Investigating the use of Magneto-Rheological Fluid in an Active Compliant Actuator for a Stroke Rehabilitation System

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Abstract

This paper investigates the use of magneto-rheological fluid in an active compliant actuator, for intended use in a stroke rehabilitation system. As magneto-rheological fluid is an emerging technology, experiments were performed to test the suitability of its use for stroke rehabilitation. The proposed use of the system is to actively exercise and strengthen the weakened hand of a person affected by a stroke. It was found that in the system's current design, magneto-rheological fluid was a feasible solution. Its viscosity was dynamically controllable and the fluid was able to supply the force and time response required. However further work needs to be conducted to address identified issues, such as settling, heating and leakage of the fluid.

1 Introduction

1.1 Scope of the project

In New Zealand there is a growing demand for stroke rehabilitation with over 56,000 New Zealanders living with the effects of a stroke and an additional 6000 added each year [2011a]. Strokes are globally the leading cause of adult disability in the developed world with over fifteen million people living with its effects. 85% of survivors experience upper limb disability that leads to some degree of dependence on caregivers for the rest of their lives [King, Personal Communication].

The link between the brain and limbs can be weakened or lost as a result of a stroke. However research has shown that repetitive movement of the weakened limb enhances motor relearning [Stein et al., 2009]. Motor relearning uses neuroplasticity, which is the ability for the brain to learn and adapt, strengthening and restructuring weakened or destroyed links [Begley, 2007].

Many hours of a physiotherapist's time is often required for rehabilitation, which some people feel guilty about using. As the number of people affected by a stroke increases, the consequent demand for rehabilitation can strain a hospital's resources. Therefore current rehabilitation processes are in need of more effective tools so that neurotherapies can be moved away from the therapy gymnasium and into the person's home [Loureiro et al., 2009].

1.2 Motivation for the project

The aim of this project is to develop an active compliant actuator with the use of magneto-rheological fluid, which is intended to be incorporated into a robot rehabilitation system. A servo motor is to be placed in series with a magneto-rheological damper to produce a compliant actuator.

1.2.1 Compliance

The fields of wearable robotics, rehabilitation robotics, prosthetics, and walking robots are growing. Variable stiffness actuators and adjustable compliant actuators are being developed because of their ability to safely interact with users and to minimize large forces due to shocks [Ham et al., 2009].

A compliant actuator is the complement of a stiff actuator. Stiff actuators are intended to travel through a fixed trajectory regardless of external forces. They have the potential to cause injury to humans through unintentional excessive force. A robot containing stiff actuators can also be damaged from strong shocks produced when contact is made with objects. A compliant actuator allows for deviations from its own equilibrium position, depending on the external force applied [Ham et al., 2009].

In the last couple of decades the two main control techniques developed to produce compliant actuators have been passive impedance control and active force control [Radojicic et al., 2009]. Passive compliant actuators contain an elastic element that can store energy, such as a spring. Active compliant actuators are not reliant on passive energy storage and can include electronic controllers. The advantage of active compliance is that the controller can adapt the compliance during normal operation [Ham et al., 2009].

Compliant dampers are analogous to muscle tendons, which have adaptable compliance and variable resistance [Vanderborght et al., 2006]. In the proposed system, an advantage of imitating muscle behaviour is to provide the operator with a more natural movement.

1.2.2 Magneto-rheological Fluid

Discovered in the 1940's, magneto-rheological (MR) fluid is still an emerging technology and has only begun being used in product development since the 1990's [Avramm, 2009] and so the extent of its capabilities and applications have not yet been explored fully. Current uses of MR fluid include shock absorbers in cars, prosthetics and seismic dampers [Loureiro and Harwin, 2006].

MR fluid consists of iron particles suspended in oil. In the presence of a magnetic field the iron particles become magnetised, forming chain like structures that align parallel to the field and restrict fluid flow, as seen in Figure 1. Due to the alignment of the particles, an object moving through the fluid needs to break the chain structures resulting in an increase in the dynamic viscosity of the fluid.

