1-1-2016

# Thermally activated paraffin-filled McKibben muscles

Danial Sangian
*University of Wollongong*, ds706@uowmail.edu.au

Sina Naficy
*University of Wollongong*, snaficy@uow.edu.au

Geoffrey M. Spinks
*University of Wollongong*, gspinks@uow.edu.au

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## Abstract

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## Keywords

mckibben, muscles, paraffin-filled, thermally, activated

## Disciplines

Engineering | Science and Technology Studies

## Publication Details

Sangian, D., Naficy, S. & Spinks, G. M. (2016). Thermally activated paraffin-filled McKibben muscles. Journal of Intelligent Material Systems and Structures, 27 (18), 2508-2516.

# Thermally activated paraffin filled McKibben muscles

Danial Sangian[1], Sina Naficy[1,2] and Geoffrey M Spinks[1,2]

[1]ARC Centre of Excellence for Electromaterials Science and Intelligent Polymer Research Institute, University of Wollongong, Innovation Campus, Squires Way, North Wollongong, NSW, 2522, Australia.

[2]School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Wollongong, NSW, 2522, Australia.

**Corresponding author:**

Geoffrey M Spinks, ARC Centre of Excellence for Electromaterials Science, Intelligent Polymer Research Institute, University of Wollongong, Innovation Campus, Squires Way, North Wollongong, NSW, 2522, Australia.

School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Wollongong, NSW, 2522, Australia.

Email: gspinks@uow.edu.au

Tel: +61 2 4220 3010

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McKibben artificial muscles are one of the most pragmatic contractile actuators, offering performances similar to skeletal muscles. The McKibben muscles operate by pumping pressurized fluid into a bladder constrained by a stiff braid so that tensile force generated is amplified in comparison to a conventional hydraulic ram. The need for heavy and bulky compressors/pumps makes pneumatic or hydraulic McKibben muscles unsuitable for microactuators, where a highly compact design is required. In an alternative approach, this paper describes a new type of McKibben muscle using an expandable guest fill material, such as temperature sensitive paraffin, to achieve a more compact and lightweight actuation system. Two different types of paraffin filled McKibben muscles are introduced and compared. In the first system the paraffin filled McKibben muscle is simply immersed in a hot water bath and generates isometric forces up to 850 mN and a free contraction strain of 8.3 % at 95$^{o}$C. In the second system, paraffin is heated directly by embedded heating elements and exhibits the maximum isometric force of 2 N and 9% contraction strain. A quantitative model is also developed to predict the actuation performance of these temperature sensitive McKibben muscles as a function of temperature.

**Keywords**

Microactuators, McKibben muscle, paraffin

# Introduction

Making and developing high performance artificial muscles (Madden, 2006; Mirfakhrai et al., 2007) is an on-going challenge for engineers and scientists (Sangian et al., 2015; Spinks, 2012). Artificial muscles are of interest for assisting human movement in cases of injury/disability or for use in robotics and medical devices (Gordon et al., 2006; Tarnita et al., 2009; Villegas et al., 2012; Tommasino et al., 2012). Artificial muscles normally offer three different types of actuation movements: torsional (Foroughi et al., 2011), tensile (Hunter and Lafontaine, 1992) and bending (Wang et al., 1999). Tensile contractile is the most common movement in skeletal muscle in humans and animals, allowing complex and agile movements as in jumping and lifting (Josephson, 1993).

McKibben artificial muscles, introduced by Joseph L. McKibben in the late 1950s, are one of the most famous and practical linear artificial muscles with a great potential for fabricating robots and surgery tools (Tondu, 2012; Tondu and Lopez, 1997; Ching-Ping and Hannaford, 1996). The muscle usually operates with pressurized gas/water, and the system requires a compressor/pump as well as a gas/water storage container (Meller et al., 2014; Tiwari et al., 2012; Mori et al., 2010; Moon et al., 2006). The pressurized fluids are used to increase the volume of the inner bladder and subsequently deform the braided sleeve that make up the McKibben muscle. The basic working concept of McKibben artificial muscles is that the braided sleeve translates the volumetric increase of the inner bladder to a lengthwise contraction of the braid that is capable of generating contractile forces much greater than an equivalent hydraulic or pneumatic system. The required compressors and pumps in the conventional McKibben muscles, however, make the actuation system heavy and bulky and unsuitable to be utilized as microactuators or in portable applications where a compact size and weight minimization are desired.

One approach towards making a more compact and lightweight actuation system is to reduce the need for compressors, pumps and valves by using a volume change material to deform the braided sleeve. Tondu and co-workers have shown that pressurized gas/water can be replaced with pH sensitive hydrogel spheres in McKibben artificial muscles to generate reasonable actuation strain and force (Tondu et al., 2009). However, there are still some remaining problems that need to be considered, such as the long response time (> 10 min), and the required pump for delivering acid/base solutions to the pH sensitive hydrogel. Recently, Justice and co-workers have developed an enclosed system where enzyme catalysed hydrolysis of urea generates sufficient $CO_2$ gas to power a pneumatic McKibben muscle (Sutter et al., 2013). Here we introduce a novel McKibben artificial muscle filled with paraffin wax as an expandable temperature sensitive material. Paraffin wax has been shown to offer high thermal stability and gives volumetric expansion of ~20% when heated from 30 $^{o}$C to 90 $^{o}$C and ~10% extra expansion between 90 $^{o}$C and 210 $^{o}$C (Lima et al., 2012). The volume change expected during the full contraction of a McKibben muscle with starting braid angles of 30-40$^{o}$ and activated by pressurized fluid is of the order of 21%-78%. Therefore, it seems reasonable that the thermal expansion of paraffin within the McKibben muscle should be able to generate useful contraction strains and forces. Thermal expansion of paraffin has recently been used to create a new generation of artificial muscles by employing twisted/coiled carbon nanotube and niobium nanowire yarns, demonstrating successful torsional and linear actuation (Lima, 2012; Mirvakili et al., 2013).

