvatum or procurvatum produced a greater change than those with varus or valgus, and those deformities in recurvatum produced the greatest changes in contact shape and the most profound reduction in contact area. Inman (1976) reported that articular congruity between ankle mortise and trochlea is best in neutral flexion and that congruity diminishes with both plantar flexion and dorsiflexion. Simulated fracture malunions in recurvatum would require the foot to be positioned in plantar flexion to achieve plantigrade contact with a level surface. This position leaves the talar dome relatively uncovered and potentially at greater risk for later developing degenerative arthropathy.

The subtalar joint acts as a torque transmitter and compensates for varus or valgus deformities in the tibia (Inman 1976), but hindfoot stiffness is common in post-traumatic conditions (McMaster 1976). The Kerlan Jobe group later repeated the initial series of experiments with the subtalar joint immobilized by a Steinmann pin to account for possible compensation by the subtalar complex (Ting et al. 1987). Subtalar motion played a significant role, and restriction of this joint affected the contact area for all deformities of the tibia as the resultant fracture angle was increased (Fig. 13-5). When subtalar motion was restricted, the ankle contact area decreased significantly in all planes of angular deformity. Restriction of the subtalar joint had a greater effect on the ankle contact area with varus deformities than with valgus deformities. Based on these results, in the presence of concomitant hindfoot stiffness, distal third tibial angular deformities in valgus and recurvatum are potentially at greatest risk of subsequently developing degenerative arthropathic changes.

McKellop et al. (1991, 1994) expanded on this approach and used a similar model to assess the effect of tibial deformities on joint contact pressures in the knee. Using pressure-sensitive film in cadaver limbs, they were able to show a relationship between the magnitude of angular deformity and the level of the deformity, with a resultant increase in contact pressure across the knee (Fig. 13-6). Analogous to the results with contact pressures in the ankle, a particular magnitude of angular deformity has its greatest effect on the nearest joint; an angular deformity in the distal tibia affects contact pressure at the ankle, whereas angular deformities of the proximal tibia have a greater effect on contact pressure in the knee. Puno et al. (1987) had already suggested this, based strictly on geometric analysis. Rather than consider angulation exclusively, they calculated malalignment based on the magnitude of angulation and the level of the deformity. Unfortunately, although first to
document this important principle, they failed to accurately distinguish malalignment from malorientation. This has resulted in some confusion when interpreting the results of their subsequent clinical studies (Puno et al. 1991).

**Clinical Longitudinal Studies**

The association of malalignment with degenerative arthropathy after meniscectomy is well established (Allen et al. 1984), but the clinical course of an untreated malaligned limb is not. The natural history of idiopathic degenerative arthropathy is more difficult to document because of the protracted clinical course and the widespread availability of several effective therapeutic measures. There are no prospective studies to compare the different treatment options available and few longitudinal data to determine the clinical result in the absence of intervention.

Many of the natural history data were compiled in Sweden, the earliest by Ahlback (1968) who presented a radiographic review but failed to correlate symptoms with radiographic appearance. He did recognize the need for weight bearing films to assess the extent of articular cartilage erosion, but the initial radiographs that he reviewed were obtained with the patients supine, limiting the value of the observations. Hernborg and Nilsson (1977) reviewed 94 knees that did not undergo surgical treatment, with a follow-up duration of 10–18 years after initial radiographs had established a diagnosis of osteoarthritis. They successfully showed that the course of the disease is generally unfavorable; the conditions of half the patients deteriorated clinically, and improvement was rare. Varus deformity, especially in women, was associated with a poor prognosis. Odenbring et al. (1991) reviewed the clinical course of 189 knees with isolated medial unicompartmental degenerative arthritis that were followed for 16 years. The majority (62%) of the knees in the original study group underwent major knee surgery, either high tibial osteotomy or total joint arthroplasty. Only 16% (31 of 189 knees) of the initial study group survived and did not undergo surgery during the follow-up period. Of these 31 knees with medial arthritis followed for the course of 16 years, 65% had a poor result and 71% functioned on a low activity level. Of the 24 untreated knees followed with serial radiographs during the follow-up period, the arthropathy increased in severity in 83%.

