The Pathophysiology of Osteoarthritis: A Mechanical Perspective on the Knee Joint

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Abstract: Osteoarthritis (OA) is the most frequent cause of disability in the United States, with the medial compartment of the knee being most commonly affected. The initiation and progression of knee OA is influenced by many factors, including kinematics. In response to loading during weight-bearing activity, cartilage in healthy knees demonstrates spatial adaptations in morphology and mechanical properties. These adaptations allow certain regions of the cartilage to respond to loading; other regions are less well suited to accommodate loading. Alterations in normal knee kinematics shift loading from cartilage regions adapted for loading to regions less well suited for loading, which leads to the initiation and progression of degenerative processes consistent with knee OA. Kinematic variables that are associated with the development, progression, and severity of knee OA are the adduction moment and tibiofemoral rotation. Because of its strong correlation with disease progression and pain, the peak adduction moment during gait has been identified as a target for treatment design. Gait modification offers a noninvasive option for seeking significant reductions. Gait modification has the potential to reduce pain and slow the progression of medial compartment knee OA.

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INTRODUCTION

Osteoarthritis (OA) is the most frequent cause of disability in the United States, with the medial compartment of the knee being most commonly affected [1]. OA is a condition with a multifaceted etiology that afflicts both load-bearing and non–weight-bearing joints. The risk of developing OA substantially increases with each decade after the age of 45 years [2]. Among reported upper and lower extremity sites, the most common region for OA to manifest is the medial compartment of the knee, and the knee will serve as the model for discussion in this review [1].

The initiation and progression of knee OA involves mechanical, structural, genetic, and environmental factors. During growth and development, the tibial and femoral cartilage adapt over time to cyclic loading during walking [3]; cartilage remodeling to loading also applies to other joints such as the hip [4]. Because knee cartilage thickens in the areas of greatest loading in both the anterior-to-posterior and medial-to-lateral regions [3], the tibiofemoral mechanics and loading patterns during walking have a significant influence on the regional development of articular cartilage. Disruption of normal gait mechanics with trauma, acute injury, ligamentous laxity, weight gain, and improper footwear can shift the loading patterns during weight-bearing activity to cartilage regions not well adapted to accepting those loads [3,5-10]. Although normal healthy cartilage responds positively to loading and increases regional thickness, diseased or injured cartilage degenerates and decreases regional thickness [3].

Although several potential biomechanical alterations may contribute to the onset and progression of knee OA, increased internal tibiofemoral rotation and peak knee adduction moment (M_{add}) during load bearing are 2 factors of particular interest. The M_{add} is recognized as a clinically important measure to study medial compartment knee OA [11,12] and is a surrogate for medial contact force [13], disease severity and progression [14,15], and pain severity [16]. Normal tibiofemoral loading may be altered in knees with either

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anterior cruciate ligament (ACL) deficiency or OA and may shift the weight-bearing stressors to cartilage regions not previously adapted for load bearing [5]. The loading of these nonadapted regions leads to cartilage fibrillation and local degenerative changes [3,5,17,18]. Correcting abnormalities of tibiofemoral rotation and/or decreasing the M_{add} are clinically relevant for the management of OA symptoms and progression.

This review will provide evidence regarding the potential roles of the separate and combined roles of tibiofemoral rotation and the M_{add} in the development and progression of knee OA. Emerging methods that favorably change these 2 parameters, and thereby OA symptoms, will be presented.

SETTING THE STAGE

With normal aging, cartilage breakdown begins in joint areas with little or no contact. As destruction advances, it moves gradually into the more heavily loaded areas. At this point, biomechanical factors such as loading patterns, tibiofemoral contact time, and motions about the joint generate shear and frictional stresses [4]. Cartilage softens and fibrillates. Aging or injury to the knee joint increases joint laxity and permits excess or aberrant motion about the knee, a process that exacerbates progression of OA.