The aim of the present study was to evaluate the performance of paraffin-filled McKibben muscles. Initially, paraffin wax-filled McKibben muscles were fabricated and heated using an external water bath. This system was used to evaluate the feasibility of using an expandable fill material to power the actuation of the McKibben muscle and to develop a quantitative model of output force and contraction strain for a given wax temperature. Secondly, a more practically useful wax-filled McKibben muscle was fabricated with an in-built electrical heating element. The output force, contraction strain and response time of both systems were evaluated.

### *Modelling of temperature driven McKibben artificial muscle*

The most common approach (Tondu and Lopez, 2000) to model an ideal pressure-driven, cylindrical McKibben artificial muscle relates the static force $F$ produced by the muscle to its contraction strain $\varepsilon$ at various pressure differences $P$ of the fluid contained inside the bladder within the braided sleeve compared with ambient pressure:

$$F(P,\varepsilon) = (\pi r_o^2)P[a(1-\varepsilon)^2 - b] \tag{1}$$

Where $r_o$ is initial radius of braided sleeve and $a$ and $b$ are constants based on the initial bias angle $\theta_0$ of the fibres within the braid: $a = 3/\tan^2\theta_o$ and $b = 1/\sin^2\theta_o$. This model assumes a full transmission of the pressure inside the inner bladder to the external braided sleeve; ignores 'end effects' relating to the non-cylindrical ends of the clamped braid; and does not include the effects of braid friction. To consider the impact of bladder stiffness on the muscle performance, theoretical (Sangian et al., 2015) and semi-empirical (Meller et al., 2014) modifications have been added to the model.

All models originated from equation (1) treat pressure as an input variable to correlate generated force with strain. In the pneumatic and hydraulic McKibben muscles this applied pressure is easily measured and can be controlled as an input signal. In these conventional McKibben muscle systems, there is essentially an infinite reservoir of fluid available to maintain the desired pressure as the volume of the McKibben muscle changes. However, in a McKibben system operating by temperature-induced volume expansion of an inner fill material (e.g. paraffin in the current study), the volume change is finite and dependent upon the starting volume and pressure-dependent thermal expansion of the fill material. Also, the controlling parameter in these systems is the applied temperature $T$, so the model presented in equation (1) must be reformulated to replace $P$ with $T$. From braid geometry, the braided sleeve volume $V$ is directly related to the axial contraction strain by the following equation:

$$V(\varepsilon) = V_o\left[b(1-\varepsilon) - \frac{a}{3}(1-\varepsilon)^3\right] \tag{2}$$

Here, $V_o$ is the initial volume within the braided sleeve, and $a$ and $b$ are the same as in equation (1). This equation suggests that the braided sleeve's volume is known at any strain $\varepsilon$ with the braid's geometry directly impacting this relationship through parameters $a$ and $b$.

Pressure will also affect the fill material volume and the coefficient of compressibility defines how pressure varies with volume at a constant temperature:

$$\left(\frac{\partial P}{\partial V}\right)_T = -\frac{1}{\kappa V} \tag{3}$$

Assuming $\kappa$ remains independent of $P$ and $V$ at low temperature and pressure ranges, from equation (3) pressure can be stated as a function of volume:

$$P = P_o + \frac{1}{\kappa}\ln(V_o/V) \tag{4}$$

$P_o$ in equation (4) is the starting pressure at which volume is $V_o$ and the temperature is $T_o$. Moreover, $\kappa$ is related to the thermal expansion $\alpha$ and thermal pressure coefficients $\gamma$ as:

$$\kappa = \frac{\alpha}{\gamma} \tag{5}$$

Where $\gamma$ and $\alpha$ are, respectively, $(\partial P/\partial T)_V$ and $\frac{1}{V}(\partial V/\partial T)_P$. Both $\gamma$ and $\alpha$ can be determined experimentally by, respectively, measuring pressure as a function of temperature at a constant volume, and monitoring volume as a function of temperature at a constant pressure. Assuming both $\gamma$ and $\alpha$ are constant and independent of pressure, temperature and volume, equation (5) can be used to calculate $\kappa$ from experimentally measured $\gamma$ and $\alpha$. When $\kappa$ is known in equation (4), equations (2) and (4) are used to replace $P$ in equation (1):

$$F(T,\varepsilon) = (\pi r_o^2)\left[\gamma(T - T_o) - \frac{1}{\kappa}\ln\left(b(1-\varepsilon) - \frac{a}{3}(1-\varepsilon)^3\right)\right][a(1-\varepsilon)^2 - b] \quad (6)$$

Where $T_o$ is the reference temperature at which $P = P_0$ and $V = V_o$.

