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Design of a Magnetorheological Prosthetic Knee

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Abstract
The magnetorheological (MR) prosthetic knee, which is the subject of this paper, is a device that has the potential to improve the biomechanical function of amputees. The knee was originally developed by MIT and put in production by Ossur Inc., a leading manufacturer of orthopaedic products. MR fluid is used to control the brake torque of the knee in response to a variable magnetic field. Hence, the stiffness of the knee can be controlled in real time as the amputee walks. This work is a part of a project to create finite element models of the knee, in order to study the effect of different design parameters, such as applied electrical current, electrical resistance, material properties and geometric shape on the magnetic flow. A sensitivity analysis of various design parameters shows variable sensitivity against the mean value of magnetic flux density. The results of the parametric study are then used to optimize the magnetic flow and hence optimize the design of the prosthetic knee with regards to function and efficiency.

Keywords: *Prosthetic knee, finite element modeling, optimal design*

Introduction
Regaining biomechanical function, comfort and quality of life is a prime consideration when designing prosthetic limbs. Recently, microprocessor-controlled prosthetic knees, which rely on magnetorheological (MR) technology, have become available and have the potential to meet these needs. The viscosity of the fluid in an MR fluid device is changed by an external magnetic source. Thus, the MR device can achieve a variable torque range through the control of an applied magnetic field. The MR prosthetic knee, which is the subject of this study, is an example of such a device. MR fluid is used to control the brake torque of the knee in response to a sensory input. Hence, the stiffness of the knee can vary in real time as the amputee walks. This results in a more natural movement of the prosthesis and a decreased fatigue level of the amputee.

Besides MR damping, the most common variable torque brakes that have been employed in prosthetic knees in the past are: dry friction brakes where one material surface rubs against another surface with variable force, and viscous torque brakes, using hydraulic fluid, squeezed through a variable sized orifice or flow restriction plate. Each of these technologies, including the MR damping, as conventionally practiced in the field of prosthetics, can pose certain disadvantages [1, 2]. The MR prosthetic knee can overcome some or all of the limitations of above technologies by providing a variable torque magnetorheologically actuated prosthetic knee [1, 2].

In addition to prosthetic devices, MR fluids have been used in many other magnetically controlled applications, including dampers, brakes, clutches, valves and shock absorbers, see for example [3, 4, 5, 6, 7, 8, 9]. Some examples of the reported advantages of these MR fluid devices are controllability, a high dynamic yield stress, allowing for small device size and a high dynamic range, simple construction of devices, low power requirements for control and fast response.

Since the torque transmissibility of MR devices depends much on the rheological properties of the MR fluid, it is important to fully understand its behaviour for different conditions. The focus of this work is to investigate the strength of the magnetic field in an MR prosthetic knee with the future goal to improve its design. The knee was originally developed by a group of scientists at MIT [2] and put in production by Ossur Inc. [1], a leading manufacturer of orthopaedic products. The knee uses a software based artificial intelligence to learn the individualt's walking style and provides a mechanism for continual monitoring and optimization of swing control. With application of a magnetic field, carbonyl iron spheres in the MR fluid are drawn together in electromagnetic chains. As the knee rotates into flexion or extension, thin rotary blades shear the particle chains to create resistance. The result is a varied fluid shear force within the knee, restoring more natural pelvic position during pre-swing and reducing fatigue levels. The response of the knee is exceptionally smooth and fast when walking into a light and free movement from a standstill, as well as when turning a corner or walking in confined spaces. Unlike existing hydraulic systems, magnetorheologic resistance is activated only when its needed and thus allowing more natural and effortless motion [1].

In the present study, a simple two dimensional finite element model, from the development phase of the product, has been significantly refined, with the purpose of determining the magnetic field in various components of the prosthetic knee. The magnetic field in the MR fluid relates proportional to the braking power of the knee, and thus the magnetic analysis is sufficient to perform a sensitivity analysis of the braking power with respect to various parameters involved in the knee design. The sensitivity analysis, which is conducted in this paper, involves changing the number of rotary blades, changing the geometry and material properties, for different values of applied current. The results give a valuable insight into which parameters should be prioritized for future changes and optimization of the prosthetic knee.

Description of the knee configuration

The MR prosthetic knee is one of the first product of bionics revolution in prosthetic solutions. The knee is a synergy of artificial intelligence, advanced sensor and MR actuator technologies. The specific technologies that achieve this synergy consist of a dynamic learning matrix algorithm, an MR fluid actuator, a microprocessor controlled stance and rheo logic software. The prosthetic knee is the first artificially intelligent knee system that has the ability to learn and adapt to its user's movements, resulting in continually improved and optimized performance [1].