TIBIOFEMORAL ROTATION

The knee joint is commonly thought of as a hinge joint with pure hinge-like motion. However, the anatomic structure of a femoral condyle is similar to a cam. As the femur rotates over the articular surface of the tibia, the motion involves both rotation and anteroposterior translation. Importantly, cartilage develops with variations in regional thickness as a consequence of the loading occurring during normal gait [3,5,17]. Thickness maps of cartilage reveal that cartilage regions are thickest at the lateral facet of the tibia and thinnest on the medial facet [19]. Alterations in patterns of knee kinematics cause a shift from normal articular contact areas to articular areas that are infrequently loaded. Aberrant loading of these areas causes fibrillation of the collagen network, loss of matrix proteoglycans, increased surface friction, increased shear stress, upregulation of catabolic factors (eg, matrix metalloproteinases and interleukins), and ultimately cartilage degradation [3,5,17]. ACL injury, ligament laxity or stiffness, decreased muscle strength, and altered muscle activation patterns can alter normal joint kinematics [3,5,17].

During knee flexion and extension, the femur and the tibia rotate and translate relative to each other through the range of motion. During a typical walking gait cycle, the greatest weight-bearing loads occur at or near heel strike and are absorbed by the areas of thickest cartilage development on the tibia and femur [5,19]. Compared with patients with healthy knees, patients with knee OA demonstrate greater femoral internal rotation, decreased tibial posterior translation, and dysfunction with the "screw home maneuver" during extension [20].

The normal rotation and translation of the tibia relative to the femur can be altered by such factors as ACL insufficiency or osteophyte formation [20]. The ACL provides anteroposterior as well as rotational stability to the knee. In patients with ACL tears, OA develops in 60%-90% of these knees within 15 years [21]. Injury to the ACL disproportionately affects the medial more than the lateral compartment. Medial compartment OA and meniscal tears are more likely to develop in knees with an ACL injury, probably as a result of the disproportionate load distribution in this compartment compared with the lateral compartment [3,5,19,21].

ACL deficiency provides a framework for understanding how alterations in knee kinematics can lead to degenerative changes in knee cartilage [3,5,19,21]. In ACL-deficient knees, the tibia remains internally rotated throughout the stance phase and the end of the swing phase compared with the control limb [5,19]. This offset leads to loading of cartilage regions not typically loaded before the ACL injury. Interestingly, ACL reconstruction has been shown to restore normal AP stability but does not consistently restore normal rotational alignment or motion [5,19]. Because knees that have undergone ACL reconstruction have a greater incidence of knee OA compared with noninjured knees, these data suggest that alterations in knee rotation influence the development and progression of knee OA [5,19].

This shift in articular contact to the medial tibial facet can be problematic. Although the lateral and medial femoral condyles are both shaped like cams, the 2 tibial surfaces with which these condyles make contact are shaped differently (Figure 1). Andriacchi et al [19] proposed that when exposed to the same joint displacement with any kinematic change, the medial femoral condyle will experience increased contact with the concave tibial surface with lower cartilage thickness than will the lateral condyle, which will experience less contact with the convex tibial facet with relatively thick cartilage. Over time, the repeated daily loading with an increase in internal rotation will adversely wear the areas of thinnest cartilage first, causing initial cartilage breakdown. Continued exposures of the vulnerable thinner cartilage to greater internal rotation will advance cartilage wear and induce symptomatic OA. Thus changes in tibiofemoral rotation that contribute to OA are complex and include the degree of internal rotation, location of rotation, and amount of contact exposure on the medial compartment.

PEAK KNEE M_{add}

M_{add} describes the load distribution across the medial and lateral tibial plateaus [5]. During normal ambulation in healthy knees, the medial compartment experiences 60%-80% of the weight-bearing load [21]. Conceptually, the M_{add}