Figure 1a schematically illustrates a McKibben muscle filled with a material that expands when heated and how the generated volume change and pressure deform the braided sleeve. Figure 1b shows the theoretical static force and contraction strain that this muscle generates. In the unheated state the muscle is relaxed at reference point $O(P_o, V_o, T_o)$. Increasing temperature to $T_1$ in isometric mode (constant length) generates the maximum muscle force (or 'blocked force') at this temperature, as shown by state *A* in Figure 1. By knowing how much pressure is generated in the muscle at state *A*, the blocked force can be obtained from equation (1) at $\varepsilon = 0$. From equation (2) it is seen that the isometric mode also corresponds ideally to a constant volume so that the pressure generated in the blocked state (i.e. state *A*) can be estimated to be $\gamma(T - T_o)$ when $P_o = 0$ and $\gamma$ is independent of temperature. Under these circumstances, the blocked force for such muscle is calculated to be:

$$F_{block} = (\pi r_o^2)(T - T_o)(a - b)\gamma \quad (7)$$

By measuring blocked force at several temperatures, equation (7) can be used as a convenient way to obtain a value for the thermal pressure coefficient($\gamma$).

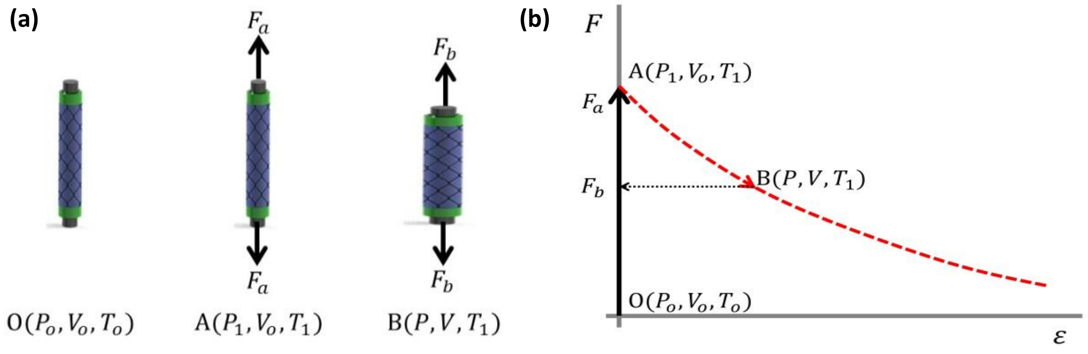


**Figure 1.** (a) Schematic illustration of paraffin-filled McKibben muscle in starting (O), isometric (A) and isotonic (B) states indicating the relationship between experimental conditions and pressure, volume and temperature. (b) Force verses strain diagram exhibiting different points plotted for different pressure and volume at constant temperature.

The full performance envelope of an actuator system in terms of the mix of force and strain produced is illustrated in Figure 1b. Experimentally, these data are collected by first measuring the blocked force under isometric conditions. Next the muscle is allowed to contract to state $B$ and further until $F = 0$ while maintaining a constant input stimulus. The force / strain curve can also be determined theoretically and in the case of thermally-induced actuation of filled McKibben muscles, the behaviour is expected to follow equation (6).

### *Paraffin filled McKibben artificial muscle fabrication*

The paraffin-filled muscle for testing with an external water bath was fabricated as follows (Fig.2a). Firstly, a solid paraffin cylinder of 7.36 mm diameter was inserted into a thin latex rubber inner tube with a thickness of 0.28 mm. Next, the inner tube was inserted into the braided sleeve (polyphenylene sulfide (PPS), obtained from JDD TECH Company China) with a thickness of 0.44 mm and finally both ends of the muscle were sealed to prevent wax escape when the muscle was immersed in a water bath. The initial, unloaded length and diameter of the muscles were 35 and 8.8 mm, respectively. The initial angle ($\theta_o$) of the braided sleeve (Fig.2) was determined by LEICA-M205 microscopy to be $34^o \pm 0.6^o$.

The muscle with embedded heating element was fabricated in a similar manner (Fig. 2b). Firstly, a heating filament was inserted into the inner tube and then melted paraffin was poured into the inner tube. Once the paraffin set, the inner tube was inserted into the braided sleeve and finally the top and bottom of the muscle were sealed. The length, diameter and initial braid angle were 35 and 6.8 mm and $29^{o}$ $\pm0.9^{o}$, respectively. Although the same braid material was used to construct paraffin-filled muscles both with and without the embedded heating element, the method of fabrication resulted in slightly different braid angles and diameters.

