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Preparation and Characterization of a Prototype Magnetorheological Elastomer for Application in Prosthetic Devices

Fjola Jonsdottir[1], Fannar Benedikt Gudmundsson[1], Ketill Heidar Gudmundsson[1],Christophe Lecomte[2]

[1] School of Engineering and Natural Sciences, University of Iceland
Hjardarhaga 6, 107 Reykjavik, Iceland
fj@hi.is

[2] Ossur Inc.
Grjothalsi 1-3, 110 Reykjavik, Iceland
clecomte@ossur.com

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Summary: *Magnetorheological elastomers (MREs) are composite materials whose stiffness can be varied with a magnetic field. The aim of this research is to investigate the feasibility of MREs as spring elements in prosthetic devices, specifically their application in a prosthetic foot, whose properties adapt to the current activity level of the user. MRE samples are prepared with variable carbonyl iron powder (CIP), isotropic and anisotropic particle distributions, variable concentration of iron, all based on a polyurethane (PU) matrix. An experimental study is conducted, characterizing the static mechanical behavior of the samples with a varying magnitude of the applied magnetic field. The design goals of a variable stiffness prosthetic foot are considered and compared to properties of the MRE samples. Results show selected samples to exhibit favorable characteristics for an application in a variable stiffness carbon-fiber prosthetic foot.*

1. INTRODUCTION

Smart materials are an exciting research field in today's material science community. A group of smart materials are also referred to as active materials since their behavior and properties can be controlled by a field. A magnetereohological elastomer (MRE) is such a material, whose mechanical properties can be varied under the influence of a magnetic field [1–4]. This research aims to introduce MREs as an adaptive spring element in prosthetics. The fluid analogues of MREs, magnetorhelogical (MR) fluids, have been successfully employed in an adaptive prosthetic knee, whereas the prosthetic foot, at the outset of this research, is passive [5]. In MR fluids, the property of interest is the field-dependent shear yield-stress, whereas in MREs the characterizing parameter is the field-dependent elastic modulus. Typically, MREs consist of micron-sized, magnetizable particles, embedded in a liquid-state elastomer matrix. When a magnetic field is applied, the particles align and are locked in place before solidification. The field-dependent properties of MREs result from magnetic dipole interactions between the particles [1]. Thus, the stiffness of the MRE can be altered by the application of an external magnetic field; the response from low (off-state) to high stiffness (on-state) being almost instantaneous.

Due to the attractive properties of MREs, they have many potential applications as can be seen by the number of MRE patents in recent years [6]. Proposed applications include automotive bushings [7, 8], vibration and noise absorbers [9–13] and actuators [14]. However, existing commercial applications of MREs are rare and the development and characterization of the materials are yet in the early stages. A common goal in the design of MRE devices is to obtain a high on-state stiffness while, at the same time, maintain a low off-state stiffness; the ratio of the two is known as the MR effect. Factors that have been found to influence the MR effect include the initial elastic modulus of the matrix, the particles magnetic properties, size and concentration, the alignment of particles within the matrix and the use of additives for better matrix-particle interaction. A number of researchers have studied the influence of these factors on the behavior of MREs [15–20]. The reported results differ considerably, based on the materials and methods used. The literature indicates that MREs with initial off-state elastic modulus from around 100 kPa to a few MPa can increase their stiffness considerably, even more than 100% [14–19]. Some researchers have reported that the MR effect depends on strain amplitude [8, 15]. However, considerable MR effect has been found for large strains of up to 100% [21]. Another issue of concern for our work is that MREs can deform under the influence of a magnetic field because of inter-particle magnetic forces, an effect called magnetostriction [22, 23]. The effect of magnetostriction can affect the feasibility of using MREs as spring elements in structures if the applied strains are of similar magnitude as the strains induced.

Intrigued by the studies mentioned above, the focus of this project is on fabricating a suitable MRE spring element to replace conventional steel or titanium springs in a prosthetic foot. Among the challenges in developing such an MRE element is to achieve a high enough MR effect for a commercial product and one that delivers an appropriate level of stiffness for the user. For example, high stiffness is required for tasks such as running and jumping, while low stiffness is required for walking or comfort while at rest. The components in a conventional prosthetic device generally have a fixed stiffness, regardless of the activity level of the user. Ideally, a device is wanted whose stiffness is controllable and adaptable to the users current activity.

