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# Variable stiffness Mckibben muscles with hydraulic and pneumatic operating modes

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**ABSTRACT**
McKibben muscles have been shown to have improved stiffness characteristics when operating hydraulically. However when operating pneumatically, they are compliant and so have potential for safer physical human–robot interaction. This paper presents a method for rapidly switching between pneumatic and hydraulic modes of operation without the need to remove all hydraulic fluid from the actuator. A compliant and potentially safe pneumatic mode is demonstrated and compared with a much stiffer hydraulic mode. The paper also explores a combined pneumatic/hydraulic mode of operation which allows both the position of the joint and the speed at which it reacts to a disturbance force to be controlled.

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## 1. Introduction

As robots become more widespread, there are changes in the environments in which they work from purely industrial manufacturing plants to arenas where they are likely to experience close physical interaction with humans. This places particular demands on the robot systems which may previously have been of little concern. The most obvious of these is the need to interact safely with and around humans. It is usual to try to prevent or limit this interaction, but this is becoming increasingly unrealistic. Hence, it is necessary to concentrate on making robotic systems safe. In order to achieve this, one of the current approaches being explored is inherent safety. A truly inherently safe system is one that is structurally unable to cause any harm to the user. Such a system would, however, possess limited performance. Thus, usually the design focuses on keeping high inherent safety levels without sacrificing performance. The highest risk factors in impacts between robots and users are the system's velocity and its inertia in the case of constrained impacts.[1] In order to help build a safe system, these two issues should be addressed. Another characteristic that could aid in increasing inherent safety is the structural compliance of soft robots.[2,3] McKibben and other pneumatic muscles are particularly well suited to fulfilling these requirements due to their low weight and compliant physical structure.[4,5] These characteristics are coupled with a high power to weight ratio that notably increases the system's performance. A validation of the McKibben muscles claim to inherent safety is their use in rehabilitation systems. Yeh [6] used the actuators to develop a powered lower limb orthosis and Wu et al. [7] developed a hand exoskeleton also for use in rehabilitation. The intrinsic safety of pneumatic muscles is also exploited in the work of Van Damme et al. [8] and Choi et al. [9]. In both cases, the muscles are mounted on an otherwise rigid structure and are shown to increase the safety of the overall structure in the case of impacts. In the work presented in this paper, an alternative avenue is explored: the inherent safety of McKibben muscles is combined with a method allowing increased stiffness through the introduction of an incompressible fluid into the actuator. In this way, both a structurally compliant and potentially safe mode of operation and a rigid but more accurate mode of operation are possible. The present paper relates the first step in this direction by describing a working mechanism that allows actuation of McKibben muscles both pneumatically and hydraulically.

In order to better explain the nature of the working mechanism described in this paper a brief description of the actuator utilised is necessary. A McKibben muscle is a two-layered system consisting of an inner elastomeric bladder surrounded by an external woven braided shell. As the actuator is pressurised it inflates and this results in a reduction in length and the generation of contractile

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force. The magnitude of this force decays from a peak at full actuator extension to zero at full contraction.[10] The amount by which an actuator contracts varies depending on its initial length and specific design but maximum contractions of 30–35% are typical.[4]

It is easy to see how such a flexible and adaptive physical structure can be exploited to achieve very different operational modes depending on the fluid used to power the muscle. However, the flexibility of McKibben muscles is also the main reason behind one of their main drawbacks: the complexity and non-linearity of their behaviour. This complexity causes difficulties in developing accurate models that would allow precise control algorithms. On the other hand, much effort has been devoted to developing both static and dynamic model of the actuators. These advanced models have considered the effects of rounding of the terminal ends of the actuators,[11] finite thickness in the containment layers,[10] fatigue life [12,13] and stretching of the braid fibres [14]. Chou et al. [10], Tondu et al. [15] and Vo-Minh el al. [16] observed an actuator hysteresis during operation and attempted to model this.

Part of the behaviour complexity of McKibben muscles is due to their inherent compliance due to air compressibility. This is one of the reasons that inspired the use of a hydraulic fluid to increase their stiffness. Ku et al. [17] and Tiwari et al. [18] explored using the actuators hydraulically to increase system stiffness. Increased structural stiffness is highlighted as a possible way to increase position accuracy.[19] Chipka et al. [20] justified their choice of hydraulic actuators due to the faster response time and better position control, compared to pneumatic actuators. The work by Focchi et al. [19] confirms that McKibben muscles can be used hydraulically to provide higher stiffness by showing that pressure and force bandwidth can be increased with the use of water. The same study also points out that water improves energy efficiency since the mass flow is reduced, but the study is inconclusive regarding positioning accuracy. The study of Mori et al. [21] shows the high force potential of hydraulic McKibben muscles, up to 28 kN, when using ultra-high strength fibre sleeves and 4 MPa pressures. In the work of Philen,[22] fluid-filled flexible matrix composite tubes are exploited to obtain a considerable change in stiffness of the system.