An alternative means of investigating the natural history of malalignment is to consider the long-term follow-up of malunited fractures (Kettelkamp et al. 1988; Kristensen et al. 1989; McKeelop et al. 1994; Merchant and Dietz 1989; Puno et al. 1991; van der Schoot et al. 1996). Although most clinicians suspect that excessive angulation of a tibial fracture may predispose the adjacent knee or ankle to subsequent osteoarthritis, there is no general agreement regarding the acceptable limits for alignment after fracture reduction (Nicoll 1964; Rosemeyer and Pförringer 1979; Sarmiento et al. 1984). Recommendations are based largely on the clinical impressions and experience of various authors, taking into consideration disturbances of gait, appearance, and the potential complications of different methods of treatment. The cause of degenerative arthropathy is undoubtedly multifactorial, and although trauma is probably the most common inciting event, there are many other associated factors. Load transmission across joints reflects additional elements beyond mechanical alignment and joint orientation. Soft tissues, including muscles, ligaments, and meniscal cartilage, also participate in joint function, and pathological conditions in these associated structures may play an important role in determining the ability of articular cartilage to respond adequately to increased stress imposed by malalignment. Conversely, pathological conditions in associated structures may be well tolerated in the normally aligned limb, yet the malaligned limb may be predisposed to premature degenerative changes. These confounding variables have made it extremely difficult to obtain meaningful data from retrospective studies of posttraumatic deformity.

Consider also the effect of patient selection on the data pool. The residual angulation after a fracture heals is either acceptable or unacceptable to both the patient and the treating physician. When judged unacceptable, it is corrected, either for functional or cosmetic reasons. Alternatively, substantial radiographic angulation may be compensated by adaptations of gait or a reduction in activity level. If at some later point the limb becomes symptomatic, reliable forms of treatment are again readily available. It would, therefore, be very unusual for a malunited limb with significant deformity to develop degenerative arthropathy and not be corrected. Any retrospective study involving the long-term follow-up of malunited fractures is, unfortunately, fundamentally flawed by this inherent bias in patient selection. The converse is also true, and a retrospective review of a series of patients treated for arthritis developing secondary to fracture malunion would be similarly flawed.

Recognizing the limitations of these studies, the results nonetheless merit careful consideration. Kettelkamp et al. (1988) provided clinical data suggesting a direct relationship between malalignment and subsequent degenerative arthritis. Fourteen patients with malaligned fractures of either the femur or tibia were evaluated 32 years after the initial injury. Using static force analysis, they noted that an increase in the angulation of the knee, beyond that due to the original deformity, was approximately a linear function of the product of increased force on either the medial or lateral tibial plateau and time since original injury. They suggested

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that the unicompartmental degeneration observed during follow-up was a result of the increased stress and mechanical demands arising from the fracture angulation and malalignment. Unfortunately, the study population from which they drew their conclusions was highly selected and the data therefore skewed.

Several other groups have attempted to assess the possible consequences of tibial malunion, and therefore malalignment, on a consecutive series of patients in a retrospective fashion. Merchant and Dietz (1989) reviewed 37 patients with isolated tibial shaft fractures an average of 29 years after original injury. They found that varus angulation greater than 5° was associated with radiographic changes in the ankle, consistent with early arthrosis, but were unable to document any significant difference between fractures of the distal third compared with fractures of the proximal third. They were also unable to distinguish any significant difference in the radiographic appearance or clinical function of the adjacent knee and ankle in those patients with a combination of 5° of angulation in the frontal plane and 10° in the sagittal plane compared with those patients with less substantial angulation. Kristensen et al. (1989) reviewed 92 patients an average of 28 years after they had sustained an isolated fracture of the tibia. Only 17 patients had angulation exceeding 10°, but all had normal function of the ankle and no pain. None of the patients in their study group developed radiographic signs of arthrosis in either the ankle or the knee. Patients who reported mild or moderate pain had an associated restriction in the range of motion of the tibiotalar or subtalar joints, validating some of the results obtained in the cadaveric studies using pressure-sensitive film (Ting et al. 1987). The conclusions based on these two retrospective studies are in general agreement that limited angular deformity is of little clinical significance.

Unfortunately, both these retrospective clinical studies assessed angulation alone and failed to consider the additional elements that contribute to malalignment. These additional elements include not only the level of the deformity but also the presence or absence of concomitant translation. Translation in the coronal plane can either contribute to the overall malalignment and be considered aggravating or may diminish the malalignment and be considered compensating (Paley et al. 1990). It would be most interesting to reassess the data after measuring the extent of MAD to determine whether there is any correlation with clinical outcome.