We present requirement specifications of a commercial carbon-fiber prosthetic foot. An experimental study is performed on the appropriate composition and structure of the MRE for meeting the requirements of the prosthetic device. A MRE structure is sought with high stiffness and a high MR effect, a structure that can withstand large cyclic deformations and good energy return and a structure allowing large elastic deformations. A fabrication setup for polyurethane (PU)-based MREs is described along with the fabrication procedure. Two grades of micron-sized carbonyl iron particles are used. An experimental setup is then described that is used to experimentally evaluate the mechanical properties of the fabricated MRE material. The feasibility of the proposed MRE structure is evaluated for a potential application in a carbon-fiber prosthetic foot. A design is proposed to integrate MREs into a carbon-fiber prosthetic foot. Hence, the stiffness of the foot can be adaptively changed in real-time, during gait which means improved quality of life for the amputee. The results indicate that MREs are an attractive option for the construction of axial spring elements.

2. POTENTIAL APPLICATION

A popular prosthetic foot design is the carbon-fiber design, where the foot is made of a layered carbon-fiber composite that extends from the amputees residual limb and aims to provide natural progression through the stages of normal gait. The stiffness of the foot and its response to load may be controlled via the thickness profile of the foot as well as its shape. Additionally, a spring may be introduced to the structure to provide further shock absorption. One such design can be seen in Figure 1, which shows the Re-Flex Rotate™ prosthetic foot, produced by Össur [24]. The Re-Flex Rotate is based on a conventional carbon-fiber foot design but has a vertical shock absorption member connecting the foot and the limb.

Figure 1. A carbon-fiber prosthetic foot used in prototyping [24].

While, from a wide perspective, many ways of applying shock absorption members to prosthetics may exist, this is one that is relatively simple and has already been used with success. The goal of this work is to design a MRE based spring to replace the current shock absorption member in the foot and provide variable stiffness in response to the user's current activity level. Using a reference design of a prosthetic foot, the stiffness requirements have the following specifications:

- Weight of an amputee: 69 kg – 77 kg
- Spring rate of shock absorption member at low activity level: k_{low} = 112 N/mm
- Spring rate of shock absorption member at high activity level: k_{high} = 122 N/mm
- Deflection during walking: d = 6 mm

3. FABRICATION OF MREs

3.1 Materials

The materials used in this study to fabricate the MREs, both the elastomer and the carbonyl iron powder (CIP), are commercially available. The PU matrix is available from Axson Technologies [26], shown in Table 1, and the CIPs are available from BASF [27], shown in Table 2.

Table 1. Axson Technologies, Cured density: $1160\ kg/m^3$ Polyurethane (PU) matrix

Material	Ordering Code	Density (kg/m^3)	Mixing ratio (by weight)
Isocyanate	UR 5801	1120	8
Polyol	UR 5825	1150	100

Table 2. BASF grade

Material	Ordering Code	Size $d_{10}(\mu m)$	Size $d_{50}(\mu m)$	Size $d_{90}(\mu m)$	Iron content
Carbonyl iron	CC	≈ 2	≈ 5	≈ 8	$\geq 99,5$
Carbonyl iron	CM	≈ 4	≈ 8	≈ 25	$\geq 99,5$

The samples where manufactured with using only the Polyol of the PU in the first steps of the preparation, thus ensuring that the pot time would be sufficient. The specified amount of CIP was added to the Polyol, which was thoroughly stirred for 1 minute and then put in ultrasonic bath for 3 minutes in order to split agglomerated CIP particles. The mixture was then placed in a degassing chamber, equipped with a high shear stirrer, where it underwent a vacuum of -1 bar. The mixture was stirred for 1 hour to get rid of any excess air bubbles. After this procedure, the Isocyanate was added to the mixture and thoroughly mixed for 5 minutes and then put back in a vacuum chamber for 5 minutes for degassing. The mix was then thrust into a mold, equipped with two permanent magnets. The polyurethane samples where then left to cure at room temperature for 24 hours before releasing them from the mold and then left to fully cure for at least 72 hours before any mechanical testing was performed, making sure that full crystallization had occurred.

The magnetic field in the mold, during curing, was created with two permanent neodymium magnets with dimensions 50 mm x 50mm x 25mm. The samples were placed in between the two magnets, aligning the iron powder during curing. The magnet was set to generate magnetic flux density, B, of approximately 0.7 T. At the time of testing, the value of the magnetic flux density was confirmed with magnetic sensor, Tesla Meter 2000 [27].

3.2 Samples

A cylindrical aluminum mold was built to fabricate the MRE samples. The samples are cylindrical with height of 20 mm and diameter of 25 mm, as shown in Table 3.