The knee comprises of a central solid core in mechanical communication with a pair of rotating core side. This includes a magnetic coil, a plurality of blades or rotor in mechanical communication with a rotating inner spline, a plurality of blades or stator in mechanical communication with a rotating outer spline and a pair of ball bearings transferring rotary motion to a pair of outer side walls or forks. The inner parts of the knee are shown in detail on figure 1. The core and core sides are made of a magnetically soft material which creates a magnetic return path around the coil. The rotors and stators are arranged to form a plurality of small gaps between adjacent blades. The gaps comprise thin lubricating films of MR fluid which is sheared during knee rotation. The gaps have a size which is optimally minimized such that when the magnetic field has a zero value there is substantially no frictional contact between the blade and the core side. The magnetic coil is responsive to an electrical signal to generate a variable magnetic field to cause a controlled change in the viscosity of the MR fluid. The bearings are in rotary communication with the rotors and a shin portion of the lower limb to transfer rotary resistive torques from the knee to the shin portion.

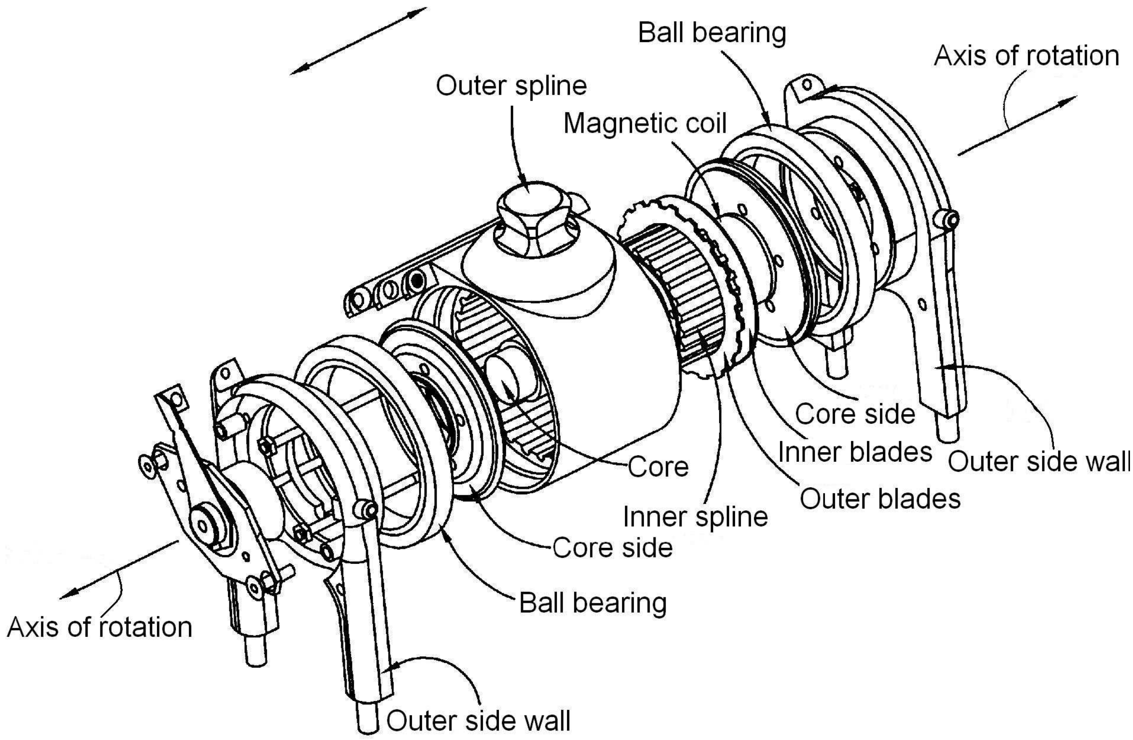

Figure 1: A detailed exploded perspective view of a magnetorheologically actuated prosthetic knee [2].

When the magnetic coil actuates a magnetic field, circuit or path is generated within the knee joint. The magnetic field passes longitudinally (parallel to the axis of rotation, see figure 1) through the central core, radially through the left core side, according to figure 1, laterally through the interspersed set of rotors and stators and the MR fluid, and radially through the right core side, according to figure 1. The orientation or positioning of the magnetic coil and the direction of current flow through it determines the polarity of the magnetic field, and thereby determines whether the magnetic field passes radially inwards or outwards through the left core side, and hence in the correspondingly opposite direction through right core side. The portion of the magnetic field passing through the core and core sides defines the magnetic return path while the active magnetic field is generally defined by the magnetic path through the rotors, stators and MR fluid residing in between [2].

Models and materials

A finite element model

A finite element model of the MR prosthetic knee was constructed in the modeling package Ansys [10], in order to accurately characterize its behavior. The prosthetic knee is approximated as an axisymmetric object; see figure 2, where the axis of symmetry is the leftmost line in the figure.

