Characterization of smart materials requirements for actuation in the robotic applications

J L Ramirez¹, A Rubiano¹, and J G Cogollo¹

¹ Universidad Militar Nueva Granada, Cajicá, Colombia

E-mail: jose.ramirez@unimilitar.edu.co

Abstract. This paper presents the requirements specification of artificial muscles based on smart materials for a robotic finger prosthesis. The first part introduces the robotic finger, designed to mimic human precision grasping. A methodology to determine three critical parameters (strain, frequency and force) is presented. The methodology uses experimental data combined with kinematics and dynamics. Obtained values are calculated using the developed finger; as a result, we define that main requirements are: (i) Minimum active strain 5.5% for extension-based actuation or 60% bending-based actuation, (ii) Frequency (8.89 Hz, 22.2 Hz), and (iii) Force (4.80 N, 6.74 N) for bending-based actuation or force (17.81 N, 25.11 N) for extension-based actuation. Finally, a review of smart materials is presented with the aim of choosing the group of materials that can be used as artificial muscles for robotic hands. We show that shape memory Alloys can fulfill the established specifications. We also stand out Ionic polymer metal composites as a very promising actuation solution for robotic hands, due to their active strain and settling time, even though the blocking force is below the requirements.

1. Introduction

The main features of a smart material based actuator are the force $f_a$, the active strain $\varepsilon$ and the frequency $\omega$. Thus, we need to define these characteristics for the artificial muscle. Considering that our goal is to design a robotic finger that will be able to mimic human precision grasping movement, the actuator features can be established from measures and analysis of the human hand, introduced in by Ramirez [1]. However, it is important to take into account that the robotic finger mechanism can modify the actuator requirements. Consequently, the used approach, to identify the artificial muscle requirements, is defined by three kind of measures: i) the human pinch force [1], ii) the settling time of the human force also introduced in [1], and iii) the kinematic and dynamic behavior of the robotic finger, measured in in this work. We use a general methodology which aims at designing smart material based actuators for particular applications. This methodology is based on the following four stages:

(1) Application requirements modeling: in this phase the main parameters and the relationships between them are modeled, allowing to establish the operating conditions of the actuators.
(2) Experimental parameters identification: once the key parameters and their relationships have been modeled, it is necessary to carry out an experiment. The experimental protocol is designed in agreement with proposed models, to measure the required parameters.
(3) Parameters quantification: Experimental data must be analyzed using the defined models to characterize the artificial muscle and quantify operational limits of the actuator.
(4) Material selection: finally, the retrieved information is used to approximate the actuator
dynamic behavior, allowing the selection of a smart material that fits the application
requirements.

In our case we are focused in artificial muscles that can be considered as smart materials
based actuators with operational similarity to biological muscles. Consequently, it is important
to take into account the human hand muscles capabilities and the robotic finger mechanisms
that also impact the actuator requirements.

Regarding smart materials, shape memory alloys (SMAs) are of high interest in research due
to their outstanding features such as high energy density and silent operation among others.
Those features make SMAs suitable for actuation application [2] and in case of robotic hand
prostheses they could constitute a key solution to several unsolved issues e.g. actuator noise,
compliance, weight, and adaptability.

Nevertheless, despite scientific advances in the understanding of material behavior [3, 4, 5,
6, 7, 8, 9], SMAs are not available to be implemented as actuator due to the lack of linkages
between the models, the problematic of robotic hand prosthesis, and the automatic control.
Consequently, in this study, we introduce a SMA–based actuator. Furthermore, the SMAs
behavior modeling is addressed, taking into account the actuator configuration and automatic
control theory.

Consequently, in this paper, we introduce the characterization of smart materials according
to the the described methodology. The article is divided in three sections: i) robotic Finger
Prototype, ii) experimental assessment of finger movement, and iii) Smart materials review and
comparison. Finally, we present our conclusions.