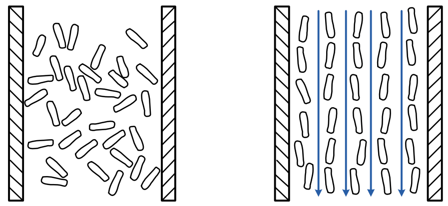

Figure 1. Effect of magnetic field on magneto-rheological fluid. The arrow indicates the direction of the magnetic field inside the fluid.

The advantages of using MR fluid include its controllability, flexibility and fast response. Varying the input current to the coils of an electromagnet will vary the applied magnetic field, thereby dynamically controlling the viscosity of the fluid. As MR fluid has high yield strength in the presence of a magnetic field and very low yield strength in the absence of a magnetic field there is a wide range of controllability [2011b; Turczyn and Kciuk, 2008]. These effects are reversible, allowing the fluid to be magnetised repeatedly.

As muscles are unable to provide instantaneous force, the ability to dynamically vary the fluid's viscosity allows the artificial system to mimic the power output curve of biological muscles (Figure 2). Therefore, during muscle movement exercises, the resistive force can be dynamically varied accordingly to provide a natural feel, aiding in the comfort of the exercise. For example, when the user begins moving their muscles, the applied force will be set at a low level, then when the velocity of the movement increases, the applied force can be increased and then lowered near the end of the movement.

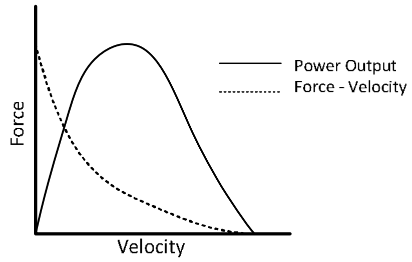

Figure 2. Idealised force-velocity and power output curves of muscles.

Due to the damper using a liquid, there is flexibility in the physical design and shape to meet cost and size requirements. MR fluid also has millisecond response times [Takesue et al., 2000], therefore the speed of response is often limited by the driving circuit. A fast response time enables the fluid to be dynamically controlled without appreciable lag, which is important for safety and the operation of the system.

There are also known problems with the use of MR fluid. The main disadvantage of using MR fluid is the tendency for the iron particles to settle and depending on the particle size irreversible iron "cakes" can form [Park and Park, 2001]. The addition of a stabilising agent such as lithium grease, "inhibits particle settling and agglomeration, reduces friction and prevents particle oxidation and wear" [Avramm, 2009]. The settling of the fluid will need to be tested for this system. Also depending on the quality of the oil and iron particle size, commercially purchased fluid can be expensive e.g. retailing for at least 750USD per litre from LORD Corporation [2011c].

Current MR fluid actuator designs include the use of Double Viscous Beams [Loureiro and Harwin, 2006] and rotary disc braking systems [Avramm et al., 2008; Kamnik et al., 2010; Park et al., 2006]. There are currently no commercial stroke rehabilitation devices that use MR fluid to actively exercise and strengthen the user's hand.

A MR fluid damper allows compactness, provides smooth operation, has an absence of backlash, increasing the safety of the system and contains no mechanical components changes. In comparison, using DC motors as a damper is highly inefficient, less safe, increases the wear of mechanical components and reduces the robustness of the system.

This paper aims to investigate the suitability of a MR fluid based compliant actuator for use in the proposed rehabilitation system and therefore no comparative experiments were carried out in relation to purely electrical and mechanical systems.

The objectives were to create a test system, test the viscosity control of the fluid and assess known and emerging problems associated with using MR fluid. A summary of the tasks of the system will be presented in section 2, followed by a section on the design considerations for the compliant damper. Section 4 provides a high level description of the overall system and then the experimental results of using MR fluid in the compliant actuator are presented and discussed.

2 Tasks of Rehabilitation Device

Following a severe stroke an affected hand often forms a fist**.** The first task of physiotherapy is to loosen the hand muscles and begin the process of neuroplasticity. The fingers are repetitively opened and closed, a motion similar to forming a power grip. It is important to note that there are no resistive forces acting against the movement and that the fingers naturally curl into a fist.

The proposed device aims to replicate this movement, actively exercising the fingers as illustrated in Figure 3.