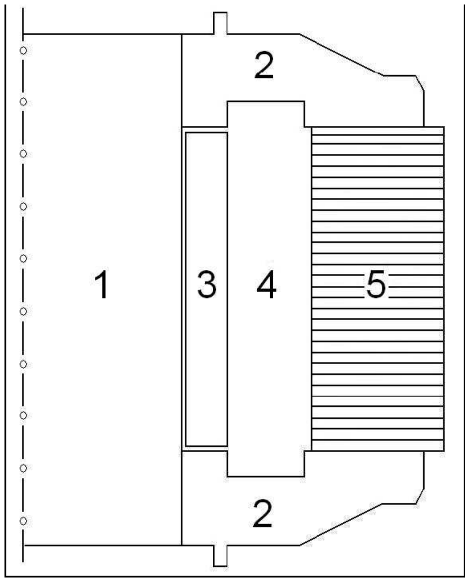

Figure 2: A schematic of an axisymmetric finite element model. 1) the core, 2) the core sides, 3) the magnetic coil, 4) the inner spline, and 5) the blades with MR fluid thins between.

Ansys includes a variety of elements that can be used in a magnetic analysis of a 2-D models. The PLANE53 element seems to be the most suitable for this analysis. The element treats 2-D, planar and axisymmetric, magnetic fields. It is defined by eight nodes and has up to four degrees of freedom per node: z component of the magnetic vector potential, time-integrated electric scalar potential, electric current, and electromotive force.

The model can handle nonlinear material properties and calculates magnetic flux in the knee which then can be used to determine the viscous braking power of the knee as a function of applied current.

Importance of materials with respect to the magnetic field

Two special purpose materials are used in the knee design. The first one is the MR fluid which contains 20 to 40% by volume of relatively pure, soft iron particles, e.g., carbonyl iron. These particles are suspended in carrier liquid; mineral oil, synthetic oil, water or glycol. The purpose of the iron particles is to form a chain between surfaces when subjected to a magnetic field, and thus increasing the viscosity of the fluid. Typically, the diameter of the magnetizable particles is 3 to 5 microns and only few of them are sufficient to bridge the gap between steel plates in the prosthetic knee.

The other important material is the core metal, CoFe alloy. This alloy has a very high threshold of magnetic saturation and is therefore ideal for carrying high density magnetic fluxes. This alloy are expensive materials, but its superior magnetic properties make it the only feasible material to use.

Analysis of design parameters

The finite elements model is used to test the knee against sensitivity of several design parameters. All these parameters can be changed easily without a change in the exterior geometric shape of the knee, however variation in these parameters results in significant difference in the internal structure of the knee. Valuable information for the design window of the knee is obtained by varying these parameters and observing the effect on the knee performance.

The magnetic field intensity was calculated for a variation in each parameter. Higher values of magnetic flux density in the MR fluid, imply a higher MR fluid viscosity, which in turn, causes more bending force and torque in the knee. The goal is therefore to receive as high a value of magnetic flux density in the MR fluid as possible.

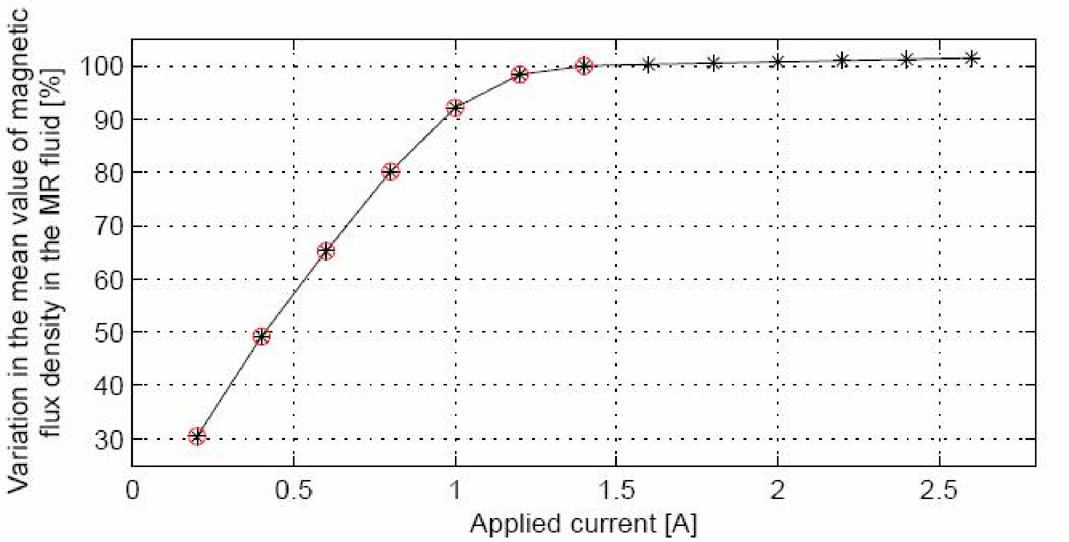

Figure 3: The variation in the mean value of the magnetic flux density in the MR fluid as a function of the applied current. The red circles in the figure denote the values currently in use.