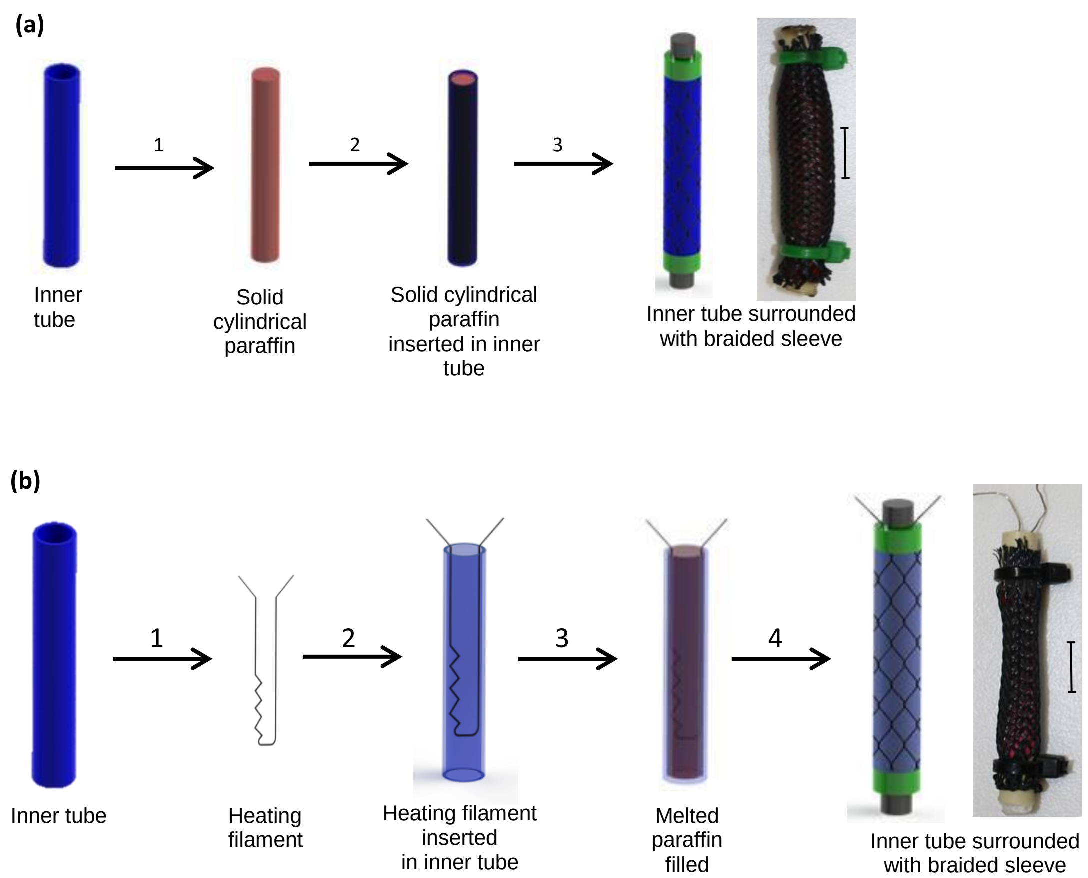


**Figure 2.** Fabrication steps for the paraffin filled McKibben muscle without (a) and with (b) embedded electrical heating. Photographs show examples of prepared samples with scale bar = 10 mm.

*Actuation test procedure.* The experimental set up for actuation testing was specially designed to measure actuation strain, isometric force, response time and sample temperature. For the water bath tests, the actuation set up (Fig.3) consisted of four main parts: a small hot plate, a small water container (80 ml), the paraffin filled McKibben muscle and a dual-mode lever arm force/distance transducer (Aurora Scientific, Model 300B). An e-corder data logger (ED 410, e-DAQ) was also used to connect the lever arm unit to a computer, and e-DAQ Chart software was used to record the data. The temperature of water was monitored with a Digitech Qm-1600 thermometer. For the muscle containing the embedded heating element, a DC power supply was used to control the voltage and current applied to the filament. The water bath was not used. An infrared camera (Micro – EPSILON/TIM160) was used to measure the surface temperature of the muscle.

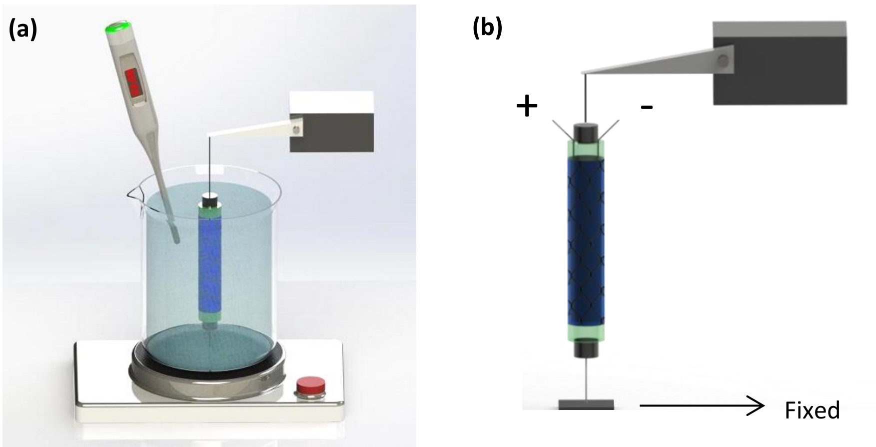


**Figure 3.** Schematic illustrations of actuation set up of paraffin filled McKibben artificial muscle heated using an external water bath (a) and embedded electrical heating element (b).

## *Water bath heated paraffin filled McKibben muscle*

The maximum forces generated by the paraffin-filled McKibben muscle were evaluated by immersing the muscle in a water bath, clamping the muscle ends to maintain a fixed length, and heating from ambient to five different bath temperatures ranging from 55 $^{o}$C to 95 $^{o}$C.

The force-strain curves at each maximum temperature were also obtained by first allowing the muscle to contract in length and measuring the force at each contraction strain and then re-stretching the muscle to its original length. The obtained force/strain curves are shown in Figure 4. As expected, with increasing bath temperature the muscle produced higher blocked forces (at zero strain) and higher maximum strains (at zero force). The volume of the paraffin increases with temperature causing circumferential expansion of the braided sleeve and shortening of the actuator. Overall, the paraffin-filled McKibben muscle's performance is very similar to that of the pneumatic or hydraulic McKibben muscles in which volume change of the braid is achieved by injecting pressurized fluid. However, the needed volume change to drive the paraffin-filled McKibben muscle occurs from inside the bladder without any connection to the outside world. The main limitation of these muscles, however, is the slow response time needed to heat the paraffin.