Apart from the increase in weight, a drawback of hydraulic systems is that they are not compliant and thus not suited for safe human interaction. Hence, one solution is to design a hybrid system that has the capability to utilise pneumatics in scenarios that involve physical human–robot interaction (pHRI) and hydraulics when high power or stiffness is required. Several past works have examined the performance of pneumatic and hydraulic McKibben muscles. Isobaric and isometric tests performed by Tiwari et al. [18] showed similar performance in pneumatic and hydraulic actuators, since static characteristics are independent of the operating fluid. The static force output depends on actuator dimension, operating pressure and stroke. In the research by Bryant et al.,[23] both working fluids are considered for a bundle of multiple fluidic artificial muscles. The resulting actuator can use variable recruitment schemes to induce a variation in the force output while maintaining a constant pressure source. None of these papers present a working system that can switch from a hydraulic to a pneumatic actuation mode, as is the case of the work described in this paper. The novel working mechanism is explained in Sections 2 and 3, Sections 4 and 5 describe the use of the control algorithm to drive the system, Sections 6 and 7 investigate controlling the speed at which the system responds to disturbances and Section 8 discusses the results obtained and outlines the possible avenues of development and application of this work.

## 2. Stiffness and volume

As has been seen in the previous section McKibben muscles have been demonstrated hydraulically and show improved stiffness performance. This work seeks to explore both pneumatic and hydraulic operation of the same actuator to allow switching between compliant and stiff modes of operation. Initial experimentation explored operating the muscle in a combined pneumatic–hydraulic mode where the muscle would contain a combination of air and a hydraulic fluid. The ratio of the two fluids would therefore determine the stiffness with maximum stiffness being achieved at 100% liquid and maximum compliance being achieved at 0% liquid.

Experimentation was performed to determine how increasing the ratio of liquid (in this case water) in the actuators affected the system stiffness. A test muscle of measured volume was filled with a known volume of liquid filler at an air pressure of 200 kPa (relative to atmospheric pressure), and a loading of 200 N was applied. The extension of the muscle was measured and the spring constant calculated, as seen in Figure 1. The test was repeated for a series of volumes of filler and at an operating pressure of 200 kPa. From Figure 1, there is a significant increase in stiffness from 1100 N/m at 0% filler to almost 5000 N/m with a fill volume of 100%.

These results clearly show that by increasing the ratio of liquid within the actuator the stiffness is increased. However, despite the promising results this approach is not practical in a real application. In the experiment the muscle remained vertical with air and water being inserted into the muscle from the top. This meant the hydraulic fluid would be held in the bottom of the muscle by gravity and there was no danger of water getting into the pneumatic circuit where it would potentially damage the

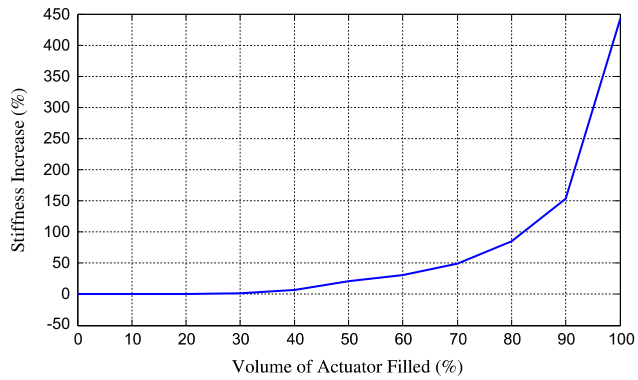


**Figure 1.** McKibben muscle stiffness increases as % water content increased.

pneumatic valves. In a real application, where the actuator could be in any orientation, there would be no guarantee that the hydraulic fluid would not enter the pneumatic circuit.

The other issue which arises is that to vary the stiffness the exact volume of hydraulic fluid in the muscle must be controlled. When the muscle contains both gas and liquid the location of the liquid will vary depending upon the orientation and motion of the muscle and this makes it incredibly complex to remove just liquid from the actuator. For these two reasons, an alternative method needed to be developed which would keep the liquid and air separate.

## 3. System operation

In the work of Focchi et al.,[19] separate hydraulic and pneumatic control circuits were used so the test actuator could be used in both modes. However, switching from hydraulic to pneumatic modes of operation is far from trivial as any hydraulic fluid needs to be bled from the actuator and supply lines before pneumatic operation can begin.

In pneumatic operation compliance is created by the air in the actuator being compressed when a load is applied to it. Therefore, if there is air in the system when operating in the stiff hydraulic mode, this will compress and thus introduce unwanted compliance. Similarly, if there is hydraulic fluid in the actuator during pneumatic operation, this will reduce the compliance, which is equally undesirable.

It takes a considerable amount of time to completely bleed the air or hydraulic fluid from the actuator meaning the system cannot rapidly switch between the complaint pneumatic mode and stiff hydraulic mode. To overcome this, a hardware scheme has been developed which allows the actuators to operate in a compliant pneumatic mode even when they contain hydraulic fluid.

The scheme is shown in Figure 2, it consists of a muscle, two control valves and a reservoir containing hydraulic fluid. The muscle is made within the department and has a maximum length of 400 mm and a minimum diameter of 10 mm. The first valve is a MATRIX 750 3/2 pneumatic solenoid valve with a maximum operating pressure of 600 kPa and maximum flowrate of 50 l/min. The second valve is a 2/2 low-pressure hydraulic solenoid valve from CNHUAL with a maximum operating pressure of 600 kPa and a CV value of 12. The actuator is attached to a loaded lever arm of length 250 mm and mass 0.33 kg via a pulley. Flexion of the joint is achieved by activation of the actuator and extension produced by gravity. A high-precision potentiometer is located at the point of joint rotation to measure the angle $\theta$.