Applied current

The applied current is a control parameter. The maximum current in the coil is normally 1.4 A. Figure 3 shows the mean value of the magnetic flux density in the MR fluid as a function of the applied current. In the figure and all the figures in following sections, the red circles denote the current working values. Other applications of using MR fluids [8, 7, 9] have shown that the mean value of magnetic flux density in MR fluids is highly dependent on the current in the coil. Figure 3 shows that a 30% decrease in the applied current results in an approximate 10% decrease in the mean value of magnetic flux density in the MR fluid. However, by increasing the applied current by 30%, the maximum value of the magnetic flux density in the MR fluid is quickly approached. This indicates saturation magnetization in the materials.

Material in the core and the core sides

The core and the core sides consist of CoFe alloy call Vacoflux 50, with a high saturation magnetization, which facilitates rapid kinetic responses when a magnetic field is applied to the MR fluid. Vacoflux 50 has the highest saturation magnetization of known materials, but it is extremely expensive. Therefore, it is interesting to study the option of using other materials in the core. Figure 4 shows the variation in the mean value of the magnetic flux density in the MR fluid as a function of the applied current for three different materials in the core and core sides; Vacoflux 50, Vacoflux 17 and Spring steel. The figure shows that Vacoflux 17 and Spring steel can not entail as high a mean value of the magnetic flux density in the MR fluid as Vacoflux 50. It is observed that Vacoflux 50 is clearly superior to the other two materials when used in core and the core sides.

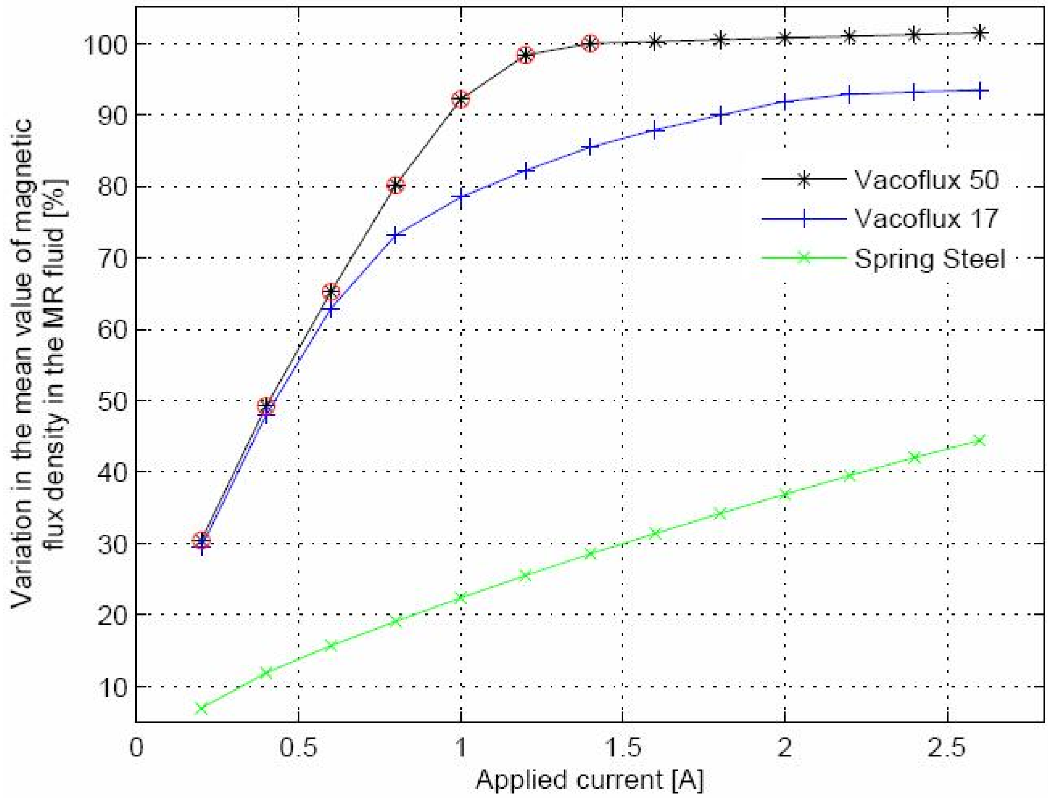

Figure 4: The variation in the mean value of the magnetic flux density in the MR fluid as a function of the applied current for three different materials in the core and the core sides. The materials are Vacoflux 50, Vacoflux 17, and Spring steel. The red circles in the figure show the values currently in use.