The paraffin-filled McKibben muscle produced the highest static force and contraction free strain, 850 mN (or a stress of 17 kPa based on the muscle cross-sectional area) and 8.3%, respectively, at a bath temperature of 95 $^{o}$C, which was the maximum temperature that could be reached. Melting tests confirmed that the paraffin used here began to melt at 55 $^{o}$C. The lowest measurable blocked force and free contraction strain (95 mN and 2.5%, respectively) were produced at a bath temperature of 55 $^{o}$C, or just on wax melting. No measurable actuation was detected at bath temperatures below 55$^{o}$C, due to the small wax volume change at these temperatures. The static stiffness of the muscle prior to activation was high as the paraffin is solid in the dry state. All force/strain curves showed some hysteresis between the contraction and re-stretch cycles as is typical of conventional McKibben muscles and is likely related to braid friction (Ching-Ping and Hannaford, 1994).

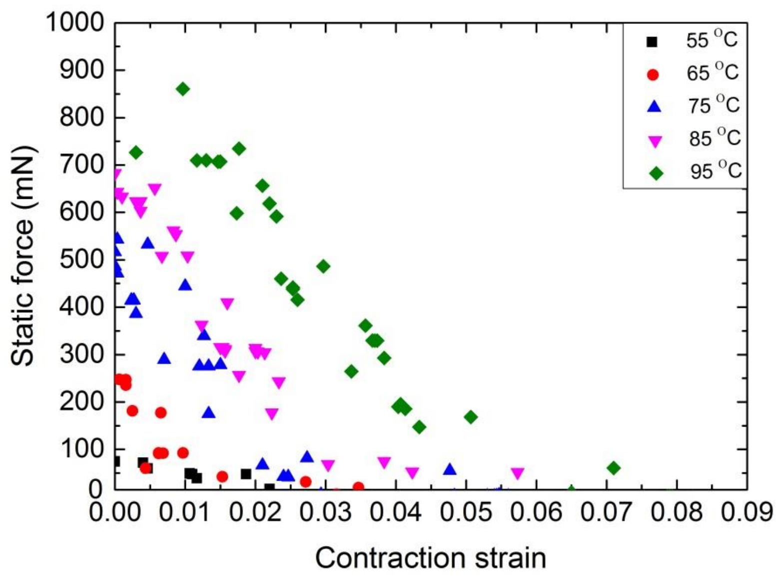


**Figure 4.** Measured force and contraction strains produced by paraffin filled McKibben artificial muscle heated to different bath temperatures, as indicated.

Equation (7) was used to estimate the thermal pressure coefficient $\gamma$ for the paraffin wax employed here. Using the blocked force data from Figure 4, the pressure at each maximum bath temperature was calculated from Equation (1) and these values were plotted against maximum bath temperature in Figure 5a. The calculated internal braid pressure exerted by the wax increased almost linearly with temperature and a least-squares linear fit gave an estimate of $\gamma$ of 87 Pa/K. The thermal expansion coefficient $\alpha$ for the paraffin wax (Fig.5b) was measured to be 0.0031 $K^{-1}$ over the temperature range from 45$^{o}$C to 110$^{o}$C and this value is almost identical to that reported by (Lima et al., 2012). The coefficient of compressibility $\kappa$ was calculated as the ratio of $\alpha$ and $\gamma$ (equation (5)). Using these coefficients, equation (6) was then used to calculate static force $F$ as a function of contraction strain $\varepsilon$. The calculated results are shown as solid lines in Figure 5c and are in good agreement with the experimental data points. The good agreement between calculated and experimental values demonstrates the validity of the modelling approach based on the pressure-dependent thermal expansion of the fill material. The model has practical utility since desired muscle force and strain can be achieved by heating to the temperature given by equation 6.

