The mechanical placement of orthopedic magnets within the human knee joint
by Deborah A Barber

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering Mechanics
Montana State University

Abstract:
A mechanical analysis of an orthopedic knee implant is presented. The analysis is performed on an orthopedic knee implant that utilizes repelling magnets placed on the articulating surfaces of the tibia and the femur. The repelling magnets theoretically serve to decrease the contact force and friction within the knee joint. A three-dimensional mathematical model of the human knee joint is utilized to analyze the mechanical effects of the implants within the knee. The geometry of the surface and the effects of the ligaments are incorporated into the model. The model is evaluated at several flexion angles.

The placement of the magnets within the knee joint is varied, and magnet strengths are proposed. The model is then solved for the contact forces at the knee joint with and without the implanted magnets. The decrease in contact force due to the presence of the magnets within the knee joint is evaluated. The initial implant design consisted of a total of four magnets on the femoral surface, two medial and two lateral, and two magnets on the tibial surface, one medial and one lateral. The initial design was evaluated and the conclusion was made that a more effective design could be proposed. An implant that utilized a series of three magnets on both the medial and lateral femoral surfaces repelling against a single magnet placed on both the medial and lateral aspects of the tibial plateau was analyzed. The final conclusion was made that the alternate design using six magnets on the femoral articulating surface and two on the tibial articulating surface is indicated to be the preferred mechanical placement for magnets within the human knee joint. A summary of results for the initially proposed implant design and the alternative design options are presented.

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APPROVAL

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Deborah A. Barber

This thesis has been read by each member of the committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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$\mathbf{c}$	position vector of a point on the tibial surface
$\mathbf{a}$	vector connecting origins of coordinate systems
a_{ij}	coefficient of joint surface polynomial
$(\mathbf{e}_x, \mathbf{e}_y, \mathbf{e}_z)$	unit vectors in (x,y,z) system
$(\mathbf{e}_\alpha, \mathbf{e}_\beta, \mathbf{e}_\gamma)$	unit vector in (α, β, γ) system
f	force in a spring
$\mathbf{F_e}$	external force
k	spring stiffness constant
l	length between tibial and femoral spring insertion points
l_o	unstrained length of spring
m	number of springs
$\mathbf{M_e}$	external moment
$\mathbf{M_r}$	flexion-extension moment
n	degree of polynomial
$\mathbf{n}$	unit outward normal
$\mathbf{p}$	contact force
$\mathbf{r}$	position vector of spring, tibial insertion
$\mathbf{T}$	rotation matrix
(x,y,z)	tibial fixed coordinate system
(α, β, γ)	femoral fixed coordinate system

δ	position vector of a point on the femoral surface
ε_j	strain in spring
ε_{rj}	strain in spring in extension
λ	unit vector for direction of flexion-extension moment
ρ	position vector of spring, femoral insertion
τ_α, τ_γ	tangent vectors to femoral joint surface
ϕ	flexion-extension angle
ϕ^T	vector describing rotations
ψ, ω	rotation angles of the femur

ABSTRACT

A mechanical analysis of an orthopedic knee implant is presented. The analysis is performed on an orthopedic knee implant that utilizes repelling magnets placed on the articulating surfaces of the tibia and the femur. The repelling magnets theoretically serve to decrease the contact force and friction within the knee joint. A three-dimensional mathematical model of the human knee joint is utilized to analyze the mechanical effects of the implants within the knee. The geometry of the surface and the effects of the ligaments are incorporated into the model. The model is evaluated at several flexion angles. The placement of the magnets within the knee joint is varied, and magnet strengths are proposed. The model is then solved for the contact forces at the knee joint with and without the implanted magnets. The decrease in contact force due to the presence of the magnets within the knee joint is evaluated. The initial implant design consisted of a total of four magnets on the femoral surface, two medial and two lateral, and two magnets on the tibial surface, one medial and one lateral. The initial design was evaluated and the conclusion was made that a more effective design could be proposed. An implant that utilized a series of three magnets on both the medial and lateral femoral surfaces repelling against a single magnet placed on both the medial and lateral aspects of the tibial plateau was analyzed. The final conclusion was made that the alternate design using six magnets on the femoral articulating surface and two on the tibial articulating surface is indicated to be the preferred mechanical placement for magnets within the human knee joint. A summary of results for the initially proposed implant design and the alternative design options are presented.