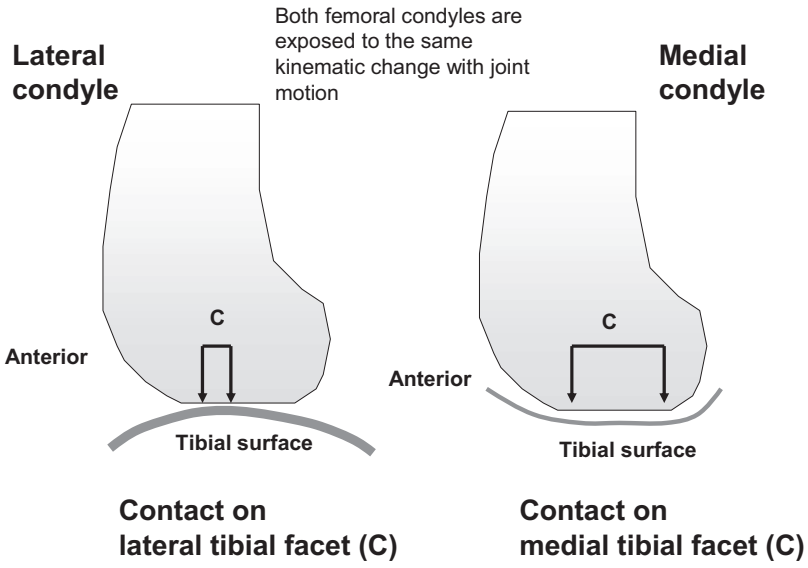

Figure 1. A comparison of the tibiofemoral contact on the lateral and medial joint compartments (lateral view). When exposed to the same kinematic change during motion, the medial femoral condyle experiences greater contact with the medial tibial facet relative to the lateral joint compartment.

can be considered the "closing force" on the medial knee compartment during gait [22]. Radiographic imaging routinely shows that joint space narrowing is present to a greater extent in the medial compartment compared with the lateral compartment. Knee malalignment that places the joint into a varus position can increase loading on the medial side of the joint. Static alignment alone does not predict the incidence of OA [23]. However, degeneration of the joint during progression of OA can cause an increase in varus malalignment [24].

During dynamic movements, medial joint loading can be estimated by measuring the M_{add} (Figure 2). The M_{add} is produced when the foot is in contact with the ground and the line of action of the force vector passes medial to the knee joint. An increased distance between the force vector and the knee joint will result in a greater M_{add} and greater loading on the medial joint. Varus alignment will cause the knee joint to move laterally relative to the position of the foot on the ground, which increases the M_{add}. On the contrary, shifting

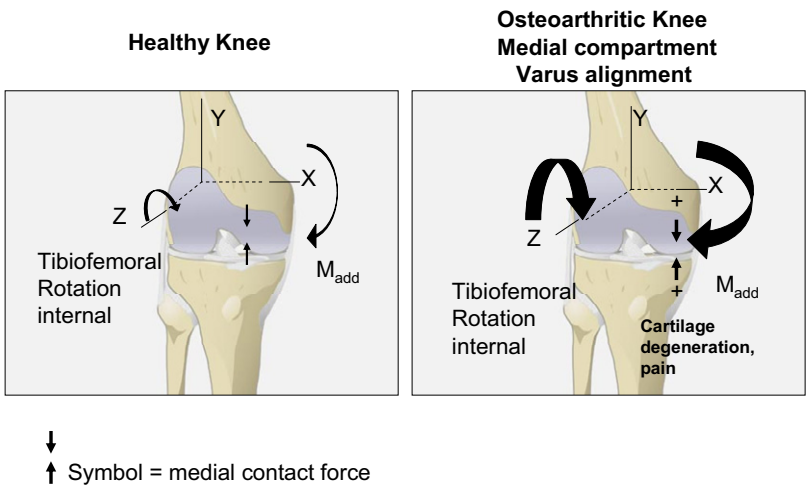

Figure 2. Summary of the knee adduction moment (M_{add}) and internal tibiofemoral rotation about the knee during loading in ambulation in healthy knees and knees with medial osteoarthritis (frontal view). Forces and rotation are shown relative to the X, Y, Z coordinate system. The thicker the arrows, the greater the forces or rotation. Greater M_{add} and internal rotation increase medial contact force; over time, the cartilage degenerates, and osteoarthritis develops and progresses.

the position of the trunk laterally can move the line of action of the ground reaction force more medial, which can decrease the M_{add} moment [25]. Increasing the M_{add} has been associated with the progression and possibly the initiation of knee OA [3,5,7-9,26]. Furthermore, the M_{add} during walking predicts OA severity, progression, and clinical outcomes in patients with medial compartment knee OA [3,26].