The actuator is filled with hydraulic fluid at all times. In pneumatic mode the hydraulic control valve is fully opened allowing free motion of the hydraulic fluid into the actuator. The pneumatic valve is then opened which forces hydraulic fluid under pressure from the reservoir, into the actuator, replacing it with air. At this point, there will be a volume of air in the reservoir equal to that of the hydraulic fluid displaced. If a load is applied to the actuator, it will force the hydraulic fluid back into the reservoir, reducing the volume available for the air and thus increasing its pressure. The system is compliant for exactly the same reason (i.e. the compressibility of air) as in standard pneumatic muscle operation, the only difference being the compressible air is in the reservoir rather than in the actual actuator.

In hydraulic mode the duty cycle of the pneumatic valve is either 100% or 0% depending on whether the actuator is required to contract or relax. If the actuator is required to contract the duty cycle of the pneumatic valve is set to 100%, this allows air from the supply to flow into the reservoir and pressurise it to a pressure equal to that of the supply. This air pressure in the reservoir forces the hydraulic fluid to flow from the reservoir, through the hydraulic valve and into the muscle. The hydraulic valve controls the flow rate into the muscle.

When the muscle is required to relax the duty cycle of the pneumatic valve is set to 0%. This vents all of the air

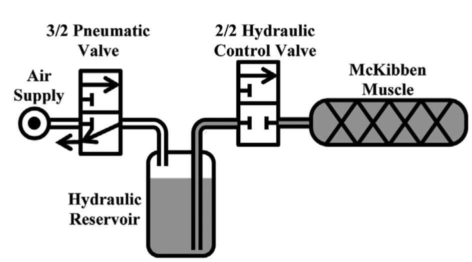


**Figure 2.** Experimental set-up pneumatic/hydraulic circuit diagram.

from the reservoir to the atmosphere returning its pressure to atmospheric pressure. The high-pressure hydraulic fluid is then able to flow back through the hydraulic valve into the (lower pressure) reservoir, as it does so it forces the air in the reservoir through the pneumatic valve to atmosphere.

When the hydraulic valve is closed and a load is applied to the actuator the hydraulic fluid is unable to flow back to the reservoir and instead remains trapped in the actuator. Due to the (theoretical) incompressibility of the hydraulic fluid, the actuator is stiff.

This system allows the actuator to operate in an apparent pneumatic mode and hydraulic mode even though the actuator permanently contains hydraulic fluid. A schematic diagram of the mechanical structure is shown in Figure 3, and the experimental test rig based on the pneumatic/hydraulic control circuit is shown in Figure 4.

## 4. Closed-loop control

The control scheme used for all experiments described in the remainder of this paper is shown in Figure 5, unless otherwise stated.

The controller includes a mode switch which allows the controller to switch between hydraulic and pneumatic modes. In hydraulic mode the pneumatic mode is disabled and vice versa. In purely pneumatic mode, the duty cycle of the hydraulic valve is set to its maximum value

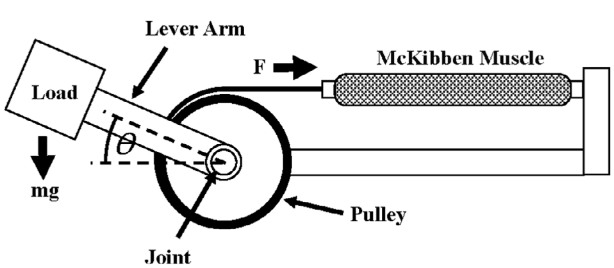


Figure 3. Schematic diagram of the mechanical structure.

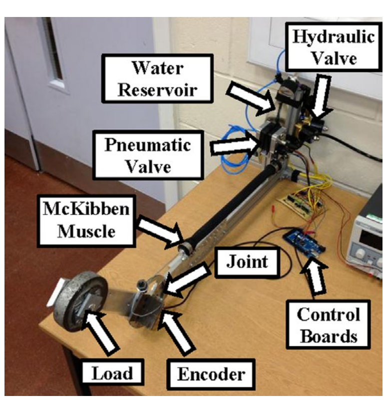


Figure 4. Experimental test rig.

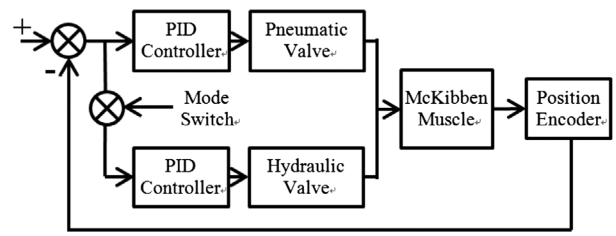


Figure 5. Control schemes (switch allows hydraulic control loop to be disabled).

so to provide minimum resistance to the flow of fluid. However, when operating in hydraulic mode the proportional–integral–derivative controller (PID) control is used to drive both the hydraulic valve (to control the flow rate of hydraulic fluid) and the pneumatic valve to pressurise or depressurise the reservoir depending on whether the muscle needs to fill or vent hydraulic fluid.