CHAPTER 1

INTRODUCTION

The knee joint is the largest joint in the human body and one of the most complex. The joint consists of several structures including bones, ligaments, cartilage, muscles, and tendons. The complex mechanism that these structures make up allows the knee to perform its major functions: motion and the transmission of forces. When the structures of the knee begin to fail, however, the ability of the joint to perform these functions is greatly diminished. Damage to the knee joint can happen in many ways. One manner is through the effects of osteoarthritis. Osteoarthritis is a disease that attacks the articular cartilage that covers the ends of bones within a moving joint, such as the knee. In general, osteoarthritis affects the older population. This disease can cause great pain to those affected making weightbearing difficult or even impossible.

One method that has been utilized for many years to alleviate the pain and deformity associated with osteoarthritis is the replacement of the affected joint. As many as 150,000 total knee replacements are performed each year in the United States alone (Lancet, 1991). Long term results of total knee replacements are good with a success rate of 98% five years after the surgical implant. Although the results for the implants have been good, the surgery is extremely invasive, with a long rehabilitation time, and the procedure is quite costly. An alternative to total knee replacement has been proposed by Jore Medical Corporation. Their alternative proposes the use of repelling magnets to create a relatively friction-free environment within a joint to restore motion and to alleviate pain by not letting the damaged joint ends grate upon each other. The use of magnets in medicine has been well documented for decades, however few applications have been found in orthopedics. At this point, only the concept has been proposed and a general design developed.

The intention of this research is to determine the precise location and strength of these magnets within a knee joint to provide for optimal mechanic behavior. This will be achieved through the use of a mathematical model of the human knee joint developed initially by Wismans, et al. (1980) and elaborated on by Huiskes, et al. (1985, 1988, 1990, 1991, 1995) and Blankevoort et al. (1991). The location of the magnets and a potential design of the implant will be proposed.

The design of an implant for the knee is a complex procedure. Knowledge of the anatomy, physiology, and biomechanics of the joint is necessary. Also, a full understanding of the modeling process and the specific model utilized is needed. In the following paper, a full background of the structures and mechanics of the knee is presented and the new knee model developed. The implications of success in this research project are staggering with the possible result being a more effective implant that would be less invasive to implant with much lower projected costs than the knee replacements used today.

CHAPTER 2

THE KNEE JOINT

The knee is an extremely complex joint. It is made up of a number of components all of which play important roles in the functioning of the joint. In the following chapter, a general review of the anatomy and physiology of the knee as well as the motions of the joint will be presented. For those not familiar with the medical terminology used, brief descriptions are provided. A glossary of terms is also provided in the Appendix to utilize as a reference tool.

Anatomy is the study of the structures of the body and the relationships between them. Because it is the study of physical relations, a number of directional terms are necessary. The directional terms are all established from a reference axis known as anatomical position. In anatomical position, the person stands upright, facing forward, with feet on the ground, hands at the sides, and palms forward. Once in anatomical position, the body can be divided into a number of planes. A sagittal plane divides the body into left and right sides. A frontal plane divides the body into anterior and posterior (front and back) sides. Lastly, a horizontal plane divides the body into inferior and superior (bottom and top) sections. Now that the reference axis and the reference planes have been defined, a number of directional terms can be defined.

Directional terms are used to describe locations and functions of anatomical structures relative to each other. There are many directional terms used in the field of anatomy. However, only those that will be needed for understanding the language within this paper will presented. The directional terms discussed are: inferior, superior, superficial, deep, proximal, distal, medial, and lateral. Inferior means away from the head or toward the lower portion of a structure, while superior means towards the head or the upper portion of a structure. Superficial means toward or on the surface of the body, while deep is simply away from the surface of the body. Proximal is nearer to the attachment of an extremity and distal is farther away from the attachment (i.e. the wrist is distal to the elbow). As previously stated, anterior refers to the front of the body (or towards the front) and posterior refers to the back of the body. Lastly, medial structures are nearer to the midline of the body or a structure and lateral structures are further from the midline. Again all of these terms are reiterated in the attached glossary. While dealing with these terms, keep in mind that a structure, for example, can be both medial and lateral depending on what the structure is being referred to. All of these terms simply describe the relations between anatomical structure not their exact positions.