In patients with mild OA, medial compartment loading can distinguish between those who are symptomatic and those who are asymptomatic [16]. Interestingly, in healthy persons, the medial/lateral cartilage thickness ratio is highest in those who demonstrate the highest M_{add}. In persons with OA, however, the cartilage is thinnest in persons with the highest M_{add} [4].

Increasing gait speed increases the ground reaction force and net joint forces and moments experienced at the joint level. Persons with OA walk more slowly compared with asymptomatic patients, which presents a confounding factor when interpreting studies in which subjects walked at a self-selected speed. In most studies [27,28] with the exception of Zeni and Higginson [29], the changes in M_{add} are not completely explained by gait speed and seem to indicate that some fundamental gait adaptation has occurred to attempt to unload the medial compartment of the knee.

MODIFYING THE PEAK KNEE M_{add}

Footwear and Assistive Devices

At least 7 assisted gait modifications can reduce the peak M_{add}, including the use of lateral wedge insoles [30,31], lateral wedge insoles combined with subtalar strapping [32], variable stiffness shoes with softer medial sides [33] or high-mobility shoes (which act similarly to natural foot flexibility) [34], valgus knee braces that use 3-point bending [35,36], canes [37], and hiking poles to offset the M_{add} generated by the opposite knee [38]. The most effective assistive gait modification methods for reducing M_{add} include variable stiffness shoes, lateral wedge insoles with the addition of subtalar strapping, or bilateral hiking poles. The ultimate goal of reducing the peak knee M_{add} is to reduce peak medial contact force during the stance phase. For gait tests performed to date, variable stiffness shoes and valgus knee braces have produced the largest reductions in medial contact force.

Although walking with knees medialized and with hiking poles reduced the first and largest peak of medial contact force by only a small amount, these gait-modification methods reduced medial contact force significantly over the remainder of the stance phase [39]. Furthermore, elimination of excessive knee flexion during mid stance also may make these 2 methods effective at reducing the first peak [39]. The peak medial contact force reduction of 23% achieved by valgus knee braces should be viewed in light of the significant discomfort experienced by the subjects for this brace setting. Although these collective data do not show a causative effect of the M_{add} on the development of knee OA, strategies to modify the biomechanical mechanisms involved in symptomatic knee OA were obtained.

Gait Modification

Although high tibial osteotomy surgery can significantly reduce the peak M_{add} [40], gait modification may be a noninvasive alternative. The best outcome of gait modification would be to reduce the peak M_{add} similar to that achieved after a high tibial osteotomy surgery. In a number of studies, investigators have evaluated the ability of these different gait modification methods to reduce the peak M_{add}. Gait modifications that can reduce the peak M_{add} include walking with decreased speed [41,42], widening the base of support in one's stance [43], pointing one's toes outward [12,44,45], medializing the knees [39,46,47], and increasing the magnitude of medial-lateral trunk sway [48,49]. Of these methods, walking with knees medialized and a medial-lateral trunk sway have produced M_{add} reductions exceeding 10% and on the order of those achieved by high tibial osteotomy surgery.

Considerations in Data Interpretation

Several important points must be considered when interpreting data from gait modification research. First, when a patient's gait pattern is changed, a decrease in peak M_{add} does not guarantee a decrease in peak medial contact force. For example, in a study that explored the effect on peak M_{add} of walking with knees medializing or with hiking poles [39], both modifications produced little change in peak medial contact force, despite significant reductions in the peak M_{add}. Second, beneficial changes at the knee could induce detrimental changes at other joints [50]. Such changes are most likely to occur at the ankle or the lower back, where load changes are the largest depending on the gait modification. Because ankle OA induced by lateral heel wedges has not been reported, it is unlikely that gait modifications that alter ankle loads will be detrimental. Third, different M_{add} calculation methods yield different interpretations of the effectiveness of a particular gait modification [51]. Many studies do not provide details of how the peak M_{add} was calculated, making it difficult to compare results from different studies. Furthermore, several studies have suggested that the knee adduction angular impulse, which is the area under the knee M_{add} curve during stance phase, may be a better clinical target than M_{add} [16,52,53].