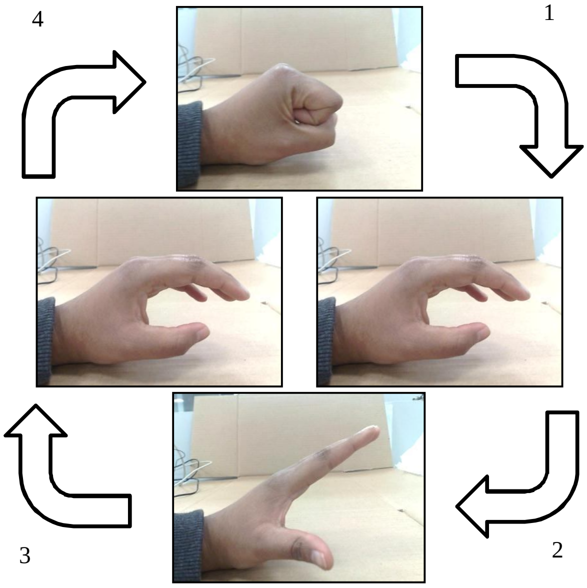

Figure 3. Desired finger exercise movements for the proposed device.

There are two stages to stroke rehabilitation considered [Mann, Personal Communication]. Directly after a stroke, stage one involves repetitive hand exercises to encourage neuroplasticity. Stage two begins once movement and control have been regained in the affected hand and concentrates on strengthening the weakened muscles. Motivation is also important as people report becoming bored and even uncomfortable during rehabilitation.

3 Design considerations for MR damper

The role of the damper is to oppose the movement of the user, thereby increasing muscle strength.

The fluid used in this project was made using an available online recipe [2011b], due to the high cost of commercial MR fluid. Experiments were carried out to determine whether the fluid would operate as expected from literature and also if MR fluid was a feasible solution for this system, see section 5.4.

Important design considerations and influential factors for the compliant damper are outlined as follows.

3.1 Functionality of the compliant damper

The damper will have two modes of operation, one passive and the other active. During stage one the damper is in passive mode and no additional resistance should be felt by the user. Also as a motor is required to lift the user's fingers, any additional resistance introduced by the damper will increase the load on the motor, resulting in additional wear on the components. In stage two current will be driven through the damper to oppose the movement of the user, hence increasing muscle strength.

3.2 Settling of fluid

As indicated in the literature the iron particles in MR fluid have a tendency to settle. To reduce the likelihood of iron cakes forming, the damper will need to be designed in such a way that helps mix the fluid, keeping the iron particles suspended.

3.3 Size of magnetic field

As the viscosity of the fluid is dependent on the generated magnetic field, the amount of fluid, input current and number of coil windings needs to be considered and determined experimentally. In order to best utilise the magnetic field, it is important to concentrate it in the regions of interest. Any external magnetic field needs to be below 100 µT to avoid violating New Zealand Health and Safety Regulations [2009a].

3.4 Minimising power consumption

To reduce power consumption the damper will need to minimise the required operational current. There is a trade-off between the number of coil windings needed (which influences the size of the damper) and the amount of current required to provide the same magnetic field strength.

As the device could potentially be portable and therefore reliant on batteries, the smaller the power consumption, the smaller the batteries and lighter the device will be. The batteries would also be replaced or recharged less frequently.

4 Overall System

The relational diagram (Figure 4) shows the interaction between the different components of the system.

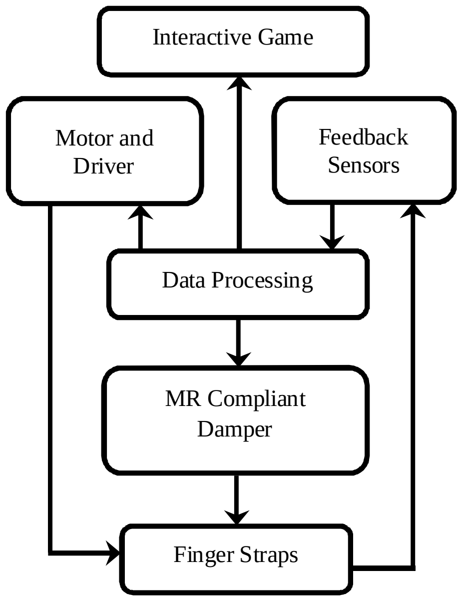

Figure 4. High level view showing the interactions of the main components of the system.