The Pulse-width modulation (PWM) duty cycle of the signal applied to the two valves is given by the following pseudocode, where Hydraulic_PWM and Pneumatic_PWM are the duty cycles for each valve type:

*Pneumatic mode*

Hydraulic_PWM = 100%

Pneumatic_PWM = PID(Target Position − Position Encoder)

*Hydraulic mode*

Hydraulic_PWM = PID(Target Position − Position Encoder)

If(Target Position < Position Encoder)

Pneumatic_PWM = 100% //Pressurises reservoir to maximum

else

Pneumatic_PWM = 0% //Reduces reservoir pressure to zero

## 5. Pneumatic and hydraulic operation

In order to be of practical use the system needs to be able to respond to a step input and also track an input in both modes of operation without significant degradation in performance. Two PID position controllers were developed to vary the duty cycle of the PWM signal applied to the valves. This essentially meant the controllers were controlling the direction and flowrate of fluid into or out of the actuator.

### *5.1. Step response*

In the first experiment the response of the system to a step input was analysed. The controller was supplied with a square input signal driving the joint through 40° of motion at a frequency of 0.5 Hz. Initially, the duty cycle of the

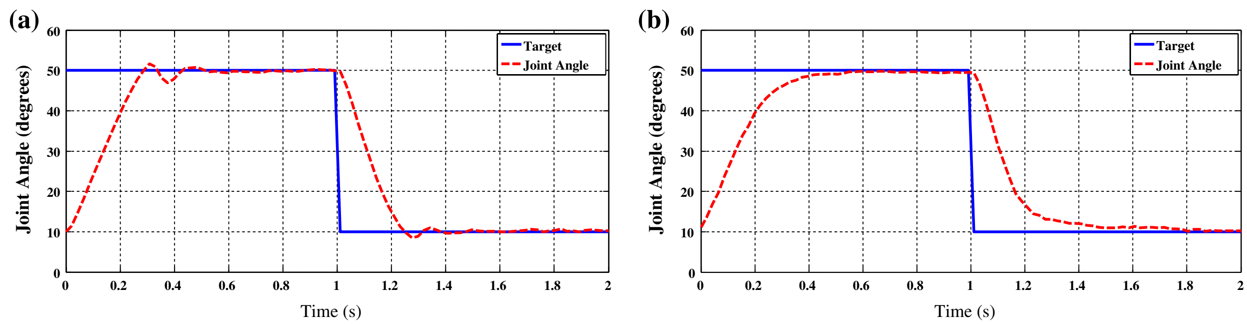


**Figure 6.** Step response in pneumatic mode (a) and hydraulic mode (b).

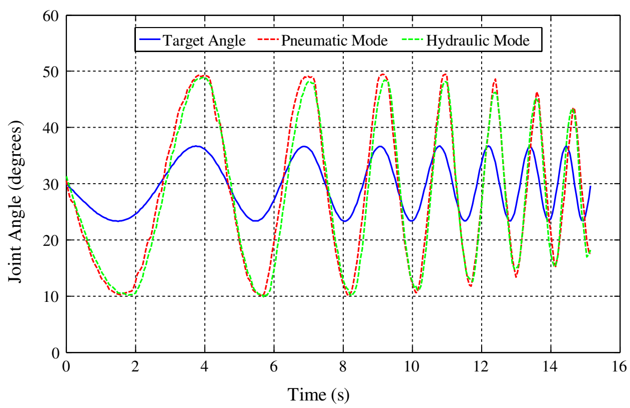


**Figure 7.** Cut-off frequency in pneumatic (1.1 Hz) and pneumatic-–hydraulic (1.08 Hz) modes (Input scaled for clarity).

hydraulic valve was set to 50%. It was found that any a duty cycle above 40% caused the valve to be in its fully open state and therefore present minimal restriction to the flow of hydraulic fluid.

With the hydraulic controller effectively disabled, the step response of the actuator, shown in Figure 6(a), is as expected. The joint overshoots by approximately 2° and oscillates twice before settling after 0.51 s. In Figure 6(b), the hydraulic controller is switched on, it can be seen that in this mode of operation the joint does not overshoot and the joint has a settling time of 0.48 s. The margin of error used to define if the system was settled was ±0.5°.

### 5.2. Tracking and cut-off frequency

To assess the ability of the system to track an input it was provided with a sinusoidal input as the target angle for the position controller. The target angle moves the joint back and forth between 10° and 50° with a frequency slowly increasing from 0.2 Hz. Figure 7 shows the performance of the system in both modes of operation. It can be seen that the system tracks the input equally well in both modes. For clarity Figure 7 shows a relatively rapid increase in frequency over time, whereas when determining the exact cut-off frequency the frequency of the drive signal was increased much more slowly. The target angle has been scaled by a factor of 0.5 also to make the graph more clear.

In order to determine if the dynamic behaviour of the system remained the same in both modes of operation, the frequency of the input signal was gradually increased allowing cut-off frequencies to be determined. This was achieved by measuring the difference between the minimum and maximum joint angles achieved as the frequency increased. The cut-off frequency was determined at the input frequency which caused the measured displacement to reduce to 70.7% of the desired range of motion. The cut-off frequency was found to be 1.1 Hz in pneumatic mode and 1.08 Hz in hydraulic mode.