Number of blades

Generally, there are 59 blades in the knee as it is manufactured today. The model was tested against variation in the number of blades from 47 blades to 75 blades, without a change in the total thickness of the blades and the MR fluid gaps. That is without changes in the exterior of the knee. The thickness of each MR fluid gap is a constant. Therefore, remodeling the number of blades results in thicker or thinner blades. Figure 5 shows the variation in the mean value of the magnetic flux density in the MR fluid as a function of the variation in the number of the blades. The value of the number of blades has almost no influence on the mean value of the mean value of the magnetic flux density for the applied current of 1.4 A. For the applied current of 0.7 A and of 0.2 A, the mean value of the magnetic flux density increases with decreasing the number of blades. Reducing the number of blades, results in fewer MR fluid gaps, which in turn results in less MR fluid area in each knee and thicker blades. The MR fluid has lower saturation magnetization than the Spring steel, in the blades. Reducing the number of blades and the MR fluid area, and at same time enlarging total thickness of the blades will therefore result in higher mean value of the magnetic flux density. If the number of blades is enlarged, the reversed effect can be seen; the MR fluid area increases and the mean value of the magnetic flux density decreases.

Wall thickness of the core

The core is a solid cylinder with a diameter of about 20 mm and is made from Vacoflux 50. Reducing the wall thickness of the core will reduce the total mass of the knee which is an important design issue. It is therefore of interest to investigate the effect of making a hole in the center of the cylinder. Figure 6 shows the variation in the mean value of the magnetic flux density in the MR fluid as a function of the variation in the wall thickness of the core. The

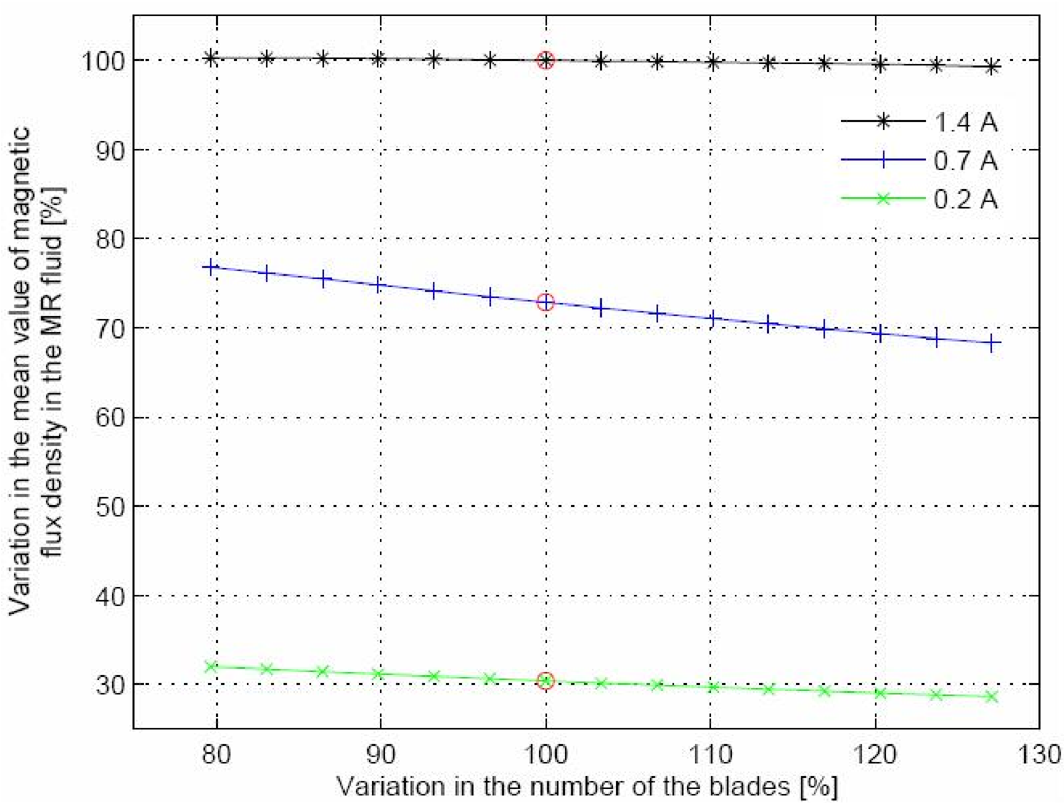

Figure 5: The variation in the mean value of the MFD in the MR fluid as a function of the variation in the number of the blades, for three values of the applied current: 1.4 A, 0.7 A, and 0.2 A. The red circles in the figure indicate the current working value.

wall thickness is reduced up to 75% in Figure 6. The mean value of the magnetic flux density decreases rapidly for applied current of 1.4 A. This causes saturation magnetization in the core. For applied current of 0.7 A, the same saturation magnetization is obtained by more than 50% reduction of the wall thickness. This shows that it is infeasible to reduce the total mass of the knee by reducing the amount of core material.

Radius of the core

Reducing the radius of the core causes increase in the inner spline and, reversely, enlarging the radius of the core causes decrease in the inner spline. Figure 7 shows variation in the mean value of the magnetic flux density in the MR fluid as a function of the variation in the radius of the core. The mean value of the magnetic flux density increases rapidly with enlarging the radius of the core for the applied current of 1.4 A. Enlarging the radius of the core has fast no effect for other values of the applied current. For reducing the radius of the core the mean value of the magnetic flux density decreases rapidly for applied current of 1.4 A. This causes saturation magnetization in the core; see also Figures 6. As for the the wall thickness of the core, this shows that it is infeasible to reduce the total mass of the knee by reducing the core. Enlarging the core can be option to increase the mean value of magnetic flux density in the MR fluid.

