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Quantification of Dynamic Property of Pneumatic Muscle Actuator for Design of Therapeutic Robot Control

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Abstract—**Robot-assisted therapy has shown potential in neuromotor rehabilitation. A therapeutic robot driven by pneumatic muscle actuators has been developed in our research group. However, the design of fine and real-time feedback robot control is a challenge. One of the difficulties is the lack of a general dynamic model of the pneumatic muscle actuator. In this study, a phenomenological model has been developed to quantify the dynamic behavior of pneumatic muscle actuator by fitting the experimental length response of the pneumatic muscle, to a step pressure input. In addition, comparison of the dynamic responses of two pneumatic muscles of different dimensions has also been studied. Several control strategies for the pneumatic muscle actuator are discussed based on the results from this study.**

Keywords—**rehabilitation robot, pneumatic muscle actuator, feedback control**

I. Introduction

ROBOTS, functioning as exoskeleton, can assist patients with motor deficits to rehabilitate with higher intensity and receive instant evaluation of performance. Clinical studies have demonstrated the potential of robot-assisted therapy to enhance motor recovery [1-5]. For example, the result of random controlled trials (RCT) demonstrated that patients trained with a therapeutic robot (MIT-MANUS) have more motor improvement than the control group with sham robot training [1].

In a previous report from our research group, the design and fabrication of a four degrees-of-freedom (DOF) therapeutic robot (Robotic Upper Extremity Repetitive Therapy (RUPERT)) for training hemiparesis patients to perform reaching and self-feeding tasks, repetitively, were described [6]. The therapeutic robot is driven by four pneumatic muscle actuators (PMA), each actuating one DOF, while utilizing either gravity or existing muscle control as antagonists. One benefit of RUPERT compared to other therapeutic robots is that the actuators are compliant and low-cost. However, the design of a closed-loop control system requiring high precision and rapid response is a considerable challenge. Some of the difficulties come from the non-linear behavior and slow response of PMA [7], and the lack of a general mathematical model describing the dynamics of PMA as functions of various parameters.

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PMA is made from inexpensive materials, like rubber for the internal tube covered by a polymer based braid (Fig. 1). When the internal bladder (rubber tube) is pressurized, it expands radially against the braided shell. The radial pressure on the inside of braid causes it to contract.

PMA was first developed in the 1950's for rehabilitation robotics. But, the use of PMA remained in hiatus because of difficulties involved with the control of PMA. This was attributed by Caldwell to air compliance [8]. Since its conception, various types of PMAs have been developed. The PMAs used in RUPERT and our study were Mckibben type pneumatic muscles (braided/netted type).

Majority of the literature on PMA (Mckibben muscle) modeling deals with static models that relate the force generated by a PMA to the properties of the internal bladder, the geometric arrangement of the braided sheath covering it and the pressure inside the PMA [8-10]. These models are not suitable for control system design because some of the parameters needed for these models are difficult to measure and the static models do not provide complete information on the dynamic behavior of the actuator. Reynolds *et. al.* developed a phenomenological model that describes the length response of PMA using a second order model [11]. The variation of the second order model parameters with input pressure was also quantified by the authors. Though, this model is a good first step towards developing a dynamic model of the PMA, the model is far from complete. The study by Reynolds *et. at.* did not consider the model variation with external load and the authors assumption that the model parameters are independent of external load needs justification. Besides, the model does not discuss the dynamic force response of the PMA which is essential for feedback force control.

Therefore, the objective of this study was to develop a dynamic model of the PMA that takes into consideration the two important aspects of the PMA response namely, the model variation with respect to (a) input pressure and (b) external load. Furthermore, study will obtain a relationship between the force, length and pressure of PMA. The results from this study will facilitate the design of an adaptive controller for therapeutic robots for neuromotor rehabilitation.

Fig. 1. Pneumatic muscle actuator (Mckibben Muscle) made in lab.

II. Methods

A. Robotic Upper Extremity Repetitive Therapy

RUPERT, a 4-DOF therapeutic robot (KMI, Tempe, Az), consists of four PMAs actuating shoulder extension, elbow extension, forearm supination/pronation, and wrist extension, individually. Fig. 2 shows the current prototype of RUPERT.

RUPERT utilizes inexpensive and compliant PMAs that mimic some of the properties of real skeletal muscles. Therefore, RUPERT is back-drivable that makes the robot safe for patients who have spasticity and hypertonia. Moreover, RUPERT is much cheaper than the existing therapeutic robots.

Fig. 2. Structure of RUPERT (KMI, Tempe, Arizona).

