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A Simulation Study on Temperature Control of a SMA-based Ring-actuated Glove for Thermal Comfort

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Abstract: The past few decades have seen a drastic development of robotic wearables, from rigid exoskeletons to soft robotic apparatus. An important function for the latter is their ability to change their shape to fit the human anatomy. Shape Memory Alloy (SMA) has been widely used as an actuator to achieve such compliance. However, previous studies ignored the negative impact on user experience produced by the heat generated from those actuators. This study sets a temperature threshold for SMA-based actuation, by considering thermal change characteristics as an integral part of the design of ring-based, shape-changeable, gloves. The radius variation of each ring under SMA shrinkage is simulated based on the simplified Liang and Rogers model, which emulates temperature change under several parameters. This paper aims therefore to provide a simulation tool for implementing future SMA-enabled wearables.

Keywords: Wearable Technology, Shape Memory Alloy (SMA), Shape-changing Material

1. Introduction

Research in shape-changeable, and soft, compliant, robotic wearables is drawing increasing attention, with numerous applications in the medical field, as well as in sports and fashion-related endeavour, for example in assisting patients in healthcare with grasper control [1]. Driving these robotic apparatuses usually require many actuators, with their own advantages and limitations. However, as robotic wearables become more compliant and adaptable to the human anatomy, actuators with completely novel characteristics, such as shape-changeable or auto-fitting properties, are needed. In that regard, shape-memory alloys have gain interest in the design of soft robotic wearables due to their intrinsic advantages, such as small size, lightweightness and high power-to-weight ratio. In this paper, we implement a SMA-based actuator for the design of a robotic glove.

Although concerted research effort has been focused on the user experience of shape-changeable robotic systems, there is still a lack of discussion on the negative effect of the temperature generated by SMA actuators with close skin contact. In addition, if a glove is not properly fitted, dexterity will be affected. Therefore, in this study, our aim is two-fold: we propose the simulation of a SMA-based ring-actuated glove prototype, in the form of 1) a shape-changing, auto-fitting glove and 2) meeting temperature requirements for close-skin contact. A temperature threshold for the glove operation is therefore met in this simulation, based on a simplified version of the Liang and Rogers model [2].

In this study, we focus on adjusting the temperature range of a SMA wire, specifically, so as to mechanically adjust via contraction the diameters of rings mounted on a glove. Conceptually, upon SMA actuation, each ring would constrict the fabric around the user's finger, therefore fitting the glove to the wearer, automatically. As SMA can generate heat above a tolerable range, or temperature threshold, that we estimate at 42°C, we are looking for optimal material characteristics that minimize heat, while maximizing shrinkage.

The temperature threshold and material phase temperatures will therefore be our model constraints, the latter influencing the strength of the SMA contractions. Those constraints are directly related to the SMA material characteristics. In our work, we find that the adjustable temperature ranges are almost the same for different initial ring diameters (determined by the size of each finger), but as those initial diameters may vary greatly among users' hand profile, determining a ring size will directly contribute in choosing the right SMA characteristics, thanks to our model.

2. Related work

Wearables, and exoskeletons alike, can be considered as a mapping of the human anatomy. However, rigid joints and frames can be detrimental to the wearer's mobility and comfort. In the last decade, wearable technology has seen a rapid expansion in research for developing soft and compliant materials. Instead of rigid links, a growing number of academic and industrial research groups have been designing wearable robots, made of textiles and elastomers, allowing the devices to be lightweight and relatively small, while also being less restrictive in assisting the users' movements. In some study [3], robotic wearables have been explored. Both exoskeletons and soft robotic wearables can be used in human motor assistance, rehabilitation for patients and other applications. The SMA-based ring-actuated glove proposed in this paper will focus on the aspect of compliance (auto-fitting) and temperature control [3][4].

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2.1 User experience

To better improve the user experience, we implement the function of a shape-changeable material in our wearable apparatus. Reducing the gap between the wearable's material and skin, the actuation evenly distributes compression and temperature over the user ' s skin, all factors contributing to the overall experience and comfort. Similarly, in other related study [5][6][7], the user experience of garment technologies has been investigated to describe the effects of compression.