Table 3. MRE samples

Sample No.	Matrix Material	Size CIP Type	Particle Distribution
1-3	PU	CC	Aligned
4-6	PU	CC	Isotropic
7-10	PU	CM	Aligned
11-14	PU	CM	Isotropic

The samples were selected to investigate the effect of 1) iron loading, 2) particle size and 3) particle alignment on the behavior of MREs. Although these research questions have been addressed before [3, 7, 8], this research is conducted in the context of the proposed application in a prosthetic foot.

4. MECHANICAL TESTING OF MREs

The mechanical testing was performed with an axial material testing machine [28]. Static mechanical tests were performed with and without a magnetic field. The experimental setup is shown in Figure 2.

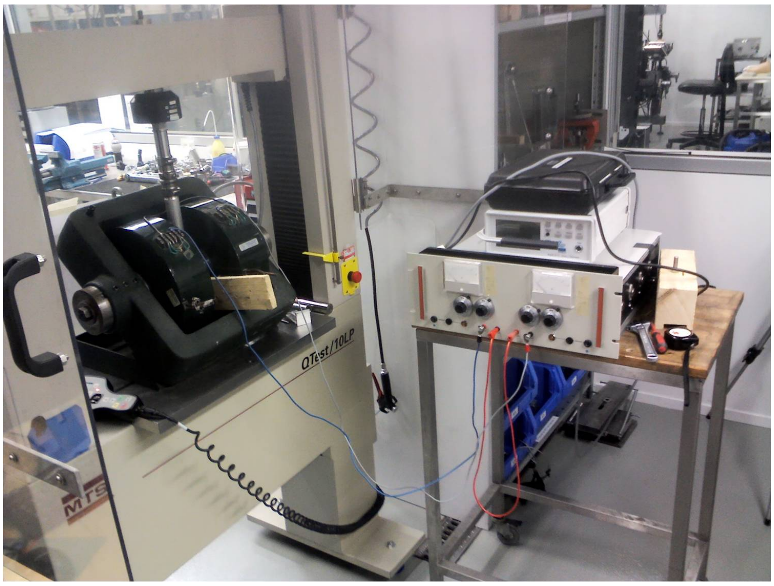

Figure 2. The mechanical testing equipment.

To make sure that the magnetic field generated by the magnet would not affect the load cell on the testing machine, the pin pressing down on the sample was manufactured from aluminum and the foundations where made from stainless steel. The diameter of the foundation and pin were 30 mm and to make sure that maximum output on the sample could be achieved, the sample was placed on the foundation such that it would be aligned with the center of the poles. The gap between the poles was 34 mm to ensure that required magnetic field would be maintained. The magnet is water-cooled since large heat change in the coils can cause the magnetic field to be non-uniform. With a coil current of 10 A, the magnetic flux density at the surface of the MRE samples was measured to be approximately 0.7 T. All tests performed were compression tests, since compression loads are of interest for the proposed application in a prosthetic foot.

For all the compression tests, the samples were subjected to a maximum strain of 50%. Force-displacement curves were generated using the setup in Figure 2 and then transformed into stress-strain curves, taking into account the geometry of the samples. A representative stress-strain curve is shown in Figure 3. In general, the elastic modulus is the slope of a linear stress-strain curve. As polyurethane has a non-linear behavior, the stress-strain curve was divided into two parts and the elastic modulus evaluated as the linear slope of each part.

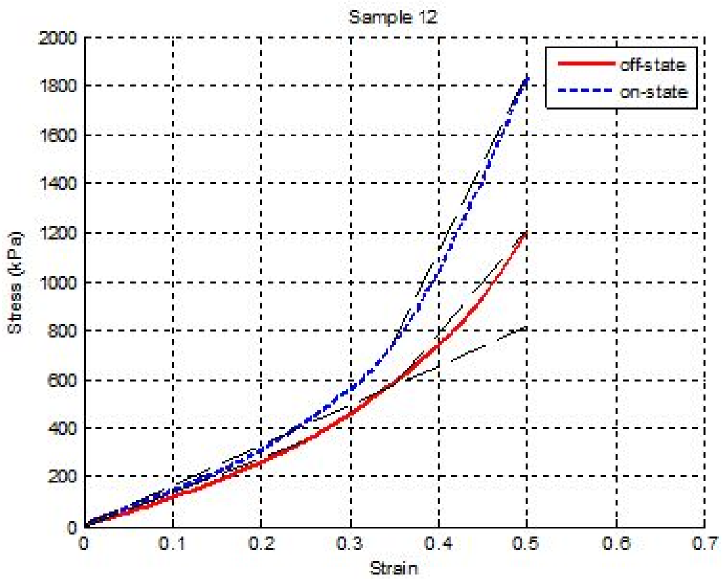

Figure 3. A CM polyurethane sample with isotropic particles.