Radius of the coil

Decreasing the radius of the coil causes reduce in the number of turns on the coil and a larger inner spline. Increasing the radius of the coil causes increase in the number of turns on the coil and a smaller inner spline. The parameters the radius of the coil and the number of turns on the coil are thus directly proportional to each other. Figure 8 shows the variation in the mean value of the magnetic flux density in the MR fluid as a function of the variation in the

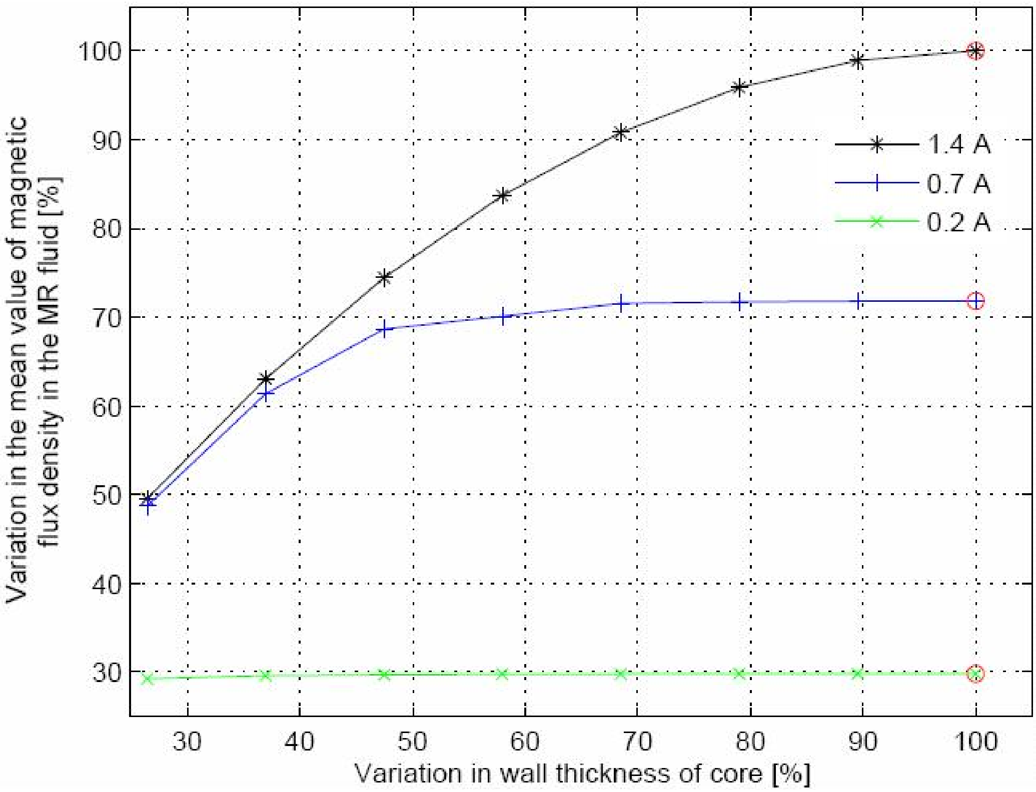

Figure 6: The variation in the mean value of the magnetic flux density in the MR fluid as a function of the variation in the wall thickness of the core, for three values of the applied current: 1.4 A, 0.7 A, and 0.2 A. The red circles in the figure show the value currently in use.