2. Robotic finger prototype
The bio-inspired soft robotic finger is based on the ProMain-II prosthesis, and has been designed
at the Universidad Militar Nueva Granada, see Figure 1. It uses the virtues of the soft
robotics, considering: i) soft epicyclic tendon-driven mechanism, which replicates functionally
human tendon-muscle mechanism, and ii) flexible bodies, which increases compliance and self
adaptability with unknown objects and reduces the contact forces. The finger has three
phalanges, following the same concept of the ProMain-II hand: proximal, medial and distal.
And also three joints: metacarpophalangeal (MCP), proximal interphalangeal (PIP) and distal
interphalangeal (DIP). MCP and PIP has one DoF to perform flexion-extension, and DIP joints
are endowed with high number of DoF, due to their flexible material of the soft link. The
soft link is reinforced with an SMA material that further can be used to actively change joint
stiffness.

Each finger (see Figure 1) is controlled by only one servo motor XL-320 Dynamixel; hence PIP phalanx is driven by the MP phalanx. The clockwise rotation of the actuator produces
the flexion and the opposite produces the extension. Thus, the angles of PIP joints depend on the
rotation angle of MCP joints, which are linked to servomotor. Joints are identified by subindex
$i$, where MCP and PIP joint are $i = 1$, $i = 2$ respectively and the DIP bending joint is represent
by $i = 3$. The relation between angles is established as $\theta_2 = 0.9\theta_1$ and the bending angle formed
by DIP joint depends on the object to grasp. Figure 1 illustrates the finger architecture, each
finger has a force sensor in the fingertip.

Finger motion is produced by the soft epicyclic tendon-driven mechanism based on smart
materials, which is mainly composed of: i) a servomotor, which is fixed to the input pulley, ii) a
driven pulley that is fixed to the proximal phalange, iii) a medial driven pulley, that is fixed to
the medial phalange, iv) a fixed pulley , that is over the finger framework v) two group of wires
$WB$, each group, contains two wires placed in parallel, made of an elastic material, and vi) two
group of wires $WA$, composed also of flexible wires in parallel. Flexion of the finger is produced
when the servomotor turns in clockwise direction, causing that the input and driven pulleys turn in the same direction to the motor rotation. It generates that the proximal phalange and the medial pulley turn. The motion of the medial pulley provides motion to the PIP phalange.

FIGURE 1. Finger prototype.

Once the finger is in contact with the grasped object, the soft link is bended depending on the size a shape of the grasped object. When the grasping task is finished, the extension movement begins, in which the servomotor turns in the counter-clockwise direction. It causes that all the mechanism rotates in the opposite way to the flexion motion.

2.1. Experimental assessment of finger movement

The proposed experiment seeks to measure the position of each joint. Thus, a platform is designed and manufactured. The platform supports a servomotor and a soft robotic finger. The servomotor is controlled through a software implemented in c++. The software performs several repetitions of flexion and extension, at the same speed and torque.

Moreover, a high-performance Canon EOS 600D camera is selected with the aim to track circular markers placed on the finger joints and the fingertip. Once the desired images are obtained, a methodology is performed to process the images with the aim to recognize markers. The image processing follows these three steps: (i) transforming in gray scale digital images, (ii) detecting edges, (iii) applying Hough transform to find marker in the image. Then, joint angles during flexion and extension are calculated for each finger segment. The \( \alpha \) angle corresponds to the bending of DIP joint, \( \theta_1 \) is the angle of the MCP joint, and \( \theta_2 \) is the angle of the MIP joint.

Several cycles of flexion and extension are performed. Figure 2, Figure 3 and Figure 4, shows the sequence of the flexion. Once the position of each marker is recognized, following three vectors linking joints are defined: (i) vector \( \vec{r}_1 \) between the MP and PIP joints, (ii) vector \( \vec{r}_2 \) between the PIP and bottom rigid element of soft DIP joint, (iii) and vector \( \vec{r}_3 \) between the upper rigid element of soft DIP joints and fingertip. These vectors are used to calculate rotation angles \( \theta_i \) as in Equation (1).

\[
\theta_i = \arccos \left( \frac{\vec{r}_i \cdot \vec{r}_{i-1}}{\| \vec{r}_i \| \| \vec{r}_{i-1} \|} \right) \quad (1)
\]

The first angle \( \theta_1 \) is calculated with respect to a reference positive vertical unitary vector \( \vec{r}_0 = \{0, 1, 0\} \). As a result, we found that the relations between angle variation in all joints are constant in time. The experiment is repetitive and corresponds to the mechanical design. Furthermore, joint motion ranges are: \( [18^\circ, 68^\circ] \) for MCP, \( [2^\circ, 56^\circ] \) for PIP, and \( [2^\circ, 16^\circ] \) for DIP soft link. Angles behaviors of MCP and PIP are shown in Figure 2 and Figure 3.