2.2 Robotic wearables with soft actuation

To achieve shape-changeable capability, specific actuators are used. For example, one study [8] introduces electric, hydraulic and pneumatic actuators applied to robotic wearables. However, these actuators have the disadvantages of being of a relatively large size, with high energy consumption and, generally loud. These factors should not be ignored, and the emergence of SMA-based actuators can alleviate those disadvantages. Some research work [9] points out that due to its promising characteristics, i.e. good force/weight ratio, simplicity, low weight and small size, SMA-based actuation represents an interesting alternative. They are, however, difficult to model and simulate. Some studies have been focused on SMA-based, embedded actuation [10], but in this present paper, we consider SMA as actuators external to the garment. In a last study [11], garment actuation was achieved to function as a semi-autonomous, self-morphing, wearable.

2.3 SMA-based actuation

2.3.1 Characteristics of SMA

Shape-memory alloys are metallic alloys with relatively large deformation (typically 5% of their length) when heated, with the capability to recover its original length (hence the memory effect), notably due to the phase transformation this material undergoes, also called shape memory effect (SME). Niche-type of applications have ranged from mechanical, electronic, chemical, to aerospace, energy and medical. Over the past decades, SMA-based actuators have shown the most promises in wearable technology.

The most prevalent shape-memory alloys are NiTi, Fe-basis and Cu-basis, such as Fe-Mn-Si, Cu-Zn-Al and Cu-Al-Ni. NiTi SMAs are preferable for most applications due to their superior thermo-mechanical performance [12].

SMA undergo two different phases: an austenite and a martensite phase. The austenite structure is stable at relatively high temperature, and the martensite structure is stable at lower temperature. When heated, the material begins to transform from a martensite to an austenite phase, with As and Af (Austenite start and finish) noted as the temperatures between which the transformation from martensite to austenite completes. Conversely, when cooling, Ms and Mf correspond to the temperature range between which the transformation from austenite to martensite is achieved, as shown in **Fig. 1**.

When choosing SMA as a actuator, we therefore need to consider the material composition (NiTi, Fe-Mn-Si, Cu-Zn-Al etc.), shape (wire, spring, strip etc.), size, heating and cooling technique, according to the purpose we aim to achieve, as explained in review [13].

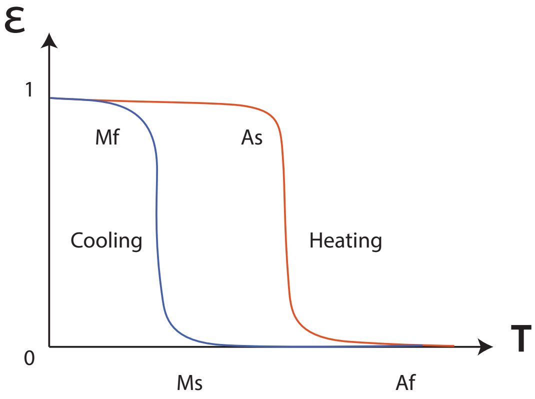

Fig. 1 Material phase temperature range. From As to Af upon heating, and in reverse from Ms to Mf upon cooling.

2.3.2 Constitutive models for SMA

Since we use a SMA-based wire as the actuator, we must consider what type of model to use when simulating our soft robotic apparatus. In some study [14], the main constitutive models, with mathematical description of the thermomechanical behavior of SMA, was reviewed. In this paper, we based our simulation on the Liang and Rogers model [2]. The [15] modified Liang and Rogers model was developed as a position control system for the SMA actuator, which also considered the influence of minor hysteresis, predicting the martensite starting temperature of minor loops. Here, we only model the outer loops for our application, hence the simplified version.

2.4 Robotic gloves

2.4.1 Smart gloves

Some research work [16] have reviewed the development history of smart gloves and found that, similarly to other soft robotic suits, smart gloves have gone from rigid, exoskeletons-like devices, to lightweight options that emphasize compliant control. Some other related research is aimed at the implementation of gripper control [17], or rehabilitation [18]. Among these researches, several studies have used SMA-based actuators to achieve control. The next section will introduce these studies.

2.4.2 SMA-based soft robotic gloves

The lightweight gloves conceived in [19] used shape memory alloy wire actuators and leveraged the self-sensing features of SMA materials to alleviate hand stress of facility workers.

