Development of a Finite Element Model of a Soft Pneumatic Actuator and MCP Joint Complex

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I. Introduction

Soft Robotics has become an important alternative for use in hand rehabilitation [1]. Soft robotics present several advantages due to their highly compliant materials, easy portability and inherent safety.

Several finite element models (FEM) have been developed as design tools for soft actuators [2]. However, these models only evaluate actuators in terms of bending angle and/or applied force, without taking into consideration the finger-actuator interaction, which can affect performance on finger support. Previous studies have studied the performance of soft actuators when coupled with dummy fingers [3]-[4], though, their interaction remains unclear due to the difficulties in measuring intrinsic parameters such as the joint stress transmitted from an actuator to coupled finger joints as well as the contact between actuators and dummy fingers. Without understanding the interaction, neither efficient and safe support can be ensured, nor a safe design of soft actuators can be completely achieved.

In this study, we built an FEM of a dummy MCP (metacarpophalangeal) joint – modular soft actuator complex for the first time. The model was tested in 2 different configurations for measuring bending angle and applied force and contrasted with experimental results. The interaction between dummy fingers and soft actuators was further investigated.

II. Design and Modeling

A. Design of the targeted soft actuator

The soft actuator under study is a modular actuator with a design based on our previous work [3]. The entire body of the actuator (see Fig.1(a)) is made of Dragonskin 10 MEDIUM (Smooth-On, Inc., US). Kevlar™ (Dupont, Inc, US) was wrapped around the actuator using a two-dimensional hitching technique [4], for constraining radial expansion and increasing bending. Design and dimension (see Fig 1(b)) of the dummy joint was based on previous work [4]. A torsion spring was placed at the joint to simulate joint stiffness. The soft actuator

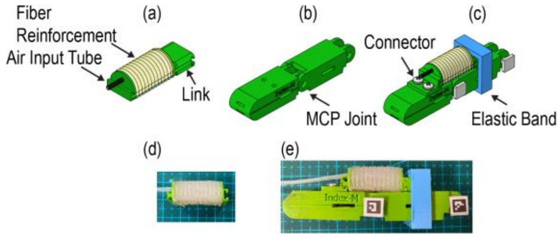

Figure 1. Actuator Design(a) Dummy MCP Joint (b) Dummy MCP Joint-Soft Actuator Complex (c)

is fixated at one end to the dummy finger and held by elastic band at the other end. A removable link is attached to the actuator for coupling.

C. Modeling of the Soft Actuator and Dummy Joint-Soft Actuator Complex

A stationary finite element simulation was run using Comsol Multiphysics®. All meshes were done using tetrahedral elements. A 3rd order Yeoh hyperelastic constituent model was used to simulate the hyperelastic behavior of the silicone sections. Dragon skin was characterized using experimental data from the Soft Robotics Materials Database Application [5]. The parameters obtained were the following: C_1=0.0408 MPa, C_2=0.0006MPa and C_3=0. The elastic band material Smooth-on Sil 950 was modeled as a first order Yeoh material model with C_1=0.34MPa [6], a simpler model was chosen as the elastic band undergoes less deformation than the actuator.

The dummy joint printed at 20% density with PLA, was modeled as a linear elastic material. A hinge joint was added directly at the joint. Symmetry boundary conditions were applied to reduce computation time. The model was configured for bending angle (θ) and applied force(F) measurements (see Fig.2) based on experiments designed on previous work [3]-[4]. Gravity is added in all models.

E. Contact Settings.

The default nonlinear contact penalty method was used to model contact between all surfaces. All contact boundaries

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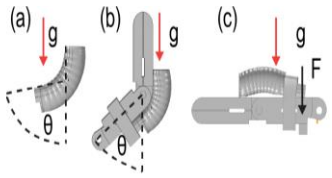

Figure 2. (a) Actuator Model (b) Actuator-Joint Complex Bending Model(c) Actuator Joint Complex Force Model

were meshed using tetrahedral elements with a maximum size of 1mm, as this showed the best compromise between convergence and computational expensiveness.