B. Experiment Setup

The pneumatic muscle used for the study was a Mckibben type. The compliance of PMA provides the safety required for a rehabilitation robot but it also poses challenge for a rapid force modulation required for real-time feedback control. To overcome this problem we will explore several strategies. One such strategy is to use two or more muscles to build a compound PMA. Two muscles of different cross-sections were tested, in the present study. One of the PMAs (large PMA) was 26mm in diameter (internal membrane) and 233.6mm in length and the other PMA (small PMA) was 3 mm in diameter (internal membrane) and 243.5mm in length. The PMA was activated using normal air supplied from a compressed air tank that was connected to the PMA via a 3-way ON/OFF valve (Fig. 3). The 3-way valve had two control signals which could connect the air tank to the PMA (filling the PMA) or the PMA to the atmosphere (exhausting the PMA). A pressure sensor (MPX5700, Freescale Semiconductor Inc.) was placed close to the inlet of the PMA to sense pressure inside. The sensor was connected to a single board computer (Versalogic) that streamed the pressure sensor data to a laptop computer through XPC interface. The length of the PMA was monitored using the VZ3000 Visualeyez™ motion capture system (Phoenix technologies Inc.) running on a separate PC. Four markers (M1, M2, M3, & M4) were used in the setup for tracking PMA length change (Fig. 3). Both pressure and marker data was sampled at 100Hz.

In the experiment, a rectangular pulse of pressure was applied manually to the pneumatic muscle. Firstly, the inlet valve was opened for certain time duration that was long enough to simulate a step pressure input. The pressure buildup inside the PMA causes it to contract (rise phase). After the PMA reached steady state, the air was exhausted from the muscle by connecting the muscle to the atmosphere (decay phase). This procedure was carried out for 5 different input pressures (20psi, 24psi, 30psi, 34psi & 40psi) and seven different external loads (5 to 35 lbs in steps of 5lbs). Six repetitions were performed for each condition.

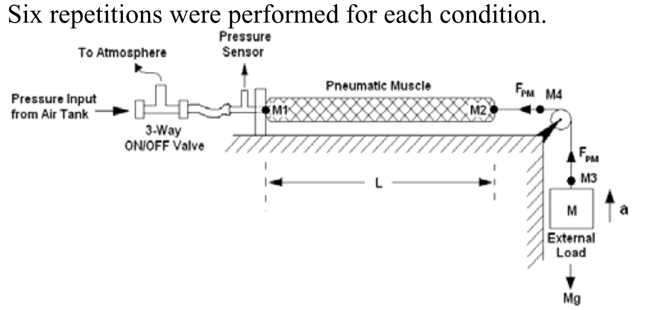


Fig. 3: Experimental Setup for PMA Dynamic Characterization.

C. Data Fitting and PMA Model Parameter Estimation

From the experiments, the dynamic response of PMA length $l(t)$ and the pressure inside of PMA $p(t)$ to a step pressure input (P_0) were recorded. A second order model was chosen for fitting the experimental length data after having tried both a first order and a second order model. The second order model was selected as it gave a better fit than the first order model.

Using the theoretical length response, the dynamic force response of the PMA was obtained by calculating the acceleration of the external load. The acceleration was calculated from the theoretical data rather than the experimental data because noisy nature of the experimental data obtained from the motion capture system (Fig. 4a and Fig. 4b).

$$a_M(t) = \frac{d^2 l(t)}{dt^2} \quad (1)$$

$$F_M(t) = M\,[a_M(t) + g] \quad (2)$$

Where, $a_M(t)$ is the acceleration of the external load, $F_M(t)$ is the force generated by the PMA, g is acceleration due to gravity and M is mass of the external load.

In addition, the length, pressure and force responses of the PMA at different input pressures (P_0) and different external loads (M) were used to obtain a force-length-pressure (FLP) relationship for the PMA. The FLP plot represents the relationship between force generated by the PMA, relative length change, and pressure inside the PMA. Because the PMA force is reported to be independent of the velocity of PMA contraction [12], the FLP relationship obtained from the dynamic experiments should be similar to that obtained from static experiments. However, the use of the dynamic length, pressure and force responses enables us to obtain the FLP relationship for low pressures and low relative length-change values, which cannot be easily obtained from static experiments.