In another study related to space exploration [20], space suit systems were catagorized as overly rigid, with materials exhibiting too much resistance on the astronaut finger motion, preventing accurate gripping. In contrast, the small-scale nature of shape memory alloys, as part of the glove actuation system, would assist hand gripping control.

Unlike the above researches that use SMA-based actuators in the form of embedded textile technology, this paper focuses, in contrast, on a different form-factor, with rings external to the glove. This design aims to let the gloves autofit the fingertips, positioning the system as an entirely novel design, to potentially increase the accuracy and control of glove-based operations. We will discuss the simulation of such prototype in the next section.

3. Prototype

3.1 Prototype of SMA-based Ring-actuated Gloves

The aim of our simulation model is to provide an autofitting solution in situations that require delicate manipulations, as gloves that are not elastic enough to fit properly (such as medical rubber gloves) will greatly impair the accuracy of the user's operation.

As mentioned before, a SMA-enabled fabrics option [10] was not considered, as the objective of this paper is to facilitate the implementation of our design on any type of pre-existing semi-rigid gloves. The actuation for each finger is envisioned as a set of constriction rings, a proven mechanism [21], and the simulation allows us to find the best temperature threshold and material with suitable phase temperatures. Moreover, using rings can be easily applied to any other shape-changeable garments. For example, when people wear clothes that lack sufficient elasticity, in order to restrict them to part of their bodies, or to attach some accessories, such as belts or laces.

Although some smart gloves may have more compliancy, the glove prototype we propose in this paper can have as many rings as required. Here, we designed our simulation model with five rings placed around each fingertip.

3.2 Temperature and user experience

Since our glove is SMA-actuated, low voltage is applied, generating heat that may be felt by the wearer. Moreover, the thermal insulation will vary greatly between types of gloves, and some will not have any sufficient thermal insulation. Temperature therefore become an increasingly important factor for user experience, which we set here as a 'temperature threshold'. When exceeding this threshold, the SMA rings will have a negative impact on the user experience. In the next section we will describe this temperature-displacement model in more details.

4. Simulation

4.1 Model

When the rings gain heat energy from the electrical current, the SMA will shift from a martensite to an austenite phase. The SMA-based rings will be deformed, resulting in displacement of the SMA and contraction of the rings. As the diameters change, the shape of the glove can be controled to the extent of the ring placement.

The input current will bring as an output a temperature T, which then leads to phase transformation, and a displacement D, as shown in the below block diagram **Fig. 2**:

Otherwise put, our simulation model can be divided, very classically, as: a Thermal Model, describing temperature as a function of current input, a Phase Transformation model, describing the different phases the material would undergo (martensite and austenite depending on temperature), and finally, a Mechanical Displacement model, which then determines the wire length, and therefore the ring diameter.

- For the thermal model:

The thermal model is based on the ordinary differential equation [15]:

$$\rho \cdot V \cdot C_p \cdot \frac{dT}{dt} = I^2 \cdot R - \pi \cdot D_0 \cdot l \cdot h \cdot (T - T_{amb}) \qquad (1)$$

Where ρ is the density of the SMA ring; V is volume of the SMA ring; C_p is the specific heat coefficient; I is the current applied, R is the resistance of the SMA ring; D_0 is the cross-sectional diameter of the SMA; l is the length of the SMA ring; h is the convection heat transfer coefficient; and T_{amb} is the ambient temperature, which we set here at 20°C.

- Regarding the phase transformation model:

The austenite to martensite transformation is characterized by the martensite fraction ϵ_m. During the heating and cooling processes, the martensite fraction is noted as ϵ_{mh} and ϵ_{mc}. The austenite fractions ϵ_a during the heating and cooling processes can be defined as $\epsilon_{ah} = 1 - \epsilon_{mh}$ and $\epsilon_{ac} = 1 - \epsilon_{mc}$.