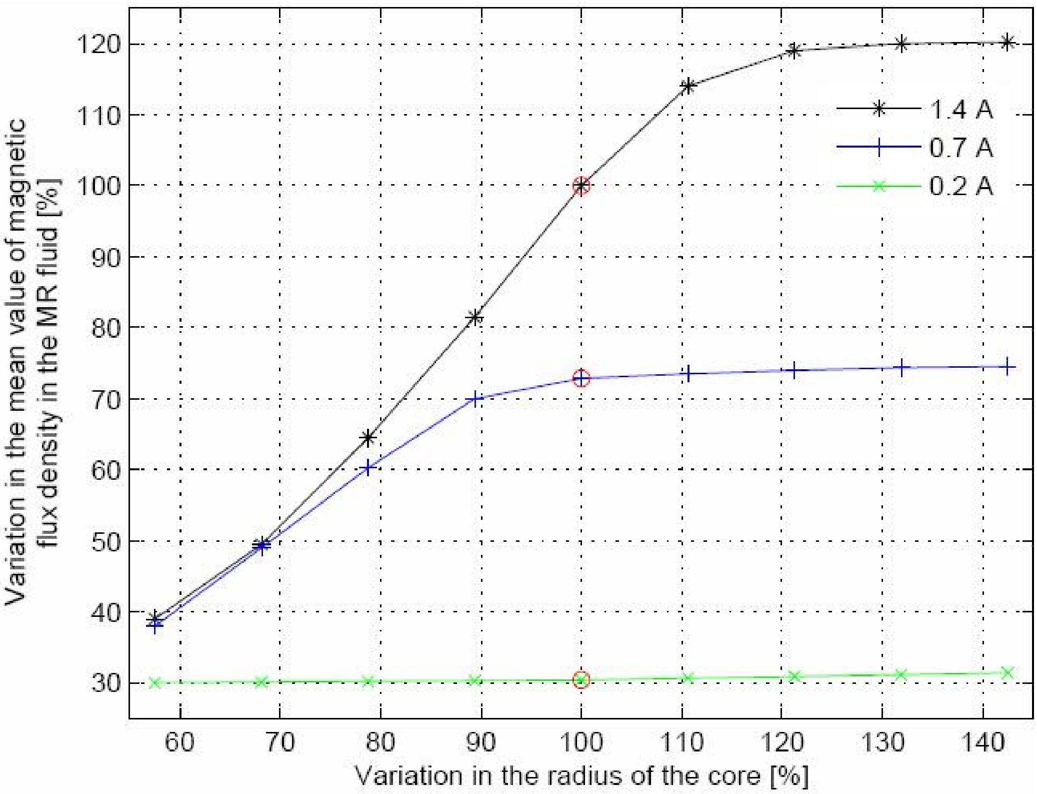

Figure 7: The variation in the mean value of the magnetic flux density in the MR fluid as a function of the variation in the radius of the core, for three values of the applied current: 1.4 A, 0.7 A, and 0.2 A. The current value used for the radius of the core is indicated with red circles in the figure.

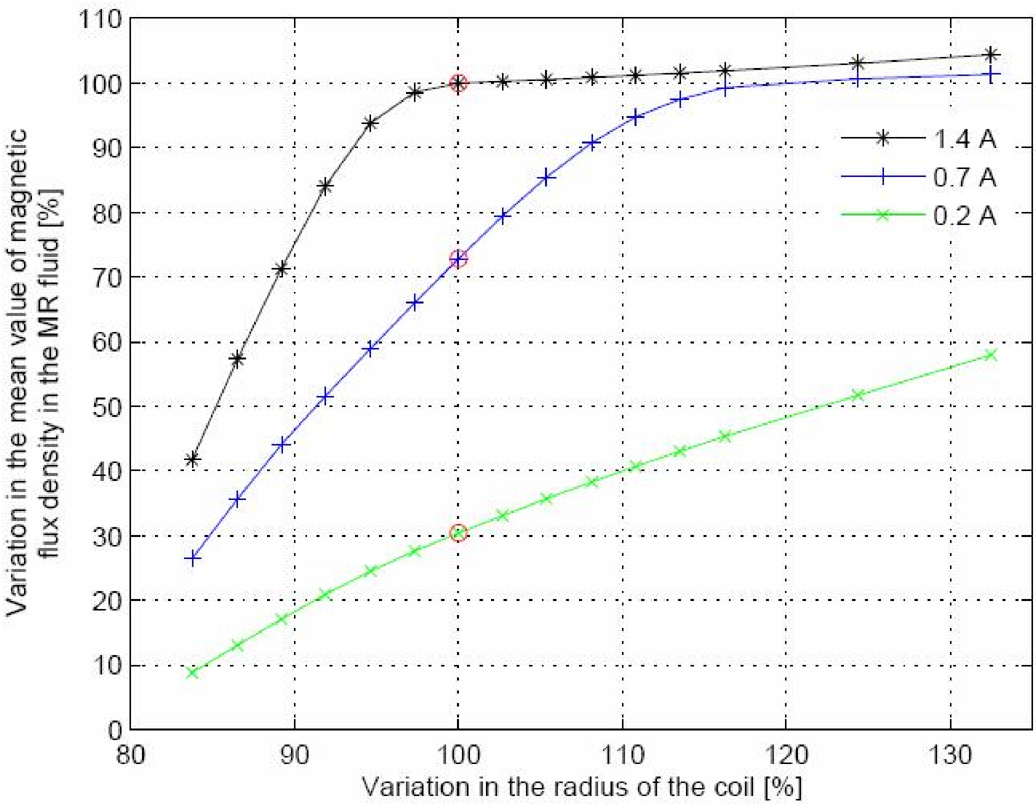

Figure 8: The variation in the mean value of the magnetic flux density in the MR fluid as a function of the variation in the radius of the core without an external change, for three values of the applied current; 1.4 A, 0.7 A, and 0.2 A. The red circles in the figure show the current working value.

radius of the coil. This figure shows the same effects as Figures 3, saturation magnetization is obtained for applied current of 1.4 A and the current working value of the number of turns on the coil. The same saturation magnetization can be obtained for the applied current of 0.7 A and a higher value of the radius of the coil. For the applied current of 0.2 A, the mean value of the magnetic flux density grows almost linearly with increasing the radius of the coil. For reduced values of the radius of the coil, the mean value of the magnetic flux density reduces rapidly for all tested values of the applied current.