III. Results and Discussion

Fig. 3(a) shows the bending angle measurement results of both the experiment and finite element model for both the actuator only and the dummy joint-soft actuator complex cases. The FEM tends to slightly overestimate the bending of the dummy finger complex. This might be due to difficulties in setting up the exact weight of the entire system. Another factor might be the losses caused by friction between the artificial finger and the soft actuator. On the force measurements (see Fig.3(b)). For the initial conditions, the experimental model showed smaller force values. This could be due to a slight underestimation of the entire weight of the system which has a more notable effect on the initial parameters. The loses due to friction with the dummy and the elastic band could be the reason why this trend didn't continue for higher air pressures.

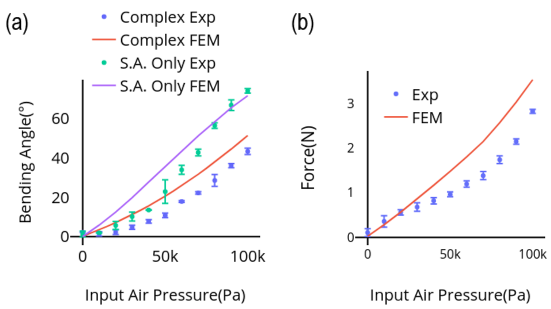

Figure 3. (a) Bending Angle vs Input Air Pressure Results for the soft actuator independently(S.A. Only) and for the Soft Actuator-Dummy Finger Complex(Complex). (b) Force VS Input Air Pressure Results

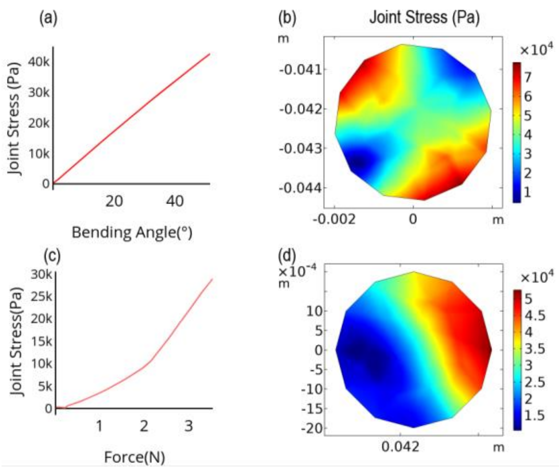

Figure 4. (a) Joint Stress vs Bending Angle (b) Bending Model Joint Stress at Pressure=100kPa. (c) Joint Stress vs Applied Force (d) Force Model Joint Stress at Pressure=100kPa

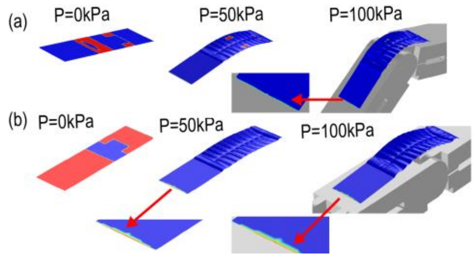

Figure 5. Contact Mapping at different air pressures (a) Bending Model. (b) Force Model. Red and green sections indicate contact

After comparing with experimental results, the model was used to study the relationship between, joint stress and bending angle (bending model) and applied force (force model). The results indicate that while the relationship between average joint stress and bending angle is almost linear (see Fig.4(a)), joint stress grows exponentially in the force model (Fig.4(b). When mapping contact area (Fig.5) we noticed that the actuator pushes the dummy mostly with its tip for both models. Furthermore, the tip of the actuator tends to start pivoting over the finger and in direction towards the joint at higher air pressures, this can cause an increased burden on the joint as it increases the force applied in its direction. This was more noticeable on the force experiment and could explain the exponential increase on joint stress seen in this case. This tip contact problem should be fixed by carefully designing the actuator. Moreover, this discovery indicates an apparent disadvantage of the rigid links used in current modular actuators, as high contact pressures between the link and the skin could lead to increased disconformity and skin injury

IV. Conclusions

In this research we developed a model of a dummy joint soft actuator complex. The model was able to replicate the results of 2 different types of experimental tests. The model could be used to study the actuator-joint interaction, i.e., to map the contact area between the actuator and the joint as well as to quantify joint stress for different air pressures. Important discoveries were made for use on modular actuator design.

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