The martensite fraction and austenite fractions characterizing the phase transformations are evaluated as [15]:

$$\begin{cases} \epsilon_{ah} = \frac{1}{2}(1 - cos(\pi \frac{T - A_s}{A_f - A_s})) \\ \epsilon_{mh} = \frac{1}{2}(1 + cos(\pi \frac{T - A_s}{A_f - A_s})) \\ \epsilon_{ac} = \frac{1}{2}(1 - cos(\pi \frac{T - M_f}{M_s - M_f})) \\ \epsilon_{mc} = \frac{1}{2}(1 + cos(\pi \frac{T - M_f}{M_s - M_f})) \end{cases} \qquad (2)$$

$(0 \leq \epsilon_m, \epsilon_a \leq 1, Af > As > Ms > Mf.)$

- Regarding the mechanical model:

the displacement D, which follows the thermal model and phase transformation model developed above, can be expressed by:

$$D = \begin{cases} g\epsilon_{ah} & (heating) \\ g\epsilon_{ac} & (cooling) \end{cases} \qquad (3)$$

where g is a constant, based on the maximum displacement of the wire, which also depends on the chosen material properties.

We also set the new length of the ring as l_n and the newly found diameter of the ring as d_n:

$$\begin{cases} {}_n = l - D \\ d_n = \frac{l_n}{\pi} \end{cases} \qquad (4)$$

4.2 Method

We adjust the parameters in our simulation as below:

- Temperature threshold: Gloves of different materials have different thermal insulation properties, so the upper temperature limit the gloves can withstand will also be different.
- Initial ring diameter: The initial ring diameter d for each user is obviously different, also according to the wearer ' s gender and age.
- Material phase temperatures: Different SMA materials have different material phase temperatures. Through changing these parameters, we will adjust the constriction range of the diameter, as the wire will exhibit more or less strength, and the space between the glove material and the skin will be more or less important.

5. Results and Discussion

First, we set the parameters as: temperature threshold T_{thr} = 42°C (the highest temperature that we estimated could be tolerated by the user); As = 40°C, Af = 45°C, Ms = 35°C, Mf = 30°C;

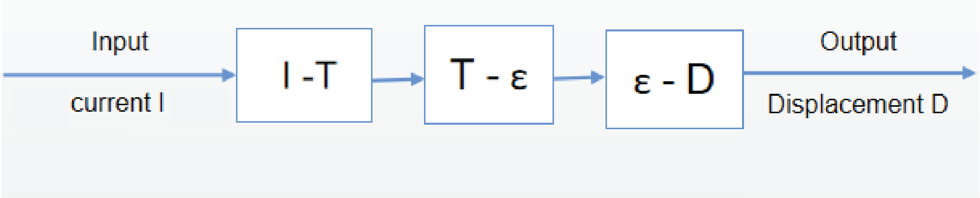

Fig. 2 The block diagram shows the tripartite simulation model: from thermal to phase transformation, to displacement.

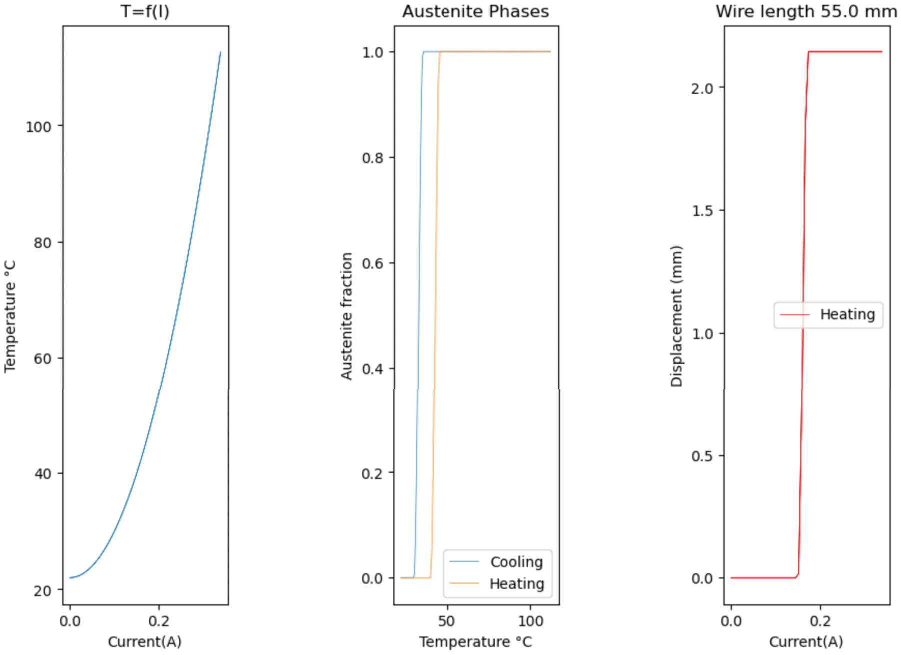

Fig. 3 Simulation result: as the current increases, the temperature increases exponentially (left plot), phases are separated between cooling and heating (middle), and current input is correlated to wire length variation (right).