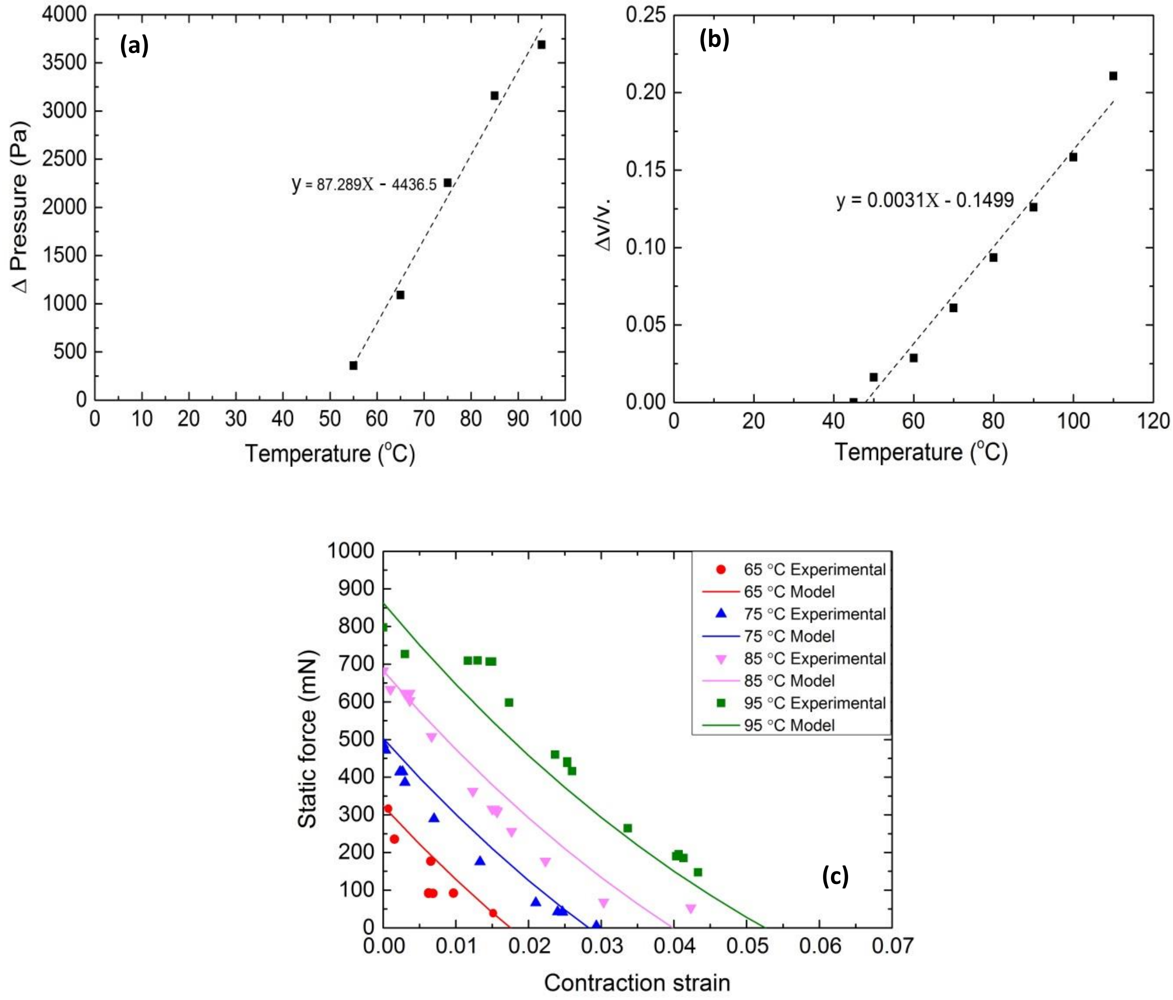


**Figure 5.** (a) Change in pressure generated by heated wax within the McKibben muscle as a function of maximum temperature; (b) fractional volume change of paraffin wax as a function of maximum temperature; (c) typical static forces and contraction strains produced by paraffin filled McKibben artificial muscle with comparison to the model lines for each particular maximum temperature.

For this configuration of McKibben muscle where heating is provided through the water bath, the response time of the muscle is limited by the heating rate of the relatively large quantity of water (Fig.6). The dynamic response of this system was evaluated during slow heating of the water bath (~8 $^{o}$C/min). The maximum isometric force (730 mN) was generated after 8.5 minutes when the water bath temperature reached 95 $^{o}$C. The rate of isometric force generation increases dramatically after 4 minutes of heating, as a result of melting and increased thermal expansion of the paraffin fill material. The isometric and isotonic cycle results were also fully reversible with a longer time needed for the returning cycles due to the slowness of the passive cooling of the paraffin wax and the surrounding water bath.

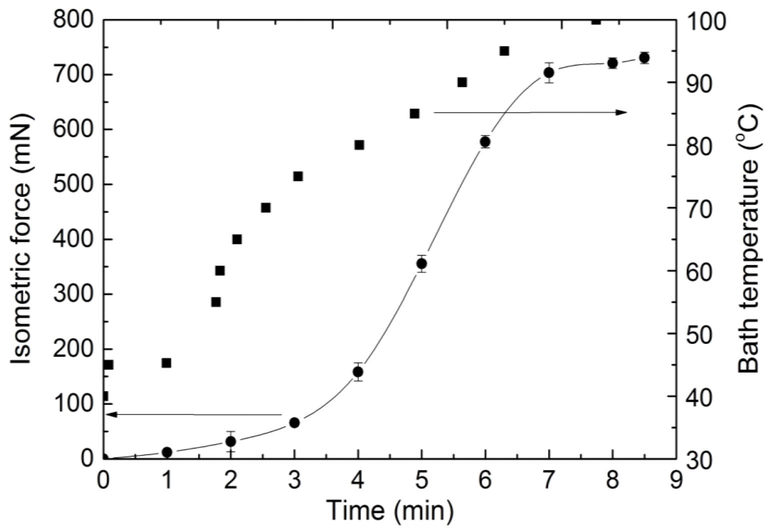


**Figure 6.** Time variation of water bath temperature and corresponding isometric force produced by paraffin filled McKibben artificial muscle.

### *Paraffin filled McKibben artificial muscle with heating filament*

The results of the previous section demonstrated that an expandable fill material, such as thermally-sensitive paraffin wax, can be used to power a McKibben muscle. However, the water bath used for heating the wax is not a practically useful system, so a second set of samples were prepared that included an electrical heating filament embedded inside the wax. The force–contraction strain diagrams for these electrically heated paraffin filled McKibben muscles were obtained at six different voltage/current values applied to the filament (Fig.7). The voltage ranged from 1.3 V to 5.8 V and current ranged from 0.30 A to 1.37 A. The muscle produced higher forces and strains with increasing the voltage/current as a consequence of higher temperatures generated within the wax. Input voltages greater than 5.8 V caused irreversible damage to the bladder and braid of the paraffin-filled muscle due to overheating at the connection to the heating filament.