The following figures are photographs of the test system. Figure 5 shows the device actively lifting the experimenter's fingers and Figure 6 displays the MR compliant damper, which is located at the base of the system. The temporary housing was needed to hold the different components of the system.

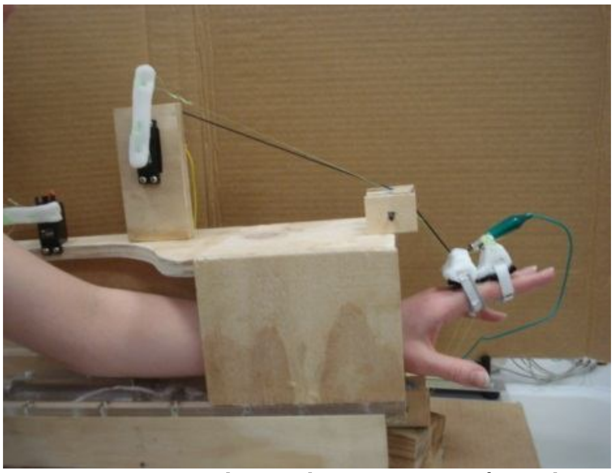

Figure 5. Test system showing the experimenter's fingers being lifted.

Figure 6. MR compliant damper located in the base of the system.

The following sections outline the operation of the system, how it addresses the two stages of rehabilitation, motivates the user and provides performance feedback.

4.1 Stage one: Active hand exercises

Once the user has strapped their fingers to the device (possibly with the assistance of a caregiver), a computer program is used to select the number of lifts required as well as the speed with which to lift the fingers. As the user's fingers are being lifted, the shaft of the damper is extended (refer to Figure 10). The damper operates in passive mode and does not actively oppose the motion of the user.

4.2 Stage two: Muscle strengthening

In stage two, the system operates similarly to stage one, but with the compliant damper in active mode. To minimise power consumption, current is only pulsed through the damper while the fingers are being lifted. The user is able to select the amount of resistive force they wish to work against them, by using the computer program. As a safety feature, this setting can be changed anytime during the exercise. Therefore, if the user becomes tired, they are able to reduce the resistance setting accordingly. A stretch sensor calibrated to the motor's encoder allows the motor to track the user's movements. This allows the motor to maintain tension with the finger straps, which prevents the user from lowering their fingers and becoming discouraged. A screen shot of the control panel is shown in Figure 7.

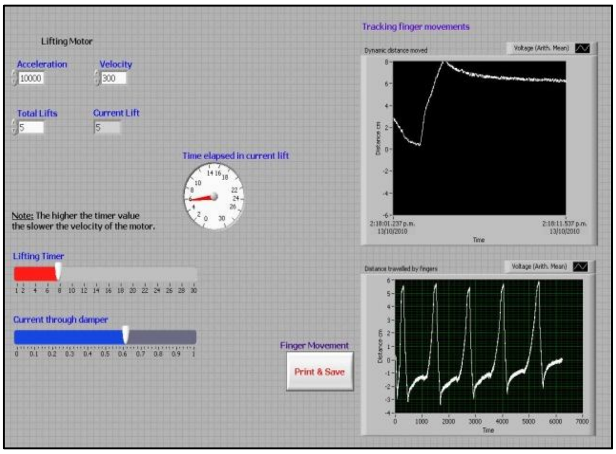

Figure 7. Screenshot of the LabView control panel showing a close-up of a current lift in progress and five previous cycles.

4.3 Motivating the user

An interactive game was created and integrated with the system. The game involves dropping an object into one of three baskets. On each lift the object begins travelling horizontally to the right. In order to release the object, sensors are used to determine when the user has raised their fingers past a threshold value.

The game tests the speed and controllability of the user's movement by rewarding points based on how quickly the object can be released and if it was accurately dropped into a basket.