The knee is the largest joint in the human body. A joint is a junction between two or more bony components. A joint in the human body is comprised of several anatomical structures. The anatomical structures that play key roles in the structure and function of the human knee joint are bone, cartilage, tendons, ligaments, and muscle. All, with the exception of muscle, are types of connective tissue.

Connective tissue is the most abundant tissue in the human body (Totora, Anagnostakos, 1990). Connective tissue, in general, serves to protect, support, and bind structures together. The structure of the connective tissue at the cellular level determines the properties and function of a tissue. At the cellular level, all types of connective tissue are made up of cells present within an intercellular matrix. The connective tissue qualities are largely determined by the intercellular substances. The intercellular substances are nonliving and can be fluid, gellike, or fibrous or combinations of these. Each type of connective tissue discussed here has this basic structure. Following, a brief description of the structure, properties, and functions of each of the pertinent connective tissues is presented.

Bone is the hardest of all the connective tissues. At a cellular level bone is a connective tissue whose solid structure accommodates for its protective and supportive role. At the microscopic level, bone consists of cells and an organic extracellular matrix. Bone differs from the other types of connective tissue, in that, within the extracellular matrix, it also contains a high volume of inorganic compounds, primarily mineral salts. The arrangement of the minerals within the organic matrix contributes greatly to the mechanical abilities of bone. The minerals are embedded within fibers of protein collagen. These collagen fibers comprise the main portion of the extracellular matrix. These collagen fibers are extremely tough and pliable, yet they resist stretching. The layers of collagen fibers and mineral salts are "glued" together by a gelatinous substance consisting of protein polysaccharides. As a result, bone is a rigid material that is pliable enough to resist large stresses.

Bone has both physiological and mechanical functions. Physiologically, bone forms blood cells and stores calcium for use in the body. Mechanically, bone, in general, serves to provide support for the body, to act as a lever system to transfer forces and facilitate movement, and to protect internal organs. Bone is an anisotropic, viscoelastic material and is extremely dynamic with the ability to remodel in response to the forces and stresses applied to it. As a result, the structural and mechanical properties change with the forces acting on the bone.

There are four bones involved in the thigh and leg regions. They are the femur, tibia, fibula, and patella. These bones are shown in Figure 2.1 on the following page.

The femur (Figure 2.2) is the longest and heaviest bone in the body. Proximally, it articulates with the acetabulum of the pelvic girdle and distally, it articulates with the tibia. The distal end of the femur has several significant landmarks. The medial and lateral condyles of the femur are of particular importance. These condyles are the articulating surfaces on the femur relative to the knee joint. A condyle is defined as a large, rounded articular prominence on a bone. On the femur, these prominences are convex and asymmetric. The medial condyle is longer and larger than the lateral condyle, however the width of the medial condyle is slightly smaller than the width of the lateral condyle. Anteriorly, the condyles are separated by an asymmetric, shallow groove called the patellar surface where the patella itself articulates. Posteriorly, the condyles are separated by a depressed area called the intercondylar fossa.