Initial ring diameter d= 17.5mm.

The **Fig. 3** below shows simulation results: due to the fact that we set the temperature threshold at 42°C, the largest current we can apply on the SMA ring is 0.16A. With such current value, the length of each SMA wire is 54.78mm, and accordingly, the new diameter of the ring is found to be 17.27mm, which means the adjustable range of the ring d_a is 0.23mm.

We then changed one of the three adjustable parameters, either temperature threshold, initial ring diameter, or material phase temperature ranges, while fixing the other two, and searched for the optimal solution.

When changing the value of the temperature threshold T_{thr}, we fix the following: As = 40°C, Af = 45°C, Ms = 35°C, Mf = 30°C, d= 17.5mm.

From **Table 1**, we can find that, when the temperature threshold is higher, the range of the adjustable diameter of the ring is larger. If the temperature threshold is lower than As, the displacement of the ring is 0. This is because the temperature threshold is lower than As, and the SMA ring will therefore not contract. The As of the SMA ring should be set lower than the temperature threshold, and when the temperature threshold is higher than Af, the displacement will not increase, because the SMA ring has reached its stable austenite phase: the ring will stop contracting.

Table 1 The adjustable diameter of ring when changing the value of Temperature threshold.

T_{thr} (mm)	d_a (mm)
40	0
42	0.23
44	0.58
46	0.68
48	0.68
50	0.68
52	0.68

We also find that, when temperature threshold is set near the Af, the ring contraction reaches its maximum value, while still being in a comfortable temperature range for the wearer, resulting in optimal temperature threshold for such SMA.

When we change the value of the initial ring diameter, while keeping the T_{thr} = 42°C, As = 40°C, Af = 45°C, Ms = 35°C, Mf = 30°C, we find from **Table 2** that even if the initial radius of the ring is slightly different, at the same temperature threshold and the same material phase temperature, the range of adjustable diameter of the ring (or displacement) is similar for all five fingers.

When we change the value of the material phase temperatures, while keeping the T_{thr} = 42°C, d= 17.5mm, as we can see in

Table 2 The adjustable diameter of ring when changing the value of Initial ring diameter.

d (mm)	d_a (mm)
15.5	0.19
15.5	0.21
16.5	0.22
17.5	0.23
18.5	0.25
19.5	0.26
20.5	0.27
21.5	0.29

Table 3 The adjustable diameter of ring when changing the value of Material phase temperatures.

As (°C)	Af (°C)	Ms (°C)	Mf (°C)	d_a (mm)
40	45	35	30	0.23
30	35	25	20	0.68
40	50	35	25	0.06

Table 3, with As = 40°C Af = 50 °C Ms = 35 °CMf = 25 °C, the adjustable diameter of the ring is 0.06mm, which is too small as a parameter. This indicates which phase temperature range is suitable for our application (first or second row in the aforementionned table).

6. Conclusion

6.1 Summary

Based on a simplified version of the Liang and Rogers model, we obtained suitable parameters to optimize our SMA-based rings. Our results show that the temperature threshold and material phase temperature ranges will significantly impact the adjustable constriction range of the rings. We also found that the adjustment range is almost the same for all fingers. Therefore, when designing an actual prototype, suitable material phase temperature should be considered: the best temperature threshold will be near Af, minimizing heat, and therefore limiting negative user experience.

6.2 Future Work

This paper provides a design and simulation tool for a soft robotic wearable, that considers temperature as part of user experience. However, there are still some limitations, for example we did not consider heat transfer, or mass distribution of our apparatus over the entire glove, and how posture or finger motion would affect the device performance [22]. In future work, we would like to explore further the following points:

- Adding more rings, based on the hand anatomy, so as to fine-tune how the auto-fitting function can be expanded.
- Taking into account the thermal insulation properties of the glove, so as to set the suitable temperature threshold of the rings.
- Considering the influence of other external factors on the SMA contractions, such as ambient humidity or temperature fluctuations.

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