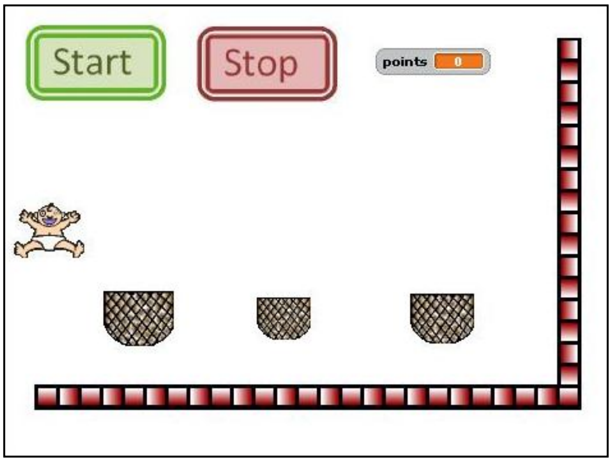

Figure 8. Screenshot of the interactive game used to motivate the user.

4.4 Performance Monitoring

Feedback is provided to the users of the system in three ways. Firstly the user's finger movements are tracked and displayed in real time on the control panel**.** Secondly the user is able to save their exercise session, for later review by their physiotherapist. Lastly feedback is received through the game in the form of points, which are intuitive to the user.

5 Results and Discussion

5.1 Settling of Iron Particles

To test the settling of the fluid, a jar of MR fluid was vigorously shaken for 5 minutes and left to sit on a bench. The fluid was checked regularly and after three days there was visible separation between the oil and iron. However due to the addition of the stabilising agent, the fluid was able to be easily reconstituted when mixed.

5.2 Heating Effects

Initial experimentation revealed that the fluid began to behave unpredictably when the current exceeded a few amps. To investigate this further an experiment was conducted. A 5 mm tube was tightly wound with 200 turns of 0.4 mm diameter copper wire and was filled to 60 mm with MR fluid. The time taken for the fluid to flow from the tube with varying coil current was recorded. Measurements were taken approximately five minutes apart to allow time for the coil to cool. The more viscous the fluid the longer it took to flow out.

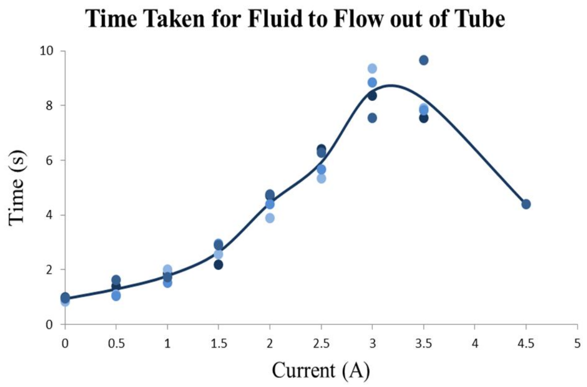

Figure 9. Heating effects influencing the viscosity of the fluid. The curve passes through the mean of each set of trials and is intended to show the general shape of the dependence.

Figure 9 shows that beyond 3A the viscosity of the fluid began to decrease. This was due to the flow of heat from the coil into the fluid. As the MR fluid began to warm up, the oil viscosity decreased, counteracting the iron alignment. Had there not been a five minute cooling period between each measurement, the fluid viscosity would have peaked at a lower current. Consequently it was decided that 1A should be the maximum operating current for the system to ensure its function remained stable.

5.3 Damper Design

Inspiration for the compliant damper was taken from existing car shock absorbers and in particular the Audi MR Suspension system [Prescott, 2008]. Figure 10 illustrates the MR compliant damper design.

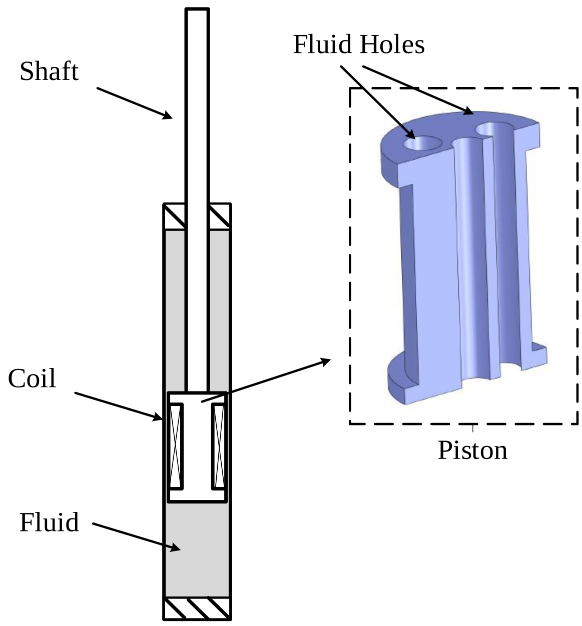

Figure 10. Cross section of the compliant damper.