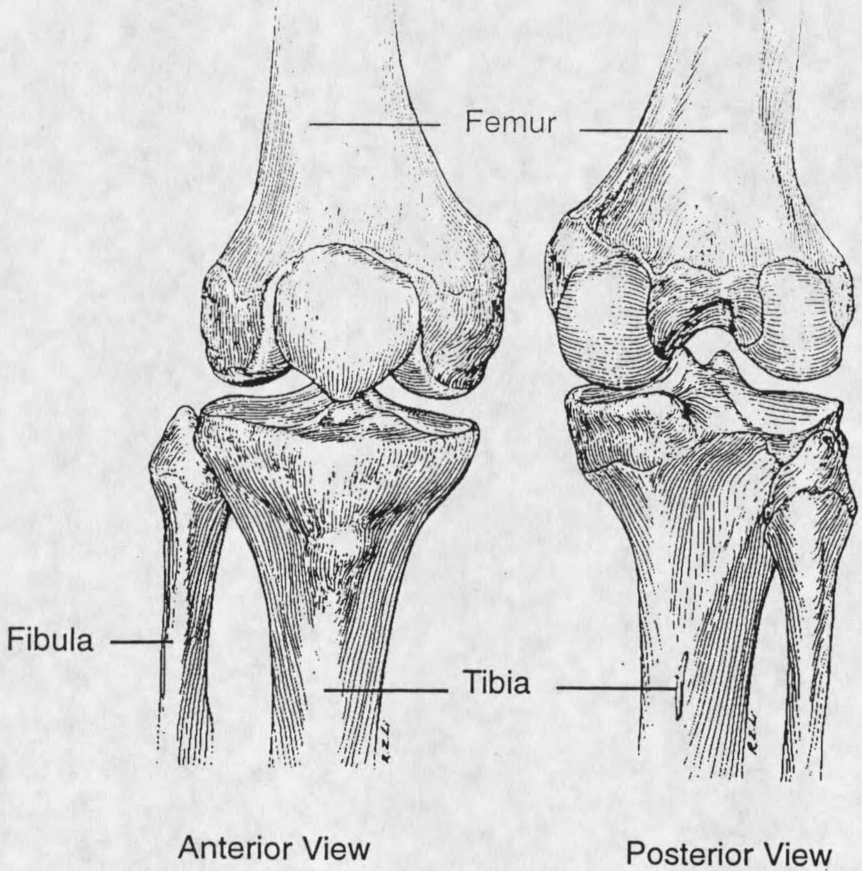

Figure 2.1

Bones of the Lower Limb

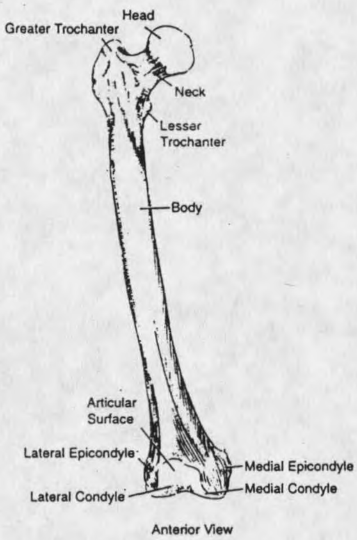

Figure 2.2

The Femur

The tibia (Figure 2.3) is the medial bone of the leg. This bone transmits the majority of weight of the body. The tibia articulates at the proximal end with the femur and the fibula and at its distal end with fibula and the talus bones of the ankle. The tibia expands at its proximal end into the medial and lateral condyles of the tibia which articulate with the femoral condyles. When comparing the femoral and tibial condyles, the circumference of the femoral condyles is twice as large as the length of the tibial condyles (Norkin, Levange, pp. 1983). The inferior surface of the lateral condyle articulates with the head of the fibula. The tibial condyles are also asymmetric, but are concave in shape. The articulating surface of the medial condyle is fifty percent larger than that of the lateral condyle (Norkin, Levange, 1983). The two tibial condyles are separated by a raised area called the intercondylar eminence. This proximal surface of the tibia is also referred to as the tibial plateau. Also of note is the tibial tuberosity. The tibial tuberosity is a roughened raised surface on the anterior side between the tibial condyles that serves as a muscle attachment site.