Puno et al. (1991) retrospectively reviewed 28 tibial fractures 6–12 years after initial injury. The patients were evaluated by compiling a clinical rating based on pain, function, motion, and radiographic appearance. Malorientation of both the knee and ankle joints resulting from the tibial angular deformity was calculated using the mathematical method they had previously described (Puno et al. 1987). Patients were then classified according to the degree of knee and ankle malorientation and not only according to the magnitude of the angular deformity. However, again they failed to properly distinguish malignment from malorientation, making it more difficult and confusing to interpret the results. They were able to document a significant correlation between clinical outcome and ankle malorientation but were unable to show any significant correlation between clinical outcome and knee malorientation. Their results suggest that malorientation, not simply angulation, is important in determining the possibility of progression to premature degenerative arthritis after malunion of an isolated tibial fracture. Malorientation is a function of the level of the apex of deformity and the magnitude of the angular deformity.

van der Schoot et al. (1996) published a retrospective analysis of isolated tibial shaft fractures and attempted to correlate angular malunion with degenerative arthropathy in the adjacent joints. A total of 88 patients were available for follow-up an average of 15 years after sustaining the injury. They reported a significant relationship between tibial malalignment and subsequent development of degenerative changes in the knee and ankle, but the data are unimpressive. The authors did determine the true magnitude of the deformity by a geometric calculation but failed to determine the extent of malalignment using standing long radiographs. Although 10 fractures healed with an angular deformity greater than 10°, this group was not distinguished from the others during statistical analysis. The data focused instead on the association of previous fractures and subsequent development of degenerative arthropathy. This is of some interest, but it fails to address the fundamental question regarding the possible relationship between malalignment and late articular cartilage degradation.

Frontal plane malalignment not only affects the distribution of load across the medial and lateral compartments of the knee but also disturbs the relationship of the patella to the trochlear groove. Elahi et al. (2000) investigated this in depth, using radiographic methods, and showed that both varus and valgus malalignment can increase the risk of patellofemoral osteoarthritis. In a review of 292 patients with degenerative osteoarthritis, the mechanical axis was assessed using standing long radiographs. The direction of the deformity correlated well with the patellar facet involved: lateral with valgus and medial with varus. Although not specifically addressed, superimposed malrotation could further influence this relationship. Combined valgus and external rotation likely has the greatest risk of premature lateral patellofemoral arthrosis.

Malalignment alone may not be responsible for osteoarthritis but is a predisposing factor. Additional factors must also be considered that reflect the demands placed on the joint over many years. Sharma et al. (2000) confirmed the intuitive relationship between obesity,
varus malalignment, and the severity of medial gonarthrosis. Varus malalignment was only one factor that, over time, rendered the knee more vulnerable to the effects of obesity.

In this chapter, we have emphasized the importance of proper alignment of the lower extremity to avoid pathological loading that could lead to osteoarthritis. However, it is just as important to maintain correct alignment in cases of total knee replacement (TKR) (Krackow 1983). A malaligned knee prosthesis can lead to early loosening and premature excessive wear of the polyethylene (Ritter et al. 1994). Ligamentous imbalance after TKR leads to faulty tracking, abnormal component contact, and excessive polyethylene wear. Mont (unpublished results) has described six potential malalignment pairs in association with TKR: varus-valgus, flexion-extension, internal-external rotation, medial-lateral displacement, proximal-distal displacement, and anterior-posterior displacement. Each of the three prosthetic components (patella, tibia, femur) could theoretically be malaligned in any combination of the above mentioned malalignment pairs, thus rendering a potential 108 combinations of malalignment. In addition, components can be undersized, leading to bone overload, and oversized, leading to limitation of motion and soft tissue pain.

Malalignment in cases of TKR may occur in association with preexisting bone deformities and/or ligamentous laxity. Bone resection and soft tissue balancing can be performed at the time of TKR to address some but not all of these preexisting conditions. In certain more severe cases, particularly if the bone deformity is not adjacent to the knee (as may occur in femoral diaphyseal malunion, for example), it may be necessary to treat the bone malunion before attempting TKR. In our experience, realignment of severe deformities in preparation for TKR results in such a satisfying clinical improvement that TKR is no longer required. The technical details and considerations of bone resection and soft tissue balancing have been described (Hungerford and Mont, unpublished results) (Hungerford 1983; Krackow 1983; Laskin 1981; Wolff et al. 1991) (see Chap. 23).

Summary

The axial relationship of the joints of the lower extremity reflects both alignment and orientation. Static considerations are useful for preoperative planning and deformity correction, but dynamic considerations, including compensatory gait, may be more relevant clinically. Laboratory animal models have been developed that simulate the deleterious effect of malalignment on articular cartilage. Malalignment disturbs the normal transmission of force across the knee, and altered stress distribution related to deformity has been shown in cadaver models using pressure-sensitive film. No prospective data are available to document the natural history of malalignment, but several retrospective studies suggest that the clinical course is one of gradual progression resulting in degenerative arthropathy. The long-term follow-up of fractures is less definitive and is difficult to interpret, considering the bias inherent in patient selection. Although direct clinical evidence of a cause and effect relationship between malalignment and arthropathy has not been possible, substantial evidence from the orthopaedic literature supports this hypothesis.

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