As the user lifts their fingers the shaft is pulled from the damper. If the viscosity of the fluid is increased, the work required to pull the shaft increases due to the movement of the piston through the fluid. By mixing the fluid during operation, the damper helps keep the iron particles suspended, reducing the settling of the fluid.

A few design iterations of the damper were needed to meet the requirements of the system. This included modifications to the piston including its length, the number of coil windings and the fluid hole configuration. The original piston design had 60 turns of wire and needed at least 3A to provide a reasonable amount of resistance. To reduce the heating effects and hence the maximum operational current, the piston was increased in length by a factor of 4 to have over 500 turns, allowing the operating current to be lowered to 0–1A. Due to the increased piston size the movement of the shaft was reduced from 110 mm to 65 mm. However 65 mm was sufficient to provide resistance throughout the lifting of the fingers. This experimentally robust configuration was selected for further testing of the fluid and system.

5.4 Viscosity

To investigate the suitability of MR fluid in the system the dynamic viscosity of the compliant damper was measured, with varying driving currents. As the force needed to lift a person's fingers is approximately 10N [Loureiro et al., 2009] a 1 kg mass was used to provide an approximate force of 10N (see Figure 11). A calibrated stretch sensor was used in conjunction with a LabView program to log the displacement of the shaft with time. Between each measurement the piston was returned to the original starting position and the fluid was mixed. The results of the experiment are shown in Figure 12.

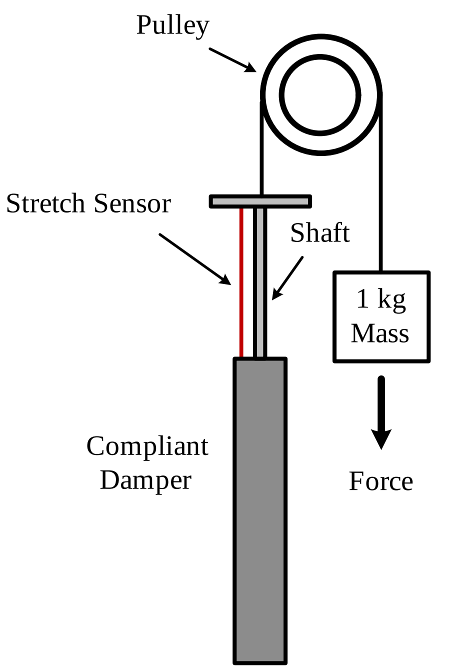

Figure 11. Schematic of the apparatus used to measure the dynamic viscosity of the fluid with varying driving currents.

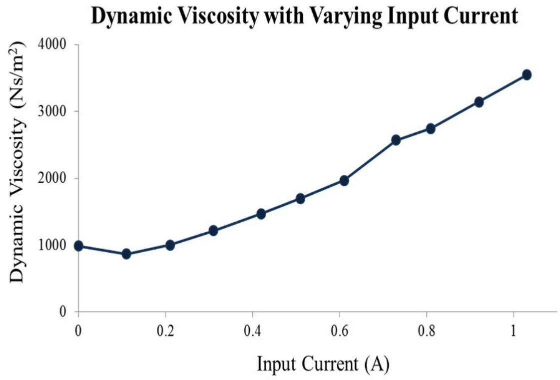

Figure 12. Viscosity dependence on current, for the compliant damper.

The results of this experiment are important in justifying the use of MR fluid in the system. With a small current range of 0–1 A applied, the viscosity was increased by a factor of four. Even with small increments of 0.1A in the applied current there are notable differences in the measured viscosity. This demonstrates that the viscosity of MR fluid is controllable and only a small range of current is required. The observed linear relationship also reduces complexities in controlling the damper.