Results, presented in Figure 4, show that \( \alpha \) decreases when the fingertip gets in contact with the obstacle. As consequence, \( \alpha \) angle linking bending depends on the object grasped that is
unknown. These results support the idea that the use of a soft link increases the compliance of finger. Moreover the compliant level could be modified considering: (i) selection of the constitutive element of soft link, (ii) the soft link geometry, (iii) and the reinforcement material.

![Graphs showing MCP, PIP, and DIP joint angles over time.](image)

**Figure 2.** MCP joint angle $\theta_1$.

**Figure 3.** PIP joint angle $\theta_2$.

**Figure 4.** DIP joint angle $\alpha$.

Regarding the force, it is obtained using the the measured mean value is 1.33N with a standard deviation of 0.07N. It is important to note a under-damped behavior appears during all the trials. Thus a maximal overshoot of 1.43N was reported during the experiments.

3. **Smart materials review and comparison**

As presented by Ramirez [1, 10, 11], there are three critical parameters defining the requirements of artificial muscles for robotic fingers: the strain (obtained from the robot features), the frequency (based on the human settling time) and the force (estimated from experiments on human hand combined with kinematics and dynamics of the robot). Applying the methodology proposed by Ramirez [11] for the robotic finger presented above, we obtain the requirements, which are summarized in Table 1. In the following, we assess several smart materials against the stated requirements by referring to state-of-the-art data gathered from an extensive bibliographic research. The aim is to identify potential candidates to be used as artificial muscles for the finger.

| Parameter          | Actuation |
|--------------------|-----------|
|                    | Extension | Bending  |
| Min active strain (%) | 5.5       | 60       |
| Frequency (Hz)       | 8.89, 22.2|          |
| Force (N)            | 17.81, 25.11 | 4.8, 6.74 |

**Table 1.** Summary of requirements of artificial muscles for robotic fingers.
Furthermore, we are interested in shape memory alloys (SMAs) due to their characteristics such as blocking force and active strain. SMAs require a thermal stimulus that can be produced by an electric current [12]. The result of the bibliographic research is summarized in Table 2 for each smart material we report the values for the 3 key features along with the reference from which the state-of-the-art characteristics have been extracted. Equation (2) and Equation (3) are used to recalculate active strain $\epsilon$ for comparison proposals. Frequency $\omega$ and force $F$ were obtained directly from authors. The reported force $F$ for the active bending materials is measured as the force applied by the material during flexion when is mechanically blocked and is named blocking force, and for the active extension materials is the pulling force exerted by the material when the external stimulus is applied.

$$\epsilon_a = \frac{\Delta l}{l_0}$$  \hspace{1cm} (2)

$$\epsilon_b = \frac{\Delta l_h}{l_0}$$  \hspace{1cm} (3)

Where $\Delta l$ is unidirectional elongation, $l_0$ is initial length, and $\Delta l_h$ is transverse deflection.