This result is as expected as the cut-off frequency of the system is determined by the components of the pneumatic/hydraulic circuit which presents the greatest resistance to the flow of hydraulic fluid. This was determined to be the hoses between the reservoir and actuator and the hydraulic valve orifice. As these were constant in both pneumatic and hydraulic modes and the same fluid (water) was passing through them the cut-off frequency would be expected to be equal in both instances.

### 5.3. Disturbances

The main driver for this research was to develop a system which was able to operate in both a stiff mode and a more compliant mode. The stiff mode should be better able to resist disturbance loads than the compliant mode.

#### 5.3.1. Uncontrolled stiffness test

In this experiment both the pneumatic and hydraulic valves were set to their maximum duty cycle (i.e. 100%) so as to present minimum restriction to air and water, respectively. The actuator was then pressurised to 100 kPa (relative) using a pressure regulator at the exit of the compressor which was then shut off so as to keep the system at a constant pressure and prevent any additional air entering the system. A load was then applied to the lever resulting in a torque being generated at the joint and a tensile force being applied to the actuator. This forces the hydraulic fluid out of the actuator and into the reservoir which in turn compresses the air in the reservoir. The resultant joint displacement and change in actuator length were recorded which allowed the stiffness of the actuator in pneumatic mode to be calculated. The load was then removed allowing the joint to return to its equilibrium position before the hydraulic valve was closed ensuring the volume of water in the muscle remained constant. The load was again applied and the resultant actuator displacement measured. As the hydraulic valve is closed fluid cannot now be forced from the actuator and into the reservoir. The stiffness of the actuator in hydraulic mode was then calculated. Due to friction in the actuator, repeated tests resulted in a range of values and so the experiment was repeated 10 times and an average obtained. To investigate whether the increase in stiffness was affected by the load applied to the actuator the experiment was repeated at a range of loads.

Table 1 shows the calculated actuator stiffness obtained by experimentation at a range of loadings. It can be seen that the percentage increase in stiffness between pneumatic and hydraulic modes is in the region of 450%.

Whilst the hydraulic mode provides a significant increase in stiffness over the pneumatic mode it is much less than that of a traditional hydraulic cylinder system. There appear to be two main reasons for this. Focchi et al. [19] reported that at low pressure (100–600 kPa) there is a greater chance of air becoming entrapped in the water. This can reduce the bulk density very significantly making the fluid compressible and thus lowering stiffness. The other reason is that as reported by Davis et al. [14] the braid used to form the actuator stretches when the actuator is loaded changing the volume and therefore length of the actuator.

### 5.3.2. Controlled stiffness test

The stiffness of the system was also explored whilst performing closed-loop position control. The controller was instructed to maintain its position at a target location and then a step load of 9.8 N was applied to the joint, generating a torque of 1.73 Nm. This was achieved by attaching the load to the joint via a flexible cable. The load was initially supported so as to apply no torque but when released a torque would be produced at the joint. The displacement of the joint was then observed, as seen in Figure 8.

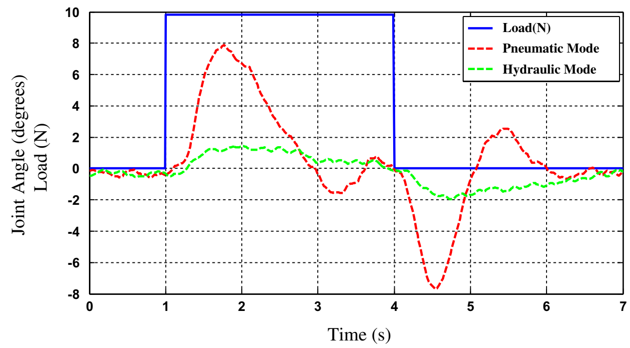


**Figure 8.** Displacement resulting from 9.8 N step loading and unloading in pneumatic and pneumatic–hydraulic modes.

In pneumatic mode, the hydraulic valve is fully open, presenting minimal resistance to the flow of hydraulic fluid. When the load is applied the actuator extends in length which results in a reduction in its volume which therefore means fluid is forced back into the reservoir. This is possible because the air within the reservoir compresses to allow space for the fluid leaving the muscle. It is the compressibility of the air which gives pneumatic actuators their compliant characteristic. The pneumatic valve then opens to increase the pressure in the reservoir and force fluid into the muscle and returns it to its initial position.

In hydraulic mode when the load is applied, the joint again deflects. The hydraulic valve opens and high pressure fluid in the reservoir is forced into the muscle to return it to the equilibrium position. As the pressure of the fluid in the reservoir is higher than in the muscle there is no opportunity for the fluid to flow back into the reservoir and consequently there is no compression of the air and therefore no compliance effect associated with it.

From Figure 8 it can be seen that the increase in stiffness, determined from the maximum deflection when the load is applied, is approximately 450%. This is broadly similar to the increase measured in the uncontrolled stiffness tests. By studying the rate of change of position of the joint as it attempts to return to the equilibrium position after the load is applied, it can be seen that the joint moves much more rapidly when in pneumatic mode than when operating hydraulically. This suggests that the hydraulic mode not only increases the stiffness of the system, but also has a significant influence on how fast the joint can move in response to a disturbance force. This will be investigated more thoroughly in the next section.