III. Results

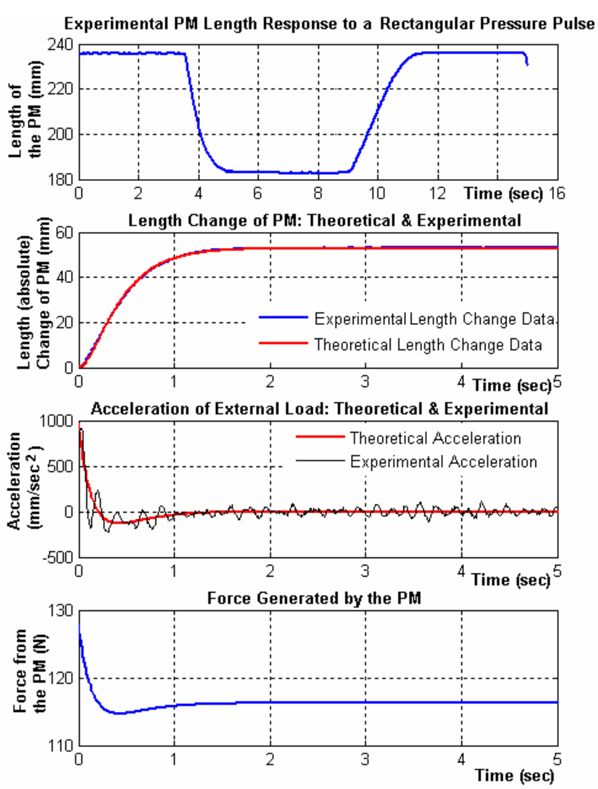
A. Transfer Function of PMA Length Response

Fig. 4 shows the data fitting results for the PMA length response using a second order model. The rise and decay responses of the PMA are different in the general shape and the duration of the response. The decay phase is slower than the rise phase (Fig.4a and Fig.4b) and gives a poorer fit to a second order function compared to the rise phase. These differences can be attributed to the hysteresis of the pressure-length relationship of PMA.

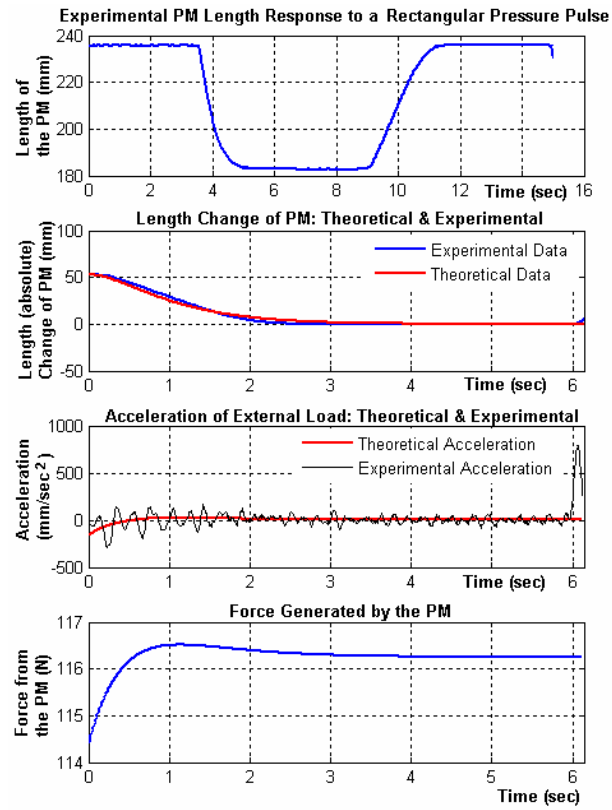
Fig. 5 shows the variation of the parameters of the fitted 2nd-order model due to input pressure (P_0) and external load (M). ζ indicates the damping ratio and ω_n denotes nature frequency of 2nd-order transfer function. The superscript *Rise* or *Decay* indicate that the parameter of the model is for the rise or decay phase. Our findings show that the parameters of 2nd-order transfer function are actually the functions of both applied pressure and the external load (Fig 5).

B. Relationship between PMA Length, Pressure, and Force

The pseudocolor plot of the FLP relationship for the large PMA is shown in Fig. 6. The plot was obtained after performing a linear interpolation, to fill gaps, on the plot obtained from the initial association of the force, length and pressure responses. The force increases as, (i) pressure increases at a given relative muscle contraction, and (ii) relative contraction decreases at a constant pressure.



(a) Rising Phase of Length Response.