The muscle produced the highest static force and free contraction strain of, respectively, 2000 mN (71 kPa) and 9% at 5.8 V/1.37 A (7.94 W). The maximum force generated was well above that measured for the actuators heated in the water bath, indicating that much higher temperatures can be produced electrically than was practical to achieve with the water bath. Interestingly, the maximum contraction strain of the electrically heated muscle (9%) was similar to that generated at significantly lower temperature in the water bath (8%). The electrically heated muscles are significantly stiffer than those constructed without the heating filament, as indicated by the higher slopes of the force-strain curves shown in Figure 7 compared with the curves in Figure 4. The presence of the electrical heating element within the paraffin wax acts additionally as a mechanical reinforcement and increases the axial compressive stiffness of the system. As a consequence of this increased stiffness, the achievable contraction strain of this electrically heated McKibben muscle is restricted compared with the water-bath heated systems. Increased contraction strains of the electrically-heated system would be possible by developing a more compliant electrical heating filament.

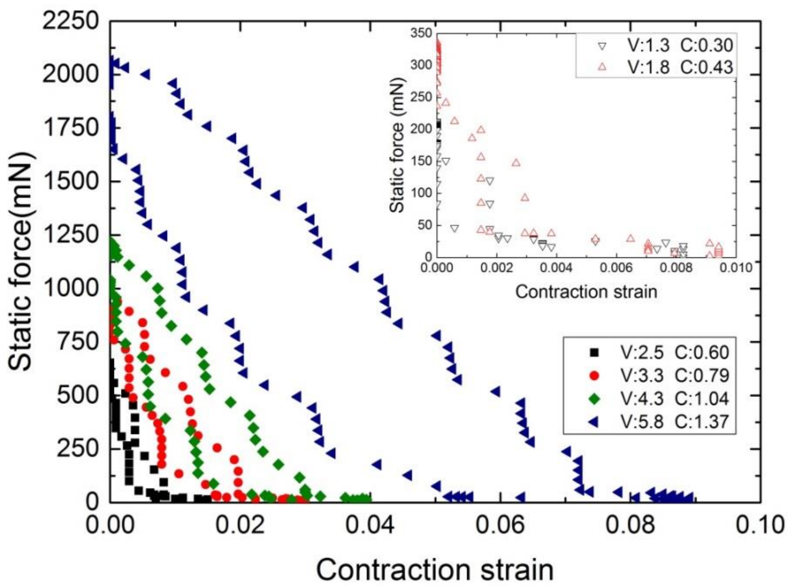


**Figure 7.** Typical forces and contraction strains produced by paraffin filled McKibben artificial muscle with embedded electrical heating filament and emphasizing the role of applied voltage/current.

In addition to enhanced practical utility, the electrically-heated paraffin filled McKibben muscles were expected to respond more quickly than the water-bath heated system in which response time was dictated by the large volume of water. Isometric tests were performed at different input voltage/current values and the force generated monitored with time (Figure 8 a). The muscle reached 750 mN blocked force in just 1.5 min using 5.8 V/1.37 A (7.94 W). In comparison, the muscle heated in the water bath system reached the same isometric force after 8.5 min. It was also noted that the response time of the electrically heated muscle could be controlled by altering the supplied voltage/current. The muscle force reached a plateau after 12.5 min at the lowest voltage/current input (i.e. 2.3 V/0.55 A), indicating that temperature had reached steady-state equilibrium. The surface temperature of the muscle at each applied voltage/current was measured using an infrared camera during the isometric tests (Fig. 9). The surface temperatures as a function of time (Fig. 8b) followed very similar trends to that of the force generation profiles (Fig 8a). The isometric and isotonic cycle results were also fully reversible with higher response time for returning cycles. In the returning cycle the paraffin cooling process was highly dependent on convection heat transfer with surrounded environment.

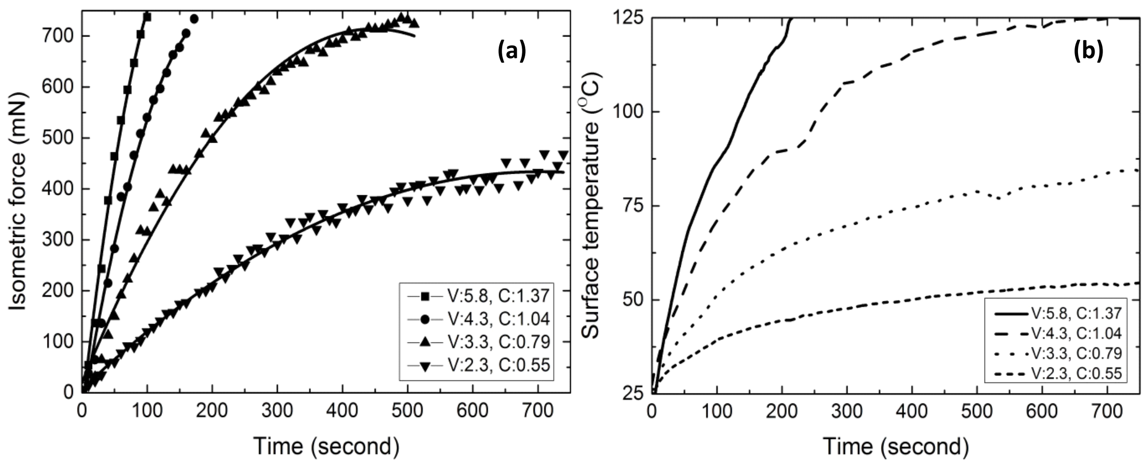


**Figure 8.** (a) Isometric force verses time produced by paraffin filled McKibben artificial muscle- heating filament emphasizing the role of time on muscle performance (b) surface temperature increase with time obtained with infrared camera.