| Material          | Frequency $\omega$ (Hz) | Active strain $\epsilon$ (%) | Force $F$ (N) | Reference |
|-------------------|--------------------------|-------------------------------|---------------|-----------|
| IPMC (B)          | 0.6, 10                  | 10, 60                        | 0.001, 0.1    | $\omega$ [13, 14] $\epsilon$ [15, 16] $F$ [17] |
| Electrolyte gels  | 0, 0.2                   | 0, 50                         | 0.001, 6      | $\omega$ [18] $\epsilon$ [19, 18] $F$ [20] |
| CPs (B)           | 0.01, 1                  | 0, 60                         | 0, $200 \times 10^{-9}$ | $\omega$ [21] $\epsilon$ [22] $F$ [21] |
| PCs (B)           | 100, 600                 | 0.002, 1.5                    | 0.25          | [23]      |
| Rheological fluid | 25, 100                  | 1.8, 1.9                      | 0.5, 3        | $\omega$ [24] $\epsilon$, $F$ [25] |
| Electronic EAP    | 1, 4                     | 10, 200                       | 0, 0.4        | $\omega$ [26] $\epsilon$ [27] $F$ [26] |
| SMAs (B, E)       | 0.23, 22.2               | 3, 110                        | 0.032, 34.9   | [11]      |

It can be seen that concerning active strain IPMC, CPs, electronic EAP, and SMA satisfy grasping requirements. Regarding frequency IPMC, PCs, Rheological fluid and SMA fulfill grasping requirements. Concerning the force, only the electrolyte gels and SMA can achieve the range of the human hand pinch force. Furthermore, the implementation of smart materials in
prostheses is bounded by other factors, e.g. the excitation voltages (see Table 3) can impact the device autonomy. Thus, an excitation voltage in the range kV can not be used.

Taking into account available state of the art regarding smart materials, we have compared the main actuator’s features with the requirements of artificial muscles for the ProMain-I hand. As a result, we find out that two kinds of materials, namely IPMC and SMAs, match at least two of the three requirements of artificial muscles for robotic hand hands presented in Table 1. Although The IPMC constitute an interesting smart material to drive prosthetic fingers, due to their attractive active strain and settling time, their blocking force is below the requirements. Consequently, the SMAs are chosen for the design of the smart material based actuation system for the evolution of the ProMain-I hand.

### Table 3. Stiffness and voltage excitation of smart materials.

| Material            | Stiffness k (MPa) | Applied voltage u (V) | Ref. |
|---------------------|-------------------|-----------------------|------|
| IPMC                | (10, 50)          | 0, 5                  | k [28] u [14] |
| Electrolyte gels    | 0.001, 0.04       | 0, 21                 | k [20] u [19] |
| CPs                 | 80, 440           | 1                     | [22] |
| PCs                 | $210 \times 10^3$ | 30, 220               | k [29] u [30] |
| Rheological fluid   | $100 \times 10^3, 650 \times 10^3$ | $3 \times 10^3, 120 \times 10^3$ | [24] |
| Electronic EAP      | $20 \times 10^{-6}, 120 \times 10^{-6}$ | $0, 6 \times 10^3$ | [26] |
| SMA                 | 103               | 1.72, 6.41            | [11] |

4. Conclusion

We have used a methodology to identify the requirements and specifications of artificial muscles for robotic finger prostheses. The methodology combines experimental data with the kinematics and force of the robotic finger to define actuator requirements. The methodology is applied to the robotic finger, and the requirements for the hand are defined as follows: (i) minimum active strain 5.5% for extension-based actuation or 60% bending-based actuation, (ii) frequency 8.89 Hz, 22.2 Hz, and (iii) force 4.78 N, 6.70 N for bending-based actuation or force 17.81 N, 25.11 N for extension-based actuation.

Consequently, the shape memory alloys (SMAs) is chosen as it fulfill all actuation requirements for precision grasping. Thus, in the following we introduce: i) a SMA-based rotary actuator modeled and identified with a constitutive model of the SMA and an experimental approach, and ii) a new prototype of robotic hand prosthesis using artificial muscles based on SMA. This paper allows us to establish that the IPMCs have the potential to fulfill precision grasping requirements. For that purpose, additional research concerning the modeling and assessment of this material is required. Consequently, we consider that an important perspective concerns the improvement of the hand mechanism and the development of a hybrid actuation system using IPMCs.
Acknowledgments
We would like to acknowledge the Universidad Militar Nueva Granada for the financial support through the project “development of a soft robotic finger prosthesis using artificial muscles”, funding number INV-DIS-2061.