To discover whether the change in viscosity had an appreciable effect when lifting the fingers, an experimenter's hand was strapped into the system. The damper was placed in series with a motor (forming the compliant actuator) and three different currents were passed through the damper (Figure 13). As the current increased the time taken to lift the fingers increased. The change in viscosity is visible in the results. The time separations in the curves indicate that the greater the input current to the damper, the higher the viscosity and therefore the more work required of the motor to lift the user's fingers.

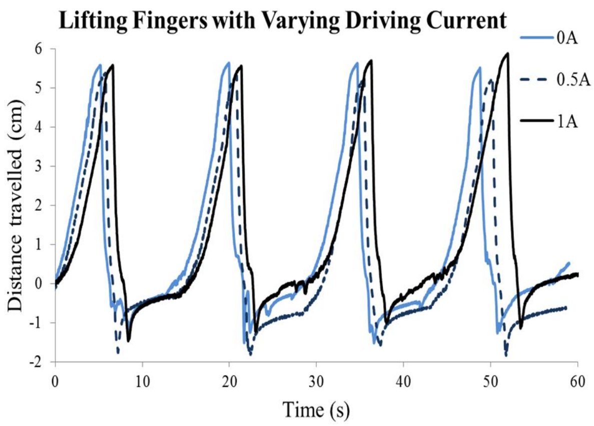

Figure 13. Time response of system when a motor was used to lift an experimenter's fingers. Three different input damper currents are shown.

5.5 Leaking of Fluid

An O-ring seal was originally used at the shaft/housing interface of the damper but was removed as it produced too much friction. When the damper was positioned horizontally, the absence of the O-ring resulted in an egress of approximately 25% of the fluid within the first 10 finger lifts.

Figure 14. Coil attachment used to reduce the leaking fluid problem.

A coil was added at the end of the housing so that the presence of a magnetic field increased the viscosity of the escaping fluid, thereby reducing the velocity of the fluid flow (Figure 14). The magnetised fluid behaved like a seal, clogging the opening to make it harder for additional fluid to leak. Due to the semisolid state of the fluid with the oil and grease it contained, the seal doubled as a lubricant, which allowed the shaft to move in and out of the housing without any opposing resistance. When the coil carried 1A the fluid leakage was reduced to 10% of the total.

5.6 Possible Improvements

The design of the compliant actuator could be modified to have the fluid and shaft separated by a medium. If the fluid was self-contained it would eliminate the issue of the fluid leaking.

Additional modifications could include scaling the size of the actuator down, which would lead to a reduction in the number of coil windings and the current required. This would also decrease the power consumption, decrease the weight and increase the portability of the system.

6 Conclusion

This paper presented the design of a compliant actuator and test system. It has the potential to be used in a stroke rehabilitation device that actively exercises the user's hand and strengthens their muscles. The use of magneto-rheological fluid in the compliant actuator was found to be a feasible solution for the proposed system, but not practical in its current state.

Variations in applied current were able to control the viscosity of the fluid and due to the fluid's fast response time, the viscosity changes appeared to be instantaneous. The actuator was able to produce the resistance needed to oppose the user's movements and as the fluid used was non-proprietary, the cost of the system was reduced.

Drawbacks of using MR fluid included settling, heating and leaking of the fluid. The design of the compliant actuator kept the iron and oil mixed, preventing the fluid from settling. By increasing the size of the piston, and therefore the number of coil windings, the operating current was reduced, consequently avoiding the issues that arise from overheating the fluid. The leaking of the fluid was reduced by the introduction of an additional coil attached at the opening of the actuator, which increased the viscosity of the escaping fluid and provided an effective seal. Although these three issues were mitigated, additional work will need to be done to better reduce the identified problems.

7 Future Work

To justify the use of MR fluid in comparison to a DC motor damper, experimental tests will need to be carried out to compare the two systems. The criteria will not only be based on functionality but also on robustness, cost and ease of manufacture.

The next stage of the project is to expand the ideas explored and to produce a workable prototype. As user insight is needed for further development, ethical approval to interview people who have had a stroke, has been applied for and granted. Further ethical approval is being sought to begin user trials for the later stages of the project.

We are currently working with Im-Able Limited to develop a device that could accompany their already successful upper limb rehabilitation product line.

Acknowledgements

The authors would like to thank Marcus King and Shelia Mann for their time and for sharing their knowledge and experiences in stroke rehabilitation.

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