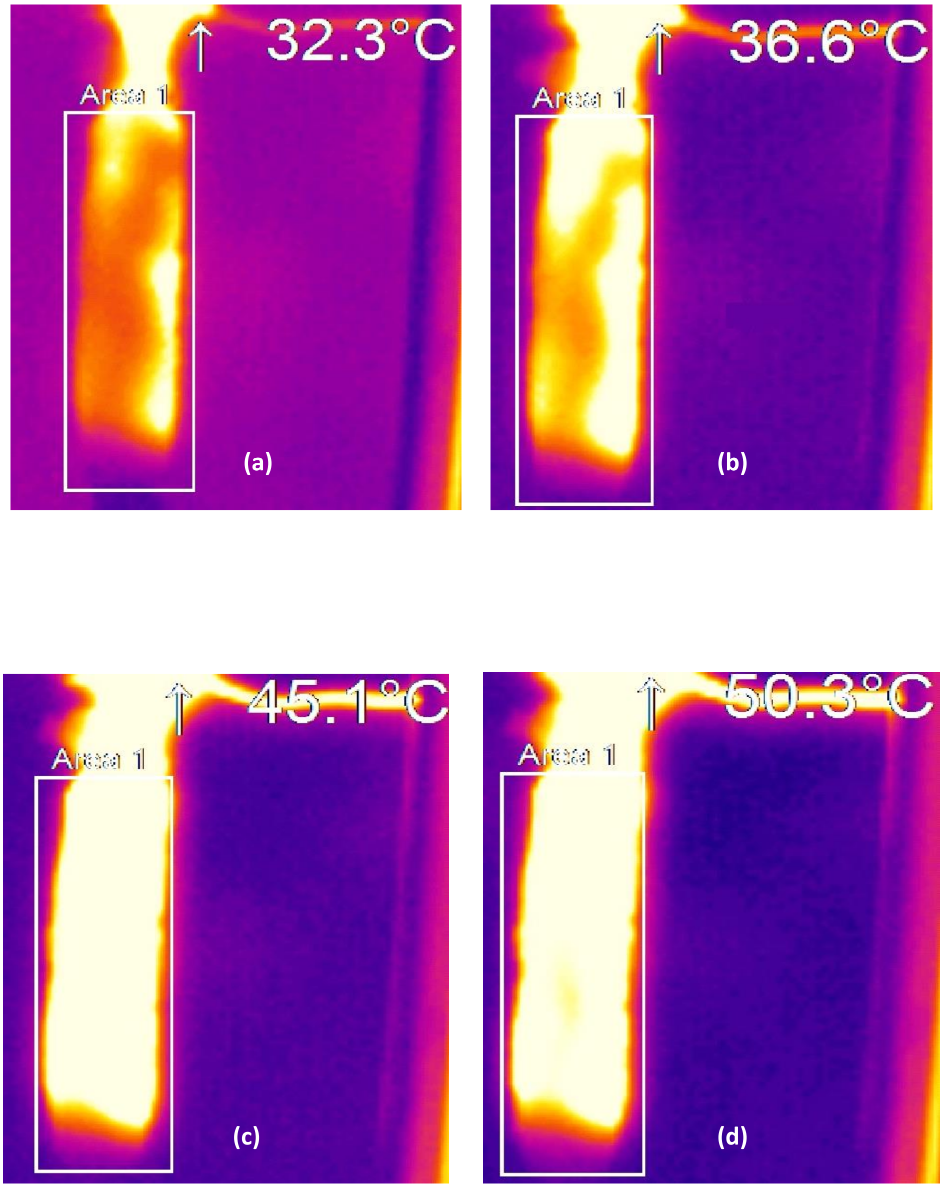


**Figure 9.** Surface temperature images obtained with an infrared camera after 30 seconds of electrical heating for four different applied voltages / currents (a) 2.3 V / 0.55 C (b) 3.3 V / 0.79 C (c) 4.3 V / 1.02 C (d) 5.8 V / 1.37 C. (The white squares indicate the approximate outline of the muscle).

## *Conclusions*

A novel, compact McKibben type artificial muscle that utilises an expandable fill material is introduced for the first time. Actuation is produced using a volume change of the fill material to increase the internal volume and cause simultaneous length contraction and tensile force generation. Thermally expanding paraffin wax heated electrically could generate a maximum force of 2N (71 kPa) or a maximum length contraction of 9%. The system does not require any pumps, valves or fluid tanks and is much more compact than a conventional fluid-driven McKibben artificial muscle. The wax-filled McKibben muscles were also characterised by controlled heating in a water bath. The experimentally produced forces and contraction strains were accurately predicted by the quantitative analysis developed here based on the input temperature and pressure-dependent thermal expansion of the paraffin.


## Acknowledgments

The authors would like to thank Mr Ali Jeirani (with financial support from The Australian National Fabrication Facility) for assistance with figures.

## Funding

The authors also thank the Australian Research Council for supporting this work through the Professional Fellowship scheme [GMS DP110101073].


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