APPLICATIONS IN PHYSICAL MEDICINE AND REHABILITATION

The concepts relating to OA and altered biomechanical parameters between 2 articular surfaces might be applied to

joint degeneration in other joints or in medical conditions, as discussed in the following sections.

Onset of Knee OA After Lower Extremity Amputation

Among populations undergoing lower extremity rehabilitation, those with transtibial amputations demonstrate biomechanical alterations that contribute to the onset of OA in the intact limb. Some prosthetic foot characteristics significantly affect the M_{Add} of the intact knee during gait [54]. For example, prosthetic feet that generate low foot-ankle push-off appear to be associated with higher intact knee M_{Add}, and their use may increase the risk and burden of knee OA in this population [54].

Hip OA

In persons with hip OA, initial cartilage degeneration occurs in the fovea below the femoral head and medial/lateral areas of the femoral head—areas with low exposure to little loading or minimal contact. Once this occurs, the contact area and motion increase frictional shear stress that facilitate the onset of OA [4]. Also, the atypical cam-shaped femoral head may alter joint motion and articular contact area with the acetabulum compared with a normal, round femoral head. Over time, the repetitive stressors with average weight-bearing activity can exacerbate frictional stress within the hip joint, causing premature cartilage breakdown and OA.

The onset of hip OA might be related in part to participation in high-performance competitive sports such as the javelin and high jump. These sport motions induce high moments with high velocity rotation within the hip. Cross-sectional data of these athletes 10 years after retirement from their sport revealed that the odds risk of developing OA was 6.1 in javelin throwers compared with control subjects [55].

Overloaded Upper Extremity Joints and OA

In patients with a spinal cord injury, the mechanical loading of upper limb joints is significantly altered compared with before the injury. Signs and symptoms of mechanical overuse appear over time and can manifest as secondary arthritis. Maximal cartilage thickness can decrease as much as 8% at 1 year after the injury [56]. The increased use of the shoulder joint through an arc of resistance during wheelchair propulsion and through body transfers places high forces on articular surfaces in the shoulder for which they were not designed [57]. This high contact stress and distribution of the stress in patients with paraplegia were related to chronic joint pain and other impingement syndromes.

Although prospective data are sparse for elbow OA, the prevalence of the condition is heaviest in heavy manual laborers, weight lifters, and athletes who engage in throwing [58]. All these populations share common exposure of the elbow joint to high forces during rotation.

Foot and Ankle OA

Biomechanical alterations to joint motion and force also are evident in the ankle and foot in dancers. The foot and ankle are vulnerable to repetitive microtrauma during dance. The prevalence of joint degeneration was found to be greater in a group of retired professional ballet dancers compared with control subjects [59]. This finding might be explained in part by the stressors placed on the metatarsophalangeal and ankle joints compared with normal loading patterns. These joints support large forces, sometimes in excess of 20 kg/cm. Furthermore, these joints are rotated into positions in the extreme ranges of motion, which causes a valgus deformity [59]. Over time, the repeated trauma with practice and performing narrows the metatarsophalangeal joint space and increases the prevalence of arthritis.

CONCLUSIONS

Knee kinematics play an important role in the development and degradation of articular cartilage. Healthy cartilage responds to loading by adapting its morphology and mechanical characteristics in the areas of greatest stress. However, once normal joint kinematics are altered, loading shifts to areas that are not well suited to accommodate the increased stress. Once the OA cycle has been initiated, the loading that once facilitated cartilage adaption now serves to facilitate the progression of cartilage degradation [5,19]. Both surgical and nonsurgical strategies that serve to re-establish normal joint kinematics have been shown to be effective in decreasing pain and functional impairments and possibly slowing progression. By changing pathological joint mechanics, gait modification may have disease-modifying potential for medial compartment knee OA, at least in terms of slowing progression of the disease.

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