Inner radius of the blades

The influence of the inner radius of the blades on the mean value of the magnetic flux density in the MR fluid is shown in Figure 9. Remodeling the inner radius of the blades changes the size of the MR fluid area in the knee directly. A decrease in the inner radius of the blades will increase the MR fluid area and reduce the inner spline. An increase in the inner radius of the blades will have the opposite effect. For the applied current of 1.4 A, the mean value of the magnetic flux density changes almost linearly with changes in the size of the MR fluid area, see Figure 9, until saturation magnetization is obtained. For the other values of the applied current, changes in the

The results from the sensitivity analysis show that the design parameters affect the knee performance differently, as expected. It is noticed that the number of blades has very little effect on performance, especially under full load at 1.4 A. On the other hand, the material in the core and the core side, the wall thickness of the core and the radius of the core are important variables and significantly changes the knee performance, if changed.

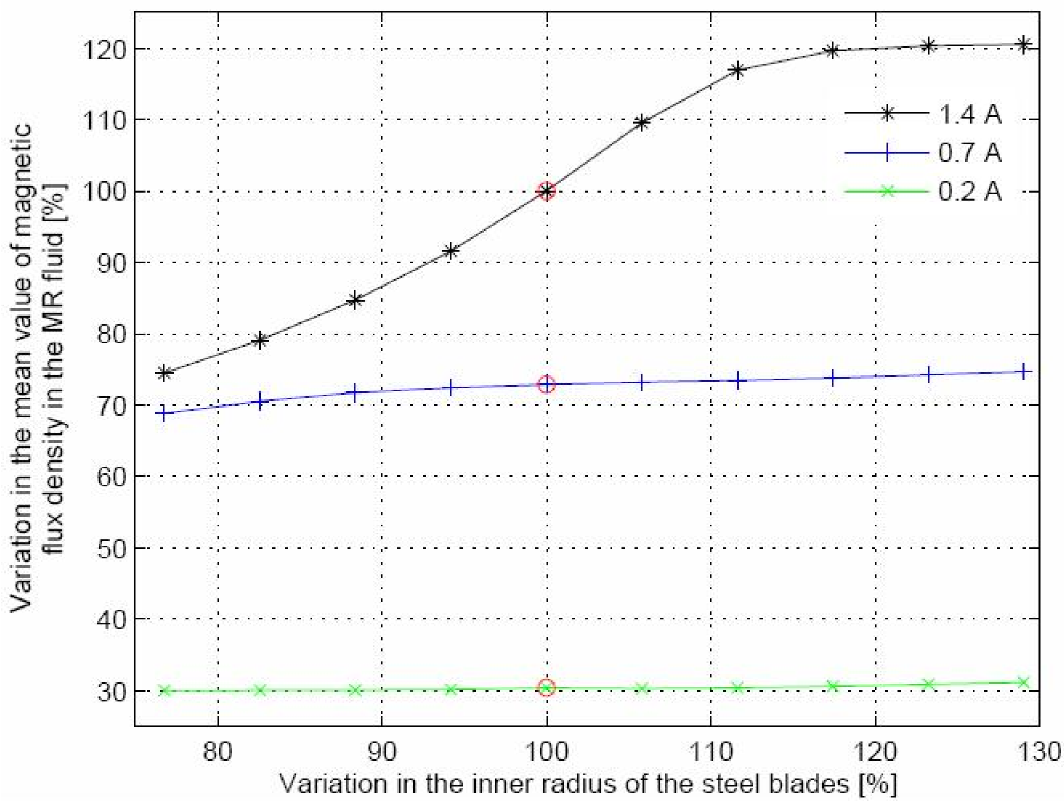

Figure 9: The variation in the mean value of the magnetic flux density in the MR fluid as a function of the variation in the inner radius of the blades without external change, for three values of the applied current: 1.4 A, 0.7 A and 0.2 A. The red circles in the figure show the current working value.

Conclusions

This study indicates that the behavior of an MR fluid in a computer controlled prosthetic knee can be modeled accurately with an axisymmetric finite element model. Such a model can be used for improving the mechanical design of the knee, both by suggesting improvements of the MR fluid itself and by understanding the relation between an applied magnetic field and the time-dependent bending torque of the knee.

In this study, calculations have been performed to analyze the effect of different geometries and other variables on the knee behavior. Results show that the effect of magnetic saturation is very important and the choice of the core size and materials in the core and the core sides greatly influences the knee performance. The results will be used in an ongoing project to optimize the design of the prosthetic knee.

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