References
[1] Ramírez J L, Rubiano A, Jouandeau N, Gallimard L and Polit O 2016 Artificial muscles design methodology applied to robotic fingers (Cham: Springer International Publishing) p 209
[2] Kim W 2016 Model-based design framework for shape memory alloy wire actuation devices (Ann Arbor: University of Michigan)
[3] Auricchio F and Petrini L 2004 International Journal for Numerical Methods in Engineering 61(6) 807
[4] Peulitter B, Ben Zineb T and Patoo E 2006 Mechanics of Materials 38(5-6) 510
[5] Auricchio F, Reali A and Stefanelli U 2007 International Journal of Plasticity 23(2) 207
[6] Auricchio F, Reali A and Stefanelli U 2009 Computer Methods in Applied Mechanics and Engineering 198(17–20) 1631
[7] Arghavani J, Auricchio F, Naghdabadi R, Reali A and Sohrabpour S 2010 International Journal of Plasticity 26 (7) 976
[8] Furst S J, Crews J H and Seelecke S 2012 Continuum Mechanics and Thermodynamics 24(4) 485
[9] Auricchio F, Reali A and Stefanelli U 2007 International Journal of Plasticity 23(2) 207
[10] Ramírez J L, Rubiano A, Jouandeau N, Gallimard L and Polit O 2016 Morphological Optimization of Prosthesis’ Finger for Precision Grasping vol 39 (Cham: Springer International Publishing) p 249
[11] Ramírez Arias J L 2016 Development of an artificial muscle for a soft robotic hand prosthesis (Nanterre: Université Paris 10 Nanterre)
[12] Furst S J and Seelecke S 2012 Journal of Intelligent Material Systems and Structures 23(11) 1233
[13] Jung K, Nam J and Choi H 2003 Sensors and Actuators A: Physical 107(2) 183
[14] Wallmersperger T, Leo D J and Kothera C S 2007 Journal of Applied Physics 101(2) 024912
[15] He Q, Yu M, Song L, Ding H, Zhang X and Dai Z 2011 Journal of Bionic Engineering 8(1) 77
[16] Noh T G, Tak Y, Nam J D and Choi H 2002 Electrochimica Acta 47(13) 2341
[17] Vokoun D, He Q, Heller L, Yu M and Dai Z 2015 Journal of Bionic Engineering 12(1) 142
[18] Bassil M, Davenas J and Talachi M E 2008 Sensors and Actuators B: Chemical 134(2) 496
[19] Kim S Y, Shin H S, Lee Y M and Jeong C N 1999 Journal of applied polymer science 73(9) 1675
[20] Westbrook K K and Qi H J 2008 Journal of Intelligent Material Systems and Structures 19(5) 597
[21] Higgins M J, Wallace G G, Molino P J, Gehni A and Zhang H 2015 Conducting polymers: Their route to nanobionics applications via atomic force microscopy (New York: Nova Science Publishers, Inc.)
[22] Ali G, Mui B and Cook C 2006 Sensors and Actuators A: Physical 126(2) 396
[23] Wang Q M, Zhang Q, Xu B, Liu R and Cross L E 1999 Journal of Applied Physics 86(6) 3352
[24] Kumar B R and Ranganatha S 2013 International Journal of Innovative Technology and Exploring Engineering (IJITEE) 3(6) 30
[25] Chen S and Liu X 1999 Smart Materials and Structures 8(4) 499
[26] Dastoor S and Cutkosky M 2012 Proceedings of IEEE International Conference on Robotics and Automation (ICRA) (St. Paul: IEEE) p 3745
[27] Bar-Cohen Y 2004 Electroactive Polymer (EAP) Actuators as Artificial Muscles Reality, Potential, and Challenges (Bellingham: SPIE The International Society for Optical Engineering) p 4
[28] Kim D, Kim K J, Nam J and V P 2011 Sensors and Actuators B: Chemical 155(1) 106
[29] Djiojiolidjardjo H, Jafari M, Wiriadidjaja S and Ahmad K 2015 Composite Structures 132 848
[30] Yoo J H, Hong J I and Cao W 2000 Sensors and Actuators A: Physical 79(1) 8