**Table 1.** Actuator stiffness in pneumatic and hydraulic operation.

| Force (N) | Pneumatic stiffness (N/m) | Hydraulic stiffness (N/m) | Percentage increase in stiffness |
|---|---|---|---|
| 9.8 | 10,694 | 59,153 | 453 |
| 19.6 | 12,542 | 69,851 | 457 |
| 29.4 | 11,967 | 62,732 | 424 |
| 39.2 | 11,868 | 63,593 | 436 |

## 6. Control of hydraulic flow

As the fluid used to power the actuator passes through the tubes and valves it experiences a resistance to flow which reduces its speed. This resistance to flow is proportional to the viscosity of the fluid meaning a system operating hydraulically (with water) will experience a resistance more than 40 times greater than if it is used pneumatically (water is ~40 times as viscous as air). This is due to the difference in viscosity between air and water.

The hydraulic valve orifice presents the greatest restriction to fluid flow, it effectively controls the speed at which hydraulic fluid is able to enter and leave the actuator. If the hydraulic valve is pulse width modulated with a low duty cycle this results in a low flow rate (equivalent to a small valve orifice). If the PWM signal has a long duty cycle this results in a higher flow rate of hydraulic fluid and therefore allows the actuator to move more quickly.

Experimentation was performed to determine how the duty cycle of the hydraulic valve affects the speed at which the system responds to a disturbance force. The pneumatic valve was fully opened and the supply pressure set to 150 kPa (relative) using a manual regulator. A 29.4 N force was then applied to the lever which produced a 5.1 Nm torque at the joint (as described in Section 5.3.1) and the displacement of the joint was observed. The applied torque resulted in a joint motion of approximately 13°, this motion is the result of the hydraulic fluid being forced out of the actuator, through the hydraulic valve and into the reservoir. The procedure was repeated numerous times with a range of hydraulic valve duty cycles and the motion of the joint was recorded over time. The results can be seen in Figure 9.

It can be seen from figure 9 that low duty cycles significantly reduce the speed at which the actuator is able to change length compared to when the hydraulic valve presents a less significant obstruction to fluid flow. To achieve 8° of joint motion takes approximately 3.5 s for a duty cycle of 10% compared to just 0.5 s when a 20% duty cycle is used.

The above results show that it is possible to vary the speed at which the system responds to the application of a disturbance force by varying the duty cycle of the signal applied to the hydraulic valve.

## 7. Combined pneumatic and hydraulic operation

To this point the two valves have not been controlled simultaneously. In pneumatic mode the hydraulic valve was permanently open and in hydraulic mode the pneumatic valve was at one of two extremes, either at maximum fill or maximum vent. However, by controlling both valves

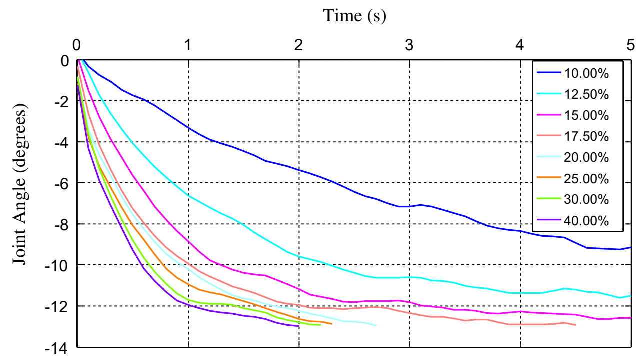


**Figure 9.** Displacement response to step load at a range of hydraulic valve duty cycles.

together it is possible to simultaneously control both the position of the joint and the speed at which it reacts to a disturbance force.

As described in Section 1, there has been increasing interest in complaint actuators in the area of safer pHRI, indeed McKibben muscles have been investigated due to their inherent compliance. In the event of a collision between a human and a traditional robot all of the energy of the impact is transferred to the person. However, in a compliant robot some of this energy is absorbed by the compliance reducing the amount transferred to the person. The disadvantage of a compliant system is that it is more difficult to achieve precise position control.

When a collision between a robot and a human does occur it is more likely to cause serious injury if the robot is moving at high speed due to the higher kinetic energy. It therefore follows that it is more important that a robot is compliant when moving at a high velocity than when static or moving slowly. The experiment described in Section 6 suggests the hardware system could be used to adjust how the system reacts to a disturbance depending on how fast it is moving at the time. For example, when moving at high velocity the hydraulic valve could be set to present minimal restriction to the flow of hydraulic fluid. This would mean that if a disturbance force was applied to the moving joint, hydraulic fluid would rapidly flow from the actuator to the reservoir compressing the air in it and introducing compliance at the actuator output (as was demonstrated in pneumatic mode in Section 5.3.2). When moving more slowly the hydraulic valve could be set to present a more significant restriction to the flow of hydraulic fluid. In this case, when a disturbance force is applied to the joint the flow rate of fluid out of the actuator is restricted. Hydraulic fluid will still flow through the valve back into the reservoir and compress the air in it, but this will occur more slowly than when the valve is fully open. The restriction to the flow of hydraulic fluid means the system is behaving in a similar manner to a spring with

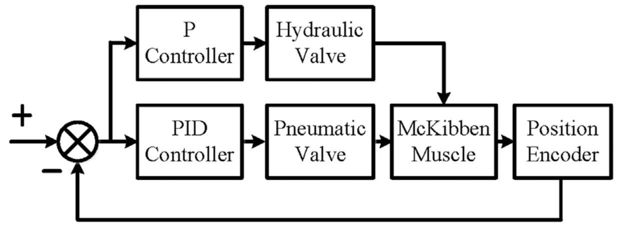


**Figure 10.** Scheme for simultaneously controlling pneumatic and hydraulic valves.

an oil damper. The hydraulic valve is effectively controlling the speed at which the system can react which has the effect of damping out high-frequency disturbances.