The stiffness moduli where calculated for all samples, both at low and high strain rates. The results are shown in Table 4 for samples 1, 6 and 12. Although other samples also showed favorable results, there were selected as all have isotropic particle distribution. For ease of manufacturing, an isotropic distribution is preferred for this application, although it is known from literature that aligned samples tend to show a higher MR effect. Table 4 shows the off-state modulus, on-state modulus and the relative change in modulus for the higher strain range, where the relative change in modulus is calculated as $E_{on}/E_{off} - 1$. Notice that the change in stiffness is much greater in the sample that was made with the larger CM particles, as to be expected.

The results in Table 4 are promising and give stiffness changes that are well on the order of

Table 4. The change in stiffness for selected samples

Sample No.	Particles	Low E_{off}	Low E_{on}	High E_{off} [MPa]	High E_{on} [MPa]	$\Delta E/E_{off}$ [%]
1	CC	-	-	2.60	3.09	19
6	CC	-	-	1.30	1.57	21
12	CM	1.20	1.65	4.66	7.24	55

acceptable stiffness change for a prosthetic foot. Hence, the next section focuses on a prototype based on results for sample 12.

5. APPLICATION IN A PROSTHETIC FOOT

The goal is to have a foot that can dynamically alter its stiffness from the low activity to the high activity level. The spring rates of the current design lie on a similar order of magnitude as the spring rates observed in the MRE sample testing. The strain at the maximum deflection is assumed to be 15% and the stress-strain curves of MREs are assumed to be independent of the cross-section and length (intensive property). A linear elasticity and constant cross-sectional area are assumed. The off-state and on-state elastic moduli, E_{off} and E_{on}, can be calculated from the simple equation for the stiffness of a bar, that is: $E = \frac{kL}{A}$ where k is the spring constant of the material, L is the length and A is the cross-sectional area of the sample. Inserting the values for k_{low} and k_{high}, given in section 2), into the equation, along with our sample sizes, gives elastic moduli of E_{off} = 4.57 MPa and E_{on} = 4.98 MPa, respectively. These are the results we are aiming for.

Our results from the previous section indicate that polyurethane bumpers with CC particles would be applicable. However, we used a polyurethane bumper with CM particles, as this configuration does show more relative change in stiffness.

Our hypothesis was that the best results would be achieved by applying the magnetic field in the same direction as the particle alignment in the material. Hence, the activating magnets were built into the mechanical design as pressure foundations with an axle joining them and the bumper material, as shown in Figure 4.

Nokia transformers were used as the base for the electromagnets. The transformers were taken apart, the I-plates thrown away and the E-shaped plates were used as a core for the magnets. The cores were wound with 1.4 gauge copper wire, estimated N = 4000 for each magnet. The permeability of the core was estimated to be $\mu = 8.0 * 10^{-4} H/m$ and L is estimated to be 20 mm. The magnetism of the electromagnet can then be calculated as

$$B = \mu \frac{NI}{L} \tag{1}$$

where I is the current used to activate the magnet.

Figure 4. The magnetic spring element used for the prototype.

Our prototype, shown in Figure 5, replaced the mechanical spring entirely from the design, using only the MRE damper as a spring element. This configuration did show usable change in stiffness between on and off-state, as discussed later on. Figure 5 shows the prototype without the spring element housing, which was made from stainless steel to limit magnetic eddy currents. The weight of this housing proved to be a problem in this initial prototype and was not used during testing. Refinements of this aspect of the design are reserved for future work.

Figure 5. A prototype of a prosthetic foot with an MRE spring element.

This prosthetic leg prototype underwent static testing analysis in the MTS QTest axial material testing machine, the same apparatus that the MRE material samples had been tested in before. The prosthetic foot was pressed down by 5 mm, both in off-state and on-state. Figure 6 shows the loading curves for the prototype. The solid curve (red) shows the prosthetic in an off-state and the broken line (blue) shows the change in stiffness during on-state when the magnets are loaded with 2.5 Ampere, which produces a magnetic field of approximately 0.3 T.