(b) Decay Phase of Length Response

Fig. 4. Response of 'Large PMA' to a Pressure Pulse of magnitude 40psi and a external load of 11.34Kg, with results from the data fitting. (a) Rising phase of the response. (b) Decay phase of the Response

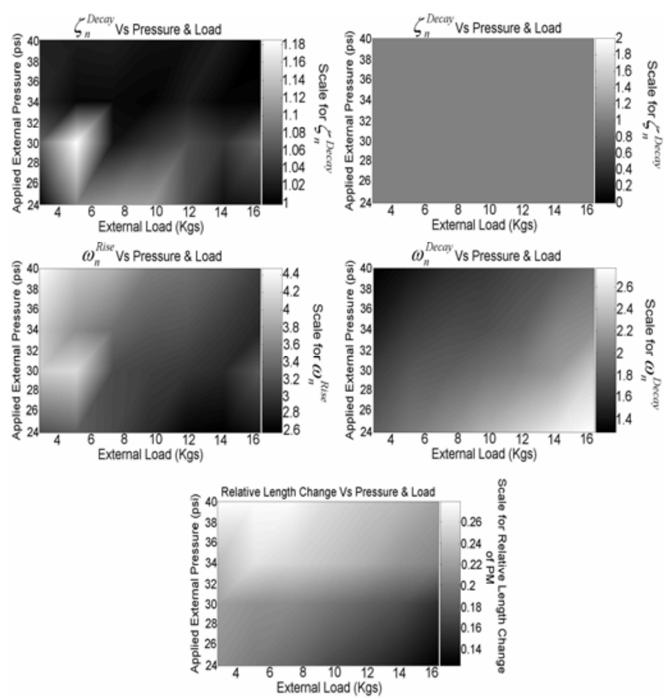


Fig. 5. Variation of the 2nd-order parameters for the rise (ζ^{Rise}, ω_n^{Rise}) and decay (ζ^{Decay}, ω_n^{Decay}) phases and the percentage length change with respect to input pressure and external load, for the 'Large PMA'.

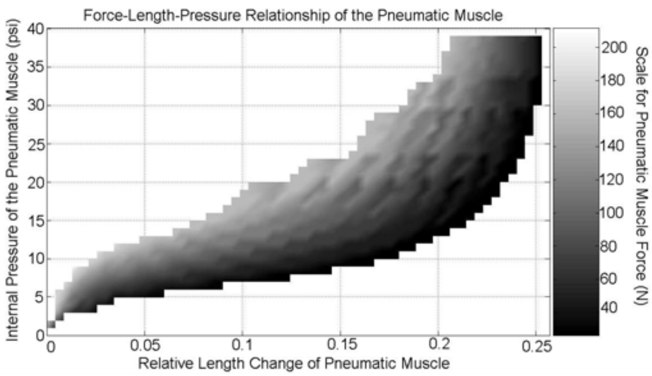


Fig. 6. Force-Length-Pressure Relationship of the 'Large PMA'

IV. Discussion and Conclusion

A second order model for the PMA length response, with the model parameters quantified as a function of input pressure and external load, has been developed. In addition, the FLP relationship was also obtained from the study.

The developed model can be of a great value in the design of simple feedback control strategies based on classical control theory, as the tools for classical control system design require an analytical model for the plant being controlled. The quantified model parameters can be used for designing feedback systems with variable feedback parameters. Such a design will reduce the dependence of the PMA response on the external load. The model will also be of good use in stability analysis of the designed control system. Additionally, the FLP relationship can serve as a very useful tool for the purpose of biofeedback during active repetitive task training. The FLP relationship can be used to quantify patient effort and robotic assistance.

In contrast to the claim/hypothesis by Reynold's *et. al.*, we found the 2nd order model parameters to be dependent on the external load (Fig 5). Therefore, in PMA control, the external load should be monitored.

PM models were developed for two different PMs – a large PM and a small PM (The results from the small PM experiments and modeling are not reported). The differences in the dynamics of these muscles can be used in designing a compound PMA consisting of muscles of different dimensions (cross-sectional area). Such a compound actuator will mimic the real skeletal muscles more closely than a single PM. As already discussed by Davis *et. al.* [13], the faster dynamics of smaller muscles come at the cost of reduced contraction and force at a given pressure. Thus, we will have to look into the other possible solutions proposed by Davis *et. al.* [13].

Future work will address two main issues namely, (i) dependence of PMA parameters on initial conditions of the muscle and (ii) adaptive robot control. From some preliminary experiments we found the model parameters to vary depending on the initial conditions of the muscle. So, the proposed model is still not complete. But the inclusion of the parameter dependence on the initial conditions will add to the complexity of the model and make the parameter estimation procedure time consuming. So, suitable experiments will be carried out to assess the extent of parameter dependence on initial conditions of PMA. And, also the proposed model will be validated by actuating the PMA with arbitrary inputs and comparing the observed and predicted responses. We also wish to look at the design of a compound PMA by utilizing some of the possible techniques for improving PMA dynamics proposed by Davis *et. al* [13].

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