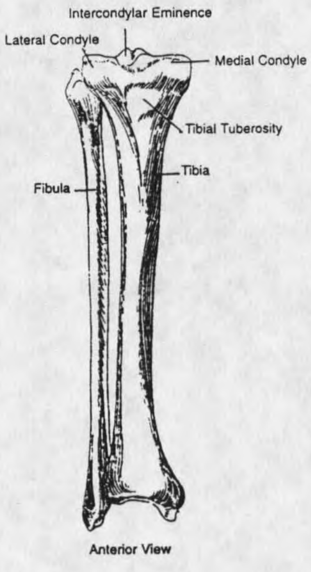

Figure 2.3

The Tibia and the Fibula

The fibula (Figure 2.3) and the patella are the two remaining bones. The fibula is lateral to the tibia and is much smaller. It is a nonweightbearing bone that serves mainly for the attachment of muscles. It articulates in the ankle but not in the knee joint. Lastly, the patella, or the kneecap as it is commonly known, is a sesamoid bone that forms within the quadriceps tendon. The patella articulates only with the femur.

The next type of connective tissue is cartilage. Cartilage is a relatively solid type of connective tissue that can resist deformation well. It is, in fact, much more resilient than bone. Cartilage consists of a dense network of collagen fibers embedded in an intercellular matrix. The matrix in cartilage consists of chondroitin sulphate, a jellylike substance. As a result, the strength of cartilage is due mainly to the collagen fibers, while the ability of it to return to its original shape can primarily be attributed to the chondroitin sulphate. The primary functions of cartilage are transferring forces between articulating bones, distributing forces within joints, and allowing joint to move with minimal friction.

There are two types of cartilage involved in the construction of joints. The first type is fibrocartilage. The intercellular area of fibrocartilage consists primarily of bundles of collagen fibers although elastin fibers may also be present. The collagen fibers in this type of tissue are thick and heavy making fibrocartilage an extremely strong tissue. Fibrocartilage must be so strong and rigid because it forms the intervertebral discs of the spine and the menisci of the knee joint and must withstand the weight of the body while allowing for joint movement. The menisci of the knee are two (medial and lateral) asymmetric, wedge-shaped fibrocartilaginous joint discs that are located on the tibial plateau. The menisci serve two major purposes. First of all, they deepen the articulating surfaces of the tibia enhancing the stability and improving the congruency of the articulating surfaces. And, secondly, they help to distribute the load across the joint during weight bearing.

The second type of cartilage involved in the construction of joints is articular, or hyaline, cartilage. Articular cartilage is the most common type of cartilage in the body. In articular cartilage, the cells are widely separated by the intercellular substance. The intercellular substance in articular cartilage consists of collagen, water, and protein-polysaccharides. As a result of its basic structure, articular cartilage has a glassy appearance and provides for a smooth surface. This type of cartilage can primarily be found covering the ends of bone at joints that are freely moveable. The main functions of articular cartilage are to absorb shock and to reduce friction within the joint. The large amount of water present in articular cartilage facilitates its ability to perform these functions. During joint motion when the joint is compressed, the fluid flows out of the cartilage and into the joint. After joint compression ceases, the fluid flows back into the cartilage tissue. As a result of the presence of this fluid, healthy articular cartilage provides an articulating surface that is relatively friction-free.

Tendons and ligaments are the next types of connective tissue. They are both comprised of a special type of connective tissue called dense connective tissue. Dense connective tissue is characterized by close packing of collagen and elastin fibers. In ligaments, collagen fibers are mixed with elastin fibers, while in tendons primarily collagen fibers are present. These constitutive differences are a result of the functions that they each must perform. In the body, ligaments connect bone to bone and tendons connect muscles to bone. The arrangement of collagen fibers and the amount of elastin fibers present vary from joint to joint depending on the extent of stability and mobility that the tendons and ligaments must provide within a joint.

Although there are many ligaments and tendons present in the knee joint (Figure 2.4), only a few will be discussed here. The first are the collateral ligaments. There is a medial and a lateral collateral ligament (MCL and LCL). The medial collateral ligament is a broad band that is fused posteriorly with the capsule of the knee joint. It runs from the medial condyle of the femur to the medial condyle of the tibia. The lateral collateral ligament runs from the lateral condyle of the femur to the head of the fibula. The collateral ligaments serve to provide medial-lateral stability of the knee joint. The next ligament is the anterior cruciate ligament, or ACL. The ACL arises from the anterior surface of the tibia