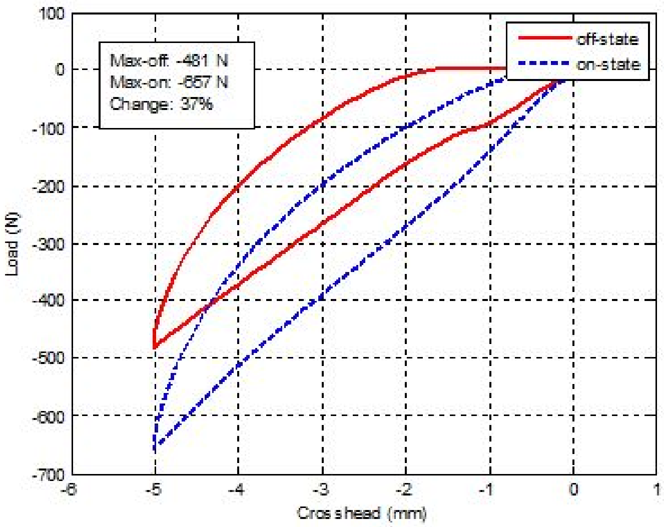

Figure 6. Loading curves for the prototype during displacement of 5 mm.

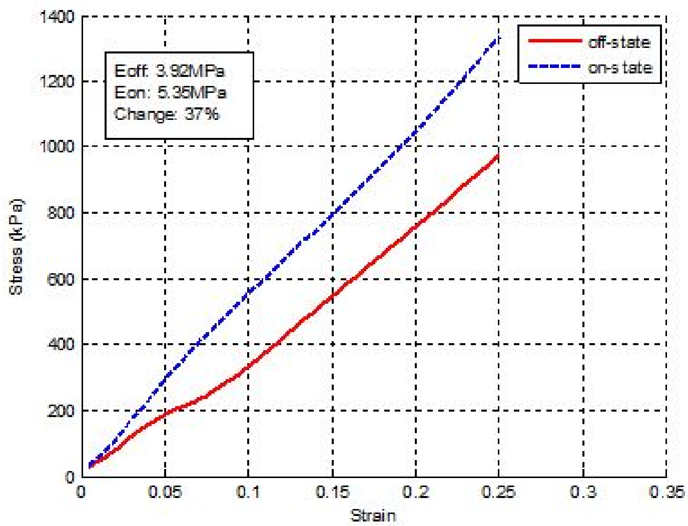

Figure 7. The change in elastic modulus in the prototype.

The loading curves are changed into standard stress-strain curves and shown in Figure 7. The measured off-state modulus is E_{off} = 3.92 MPa and the measured on-state modulus is E_{on} = 5.35 MPa. This gives a relative change in stiffness of the leg of nearly 40% which exceeds our expectations.

6. CONCLUSIONS

We have presented a design of a prosthetic foot that includes a MRE element in its damping structure. The advantage of the active design is to enable the prosthetic limb to adapt dynamically to the activity of the user. We produced and tested a prototype damping element and our initial results are promising. However, further work is needed in order to optimize this design with regards to choice of materials and geometry. Variables include the mode of loading (compression, shear and tension). One of the more troublesome aspects is the magnetic circuit, which is critical to the functionality of a MRE element. The magnetic circuit needs to be powerful enough to induce the needed change in stiffness, yet light and compact enough to fit into a production prosthetic foot. Further work is needed on the geometry of magnetic core, flux path and the coil design. Choosing a softer matrix material would mean lower off-state stiffness and should, according to previous studies, result in a larger relative MR effect. This is in it self an interesting optimization problem and one which we have studied previously [25]. We plan to address this in future work, employing finite element analysis techniques to optimize the magnetic circuit w.r.t. shape and materials.

Furthermore, the durability of the MRE material should be investigated, both in terms of static and cyclic loading. The present study considers static stiffness of the material but dynamic stiffness should be investigated in future work. The fabrication methods and choice of materials could be improved, one aspect being the alignment of particles. An assessment of the alignment could possibly be executed with the aid of image analysis.

A fully adaptive MRE spring unit with usable range and of practical dimensions would be a big step forward in the usability of this kind of prosthetic, enabling the stiffness to adapt in real-time to the activity level of the user. The same control mechanisms can be applied to optimize the battery life and reduce heating in the magnetic circuit by inducing the needed stiffness just at the time of impact, keeping the circuit otherwise switched off to conserve power. Furthermore, the impressive MR effect seen at low strains suggests applying this technology to semi-actively absorb vibrations in the structure which we plan to address in future work.

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