It is not, however, possible to develop a controller for the hydraulic valve which increases the flow of hydraulic fluid proportionally to the velocity of the joint. Were this approach used, if the joint experienced a disturbance force whilst moving, which slowed its velocity, the controller would cause the hydraulic valve to restrict the flow of hydraulic fluid. This would mean that instead of the joint deflecting compliantly it would in fact become stiffer as the reduced allowable flow would prevent it from rapidly yielding in response to the applied force.

To investigate the concept of controlling both valves simultaneously the same experimental rig used in the rest of the paper was again used, however, the control scheme was modified to that shown in Figure 10 which allowed both valves to be controlled.

The control system uses the same PID controller as used in the pneumatic mode previously described to control the pneumatic valve. As described above the input to the hydraulic valve controller could not be velocity, so instead, a proportional controller was added which set the duty cycle to be proportional to the joint position error.

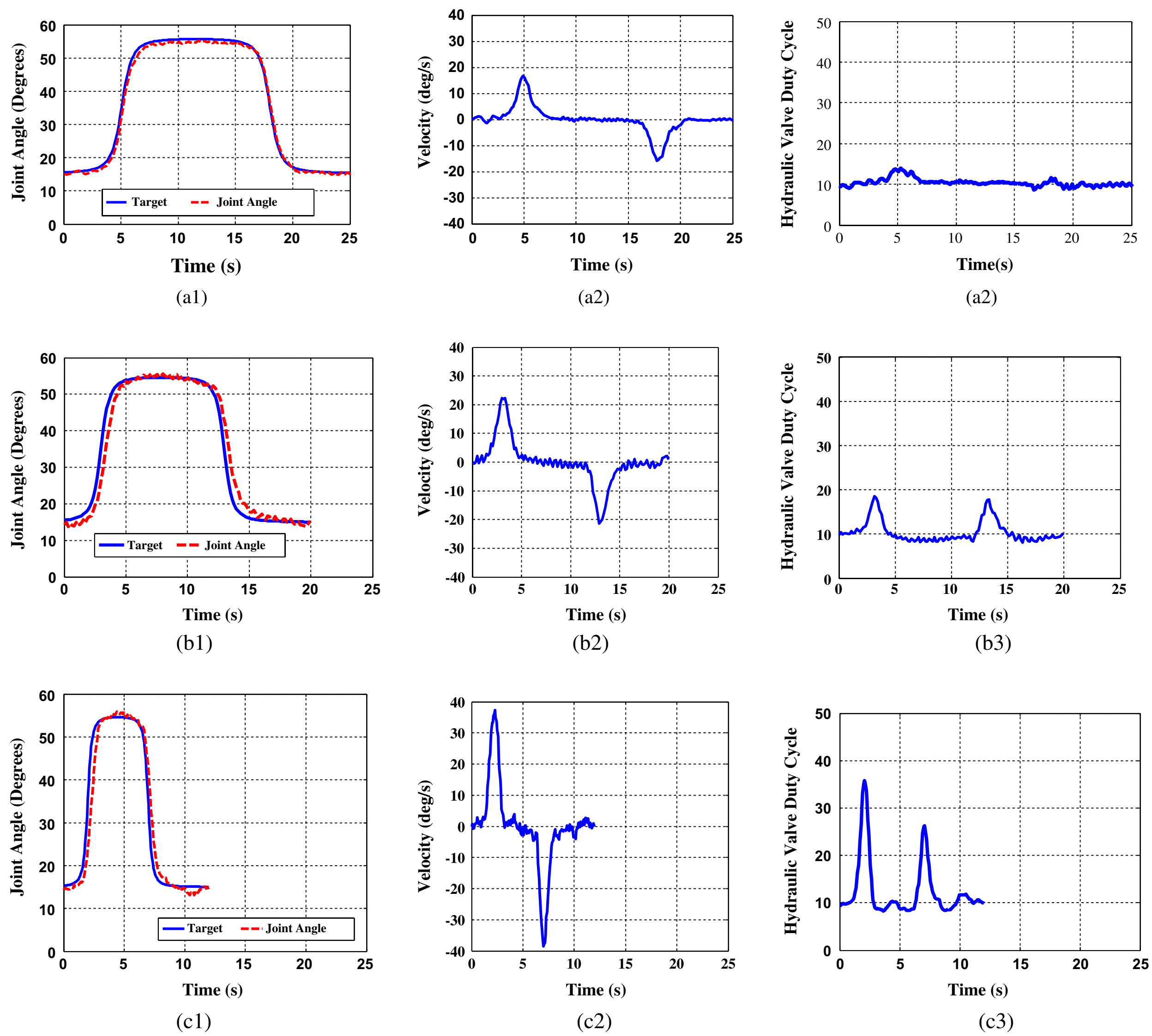


**Figure 11.** Hydraulic valve duty cycle proportional to error.

In this configuration if the joint error is high (meaning the pneumatic controller will attempt to move the joint at high velocity to reach the target position), the hydraulic valve will present minimal resistance. This means that if a disturbance force is applied at this time the hydraulic fluid can flow rapidly through the hydraulic valve allowing the joint to deflect compliantly. As the joint slows upon nearing its target position the positional error will reduce and this will cause the hydraulic valve to restrict the flow of hydraulic fluid thus preventing the joint from deflecting significantly should a disturbance force be experienced.

