Design Analysis of Variable Damping Mechanism Using Magnetorheological Fluids for Adaptive Prosthetic Foot

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The applications of Magnetorheological (MR) fluids to act as mechanical dampers are new and increasing day by day. This paper proves to be an attempt in applying variable damping properties of a MR fluid in a new application of adaptive variable damper prosthetic foot. A 3-D model of the prosthetic foot was developed on the software Autodesk Inventor Professional 2011. Design analysis of prosthetic foot was carried out and damping coefficients were calculated with the help of Dynamic Simulation Environment of Inventor. Typical specification of MR fluid was suggested to act as damper for the prosthetic foot.

Keywords: Magnetorheological (MR) Fluid, Prosthetic foot, Variable Damping

Introduction

Prosthetic feet have advanced significantly in the past years with respect to innovative design ideas and better materials. Prosthetic foot with variable damping is required and researched. The damping available in the foot will play important role in transferring vertical ground reaction force impact at knee and hip joints. Few researches have been done in the field of viscoelastic modeling of the prosthetic foot. A viscoelastic model consists of combination of springs and dampers. In this paper the capability of magnetorheological fluids has been discussed to act as dampers for the viscoelastic model of the foot. Magnetorheological (MR) fluids are materials that respond to an applied field with a dramatic change in their rheological behavior. A typical MR fluid consists of micron sized magnetizable iron particles suspended in a base fluid like silicone oil or water. The essential characteristic of these fluids is their ability to reversibly change from a free-flowing, linear, viscous liquid to a semi-solid with a controllable yield strength in milliseconds when exposed to a magnetic field. In the absence of an applied field, MR fluids are reasonably well approximated as Newtonian liquids. MR fluids can be converted from a liquid state to a solid state and vice versa by a magnetic field.

A magnetorheological damper is a damper filled with magnetorheological fluid, which is controlled by a magnetic field, usually using an electromagnet. This allows the damping characteristics of the shock absorber to be continuously controlled by varying the power of the electromagnet. The MR damper has a built-in MR valve across which the MR fluid is forced. The piston of the MR damper acts as an electromagnet with the required number of coils to produce the appropriate magnetic field. A design of a prosthetic foot consisting of 4 springs in parallel arrangement was developed by the authors using Autodesk Inventor Professional. There are few limitations of designed spring based damping mechanism like non linearity, non uniform distribution of ground reaction force. We planned to use basic properties of magnetorheological fluid to provide uniform damping. The research aim is to replace the spring arrangement with a MR fluid damper. This new approach helps to reduce the weight as well as at the same time enhance the efficiency.

Materials and Methods

Design Approach

Figure 1 shows the 3-D model of the prosthetic foot developed using Autodesk Inventor Professional software. The SACH area of available conventional foot was replaced with four identical spring. The spring were designed for patient weight from 50 Kg to 70 Kg.
Experimental data on normal male and female subjects (age: 18-35 years and weight: 40-78 kg) give the relation between the damping provided at heel and ground reaction force\textsuperscript{11,12}. The springs in the model were generated by the Design Accelerometer built-in module. A male pyramid adapter (EN8 steel) is bolted which will get attached with the SACH adapter on the prosthetic knee.

**Design Analysis**

The model was subjected to four different values of normal forces on the adapter i.e. 600 N to 750 N with a step of 50. A correlation between the force transmitted with respect to time was generated in the Dynamic Simulation environment of the software. The results are exported to Excel data sheet. Taking the peak value of the force transmitted, the damping coefficient was calculated by using the Equation 1 as follows:

$$T = \frac{F_T}{F_0} = \frac{1 + \left(\frac{2\zeta \omega}{\omega_n}\right)^2}{\sqrt{1 - \left(\frac{\omega}{\omega_n}\right)^2 + \left(\frac{2\zeta \omega}{\omega_n}\right)^2}} \quad \text{...(1)}$$

Where: $F_T$: Force Transmitted  
$F_0$: Force generated  
$\zeta$: Damping ratio  
$\omega$: Damping Frequency  
$\omega_n$: Circular Frequency

**Results and Discussion**

The foot is designed for amputees of weight range 50 to 70kgs. The simulation is run for 600N to 750N of applied force. Figure 2 depicts the transmitted force graph.
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at 600N and transmitted force graphs for 750N. Figure 3 shows the linearity of the model by correlating peak force transmitted to the force applied to adapter. The model shows linearity to the force applied, for simulation purpose the force applied is varied in the steps of 50 N and reported the calculated values of damping coefficients by the equation(1) in Table1. A MR fluid in this range of damping coefficient values is found to be a colloidal suspension of ferro fluid composed of fine (~ 0.05-15 nm) dispersions of magnetically soft, multi domain nano particles, such as Fe$_3$O$_4$, coated with surfactants in a carrier liquid.

Conclusions
The paper presents a novel approach to use the magnetorheological fluid as a damper to reduce the impact of ground reaction force. The design also addresses the need of prosthetic foot with adaptive damping properties. This damping action at heel area increases the comfort of amputees. The first design is conceptualized with the use of four springs to provide damping action for the person of weights 50-70kgs. There is inherent limitation of non uniformity and non linearity due to basic spring component. This paper discusses the capability of ferro fluids to act as a magnetorheological damper in prosthetic foot applications which also improve the previous design. The results prove the possibility of use of such kind of MR fluid would help to have a uniform cushioned heel with reduced weight of the prosthetic foot. It is also possible to get instant changes in its viscosity by varying the magnetic field and therefore instant change in the damping characteristics of the viscous fluid making it adjustable for different purposes. The high cost of magnetorheological fluid may act as limitation.

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References