The system was provided with a trajectory input which repeatedly accelerated the joint from a starting position to a constant velocity before decelerating and stopping at a second location. The pneumatic valve performed closed-loop position control, whilst the hydraulic valve was controlled to set the duty cycle of the signal sent to the valve to a value proportion to the error in the input position. Figure 11 shows the results of the experiment when performed at three increasing speeds.

Figure 11 shows the frequency of the input signal increasing from 0.035 Hz (a) through 0.05 Hz (b) to 0.1 Hz (c) (for ease of comparison only one cycle of each is shown). It can be seen that as would be expected the measured joint angle lags the input signal and there is an observable error. This error between the required and actual joint angle increases with speed, the maximum error is ~5°, ~10° and ~15° in experiments (a), (b) and (c), respectively. Figure 11(a2), (b2) and (c2) show the velocity of the joint (obtained by differentiating the joint angle with respect to time) in each of the three experiments and it can clearly be seen that the maximum velocity the joint achieves becomes higher as the frequency of the input signal is increased. Figure 11(a3), (b3) and (c3) show the duty cycle of the signal sent to the hydraulic valve. It can be seen that the peak velocity and peak hydraulic valve duty cycle values occur at the same time. This means that as the joint moves at its highest velocity the restriction presented by the hydraulic valve is at its lowest meaning should the joint collide with an object the hydraulic fluid can rapidly be forced back into the reservoir allowing the joint to deflect compliantly, as was shown in Figure 9. As the restriction presented by the hydraulic valve is proportional to the position error (not the velocity) the collision will result in an increase in positional error which will in turn further opens the hydraulic valve. Similarly, it can be seen in all three cases that when the joint velocity is zero the duty cycle of the hydraulic valve is low meaning it presents significant restriction to the flow of hydraulic fluid. Should a disturbance force be applied to the joint at this time the hydraulic valve will restrict the flow of fluid out of the muscle and the joint will resist this and deflect much more slowly, again as was shown in Figure 9.

Whilst this behaviour may appear similar to that in the hydraulic mode experiments, there is a significant difference. In hydraulic mode the pressure in the reservoir is always at the maximum supply pressure, whereas this is not the case in the hybrid mode where it may be much lower, depending upon the force the actuator is required to generate. It is the pressure in the reservoir which determines how easily the water can be forced back into it meaning in hybrid mode, when pressure in the reservoir is below that of the supply, this is easier and the joint will deflect more easily.

## 8. Conclusion and future work

The aim of this research was to develop a method which allows McKibben muscles to operate in both compliant pneumatic and stiffer hydraulic modes. The benefits of hydraulic operation have previously been shown but seamlessly switching between modes is a challenge. This paper has presented a method of achieving this by maintaining hydraulic fluid in the McKibben muscle even when it is operating pneumatically. This is accomplished through the introduction of a reservoir which contains both air and hydraulic fluid. In pneumatic mode when a load is applied to the actuator, air in the reservoir is allowed to compress resulting in compliance in the muscle. However, in hydraulic mode this air is not allowed to compress and the resultant system stiffness is higher. In both cases, the McKibben muscle is filled with hydraulic fluid. It has been shown that the performance of the actuator is broadly the same in terms of response and bandwidth in both modes of operation.

During the experimentation, it was observed that the speed at which the system reacted to a disturbance force varied depending on how much of a restriction the hydraulic valve presented to the flow of hydraulic fluid. A method of controlling both the hydraulic and pneumatic valves simultaneously has been demonstrated. In this mode of operation the pneumatic valve determines the volume of fluid in the actuator, and thus its position, and the hydraulic valve determines the speed at which fluid can enter and leave the actuator. This restriction to flow determines how the system will react to a disturbance force. If the hydraulic valve presents minimal restriction to flow a disturbance force will cause the joint to deflect rapidly under the load. However, if the hydraulic valve restricts the flow the joint will deflect much more slowly when a disturbance force is applied.

Compliant actuation has been explored in the area of safer human–robot interaction but precise position control of compliant systems is difficult. In the event of a collision with a person a robot moving at speed is much more dangerous than a robot moving more slowly, this is due to the higher energy in a fast moving system. Experimentation has shown how the hydraulic valve can be used to present minimal restriction to fluid flow when the joint is moving at high speed and greater restriction when the joint is moving more slowly. This means that should the system experience a disturbance when moving at speed (when it is most dangerous) the joint is able to rapidly deflect. However, when moving more slowly (and so is less dangerous) the joint will resist the disturbance force. The potential of this mode of operation in the area of safe pHRI will be further explored in future work.

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