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STRAIN ANALYSIS OF FLEXIBLE BIONIC DIGIT USING MATLAB SIMSCAPE

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Abstract

This study aims to determine the relation between joint orientation and strain of the flexible link affected by the joint. This study aims to advance the implementation of hand prosthetics by providing a simpler way to calculate joint parameters. The governing physics behind such a system is Hooke's Law. The strain on flexible links can be obtained using a strain gauge sensor in the quarter bridge configuration. The bionic digit was modelled using flexible bodies as links in MATLAB Simscape Multibody. The strain gauge was modelled in a Simscape Electrical environment. Actuation signals were provided in the Simulink environment. The combined model was simulated to the motion of closing the fists and this data is compared with the joint torque and joint orientation of the multibody system. The comparison was made with this data and joint orientation, to analyse the feasibility of this methodology. The observed results make it more accurate to utilize the strain data to derive joint orientation, rather than the joint torque, as a linear relation exists between strain and joint orientation. The proposed methodology could advance the field of bio-prosthesis, and reduce prosthetic development barriers.

Keywords: *prosthetics; stress; strain; multibody modelling****.***

1. INTRODUCTION

The hand is a complex system of bones, tendons, ligaments, and nerves [1]. The development of prosthetics has accelerated in recent years which can mimic human hand positions accurately, with new and varied technologies being developed using servo actuation, haptic feedback, and tactile sensors [2]. These are state-of-the-art prostheses aimed at resto The hand is a complex system of bones, tendons, ligaments, and nerves [1]. The development of prosthetics has accelerated in recent years which can mimic human hand positions accurately, with new and varied technologies being developed using servo actuation,

haptic feedback, and tactile sensors [2]. Bioprosthetic hands are composed of individual elements that enable the execution of complex motions characteristic of a human hand. These include sensors, microprocessors, actuators, power sources, and mechanical bodies. The sensors perform the muscle signal detection either in the remnant limb or brain signal where an advanced neural interface is utilized.

The sensors can be fitted in such a way that they sit on the skin while taking the muscle signals or fully operated embedded systems for controlling neural activities. With advanced algorithms, the microprocessor can also distinguish which signal corresponds to which motion from a simple grip to complex finger motion. However, its control has proven to be difficult to execute efficiently. This is due to the lack of proper feedback systems to drive the actuators since the volume of bioprosthetic needs to be as minimal as possible, the use of rotary encoders and other joint sensors is not preferred. Actuation mechanisms drive the movement of a bionic hand. Various methods have been used in modern bionic hands to replace the intricate range of movements of the human hands. These are electromechanical actuators, hydraulic or pneumatic Actuators, cable-driven actuators, and soft actuators (artificial muscles).

The study proposes a method to acquire feedback through stress and strain sensing of the links, which in this case are finger bones. The control techniques best suited for the control of bionic hands require joint error data. These data were calculated from the feedback source of the current joint orientation [5] [10]. This was achieved through MATLAB Simscape electrical, mechanical, and multibody models. The MATLAB Simscape environment provides a platform for modelling and simulating physical systems within the Simulink ecosystem. It integrates mechanical, electrical, hydraulic, and thermal components into a unified system model, allowing for the simulation of real-world behaviour without needing to derive complex equations manually. By using physical connections, Simscape enables users to design and visualize systems intuitively through graphical components, which are governed by underlying mathematical models, helping in providing real-time results.

A kinematic model of a single human digit was used to decrease the computational load. The digit model consists of three joints and a simple manipulation task of closing the fist was chosen from a variety of available tasks [3]. The skeleton model of the human digit was built in Simscape Multibody [7] with links acting as bones and revolute joints [4]. The gathering of strain data from simulation can only be performed when flexible bodies are considered, therefore the rigid links were replaced with flexible beams [6]. The general flexible beam block has inbuilt mechanical systems that simulate the dampness and spring stiffness portrayed by a flexible beam. This strain data was calculated using a strain gauge built into a quarter Wheatstone bridge and its strain factor was calculated based on the deformation seen in the simulation. This analysis provides the strain-to-joint angle relation and strain-to-joint torque relation of the different joints.

The results show that the strain gauge's output can be used as a substitute for the joint torque or orientation. Using this data a bionic could be controlled with closed-loop control, without bulky encoders or complex resolvers. The strain shows varying characteristics for different links. This shows the data is also affected by the subsequent links inferring the possibility of using it to detect grasping and collision. ring the functions of a hand that is lost or rendered useless. While conventional prosthetic devices may have their limitations in terms of movement as well as functions and features, bioprosthetic hands have technology that is sophisticated enough to mimic hand movements and feelings more accurately as well as ease the life of patients who have lost their hands or have lost them by birth.

2. BACKGROUND

A. Human hand anatomy

The human hand primarily consists of bones, tendons, muscles, nerves, blood vessels, integument, and ligaments. The focus of the study is specifically on one of the digits. In medical terms, the M-II stands for Metacarpal II (see Fig 1). The three bones from M-II to the tip of the finger are the Proximal Phalanges (PP-II), Middle Phalanges (MP-II), and Distal Phalanges (DP-II) respectively. The joint connecting M and PP is the Metacarpophalangeal (MCP) joint, and it allows pinching, gripping, and finger movement in multiple directions. A similar nomenclature is used for the other digits. The Proximal interphalangeal (PIP) joint connects the proximal phalanx and middle phalanx allowing the finger to bend and extend. The distal interphalangeal (DIP) joint connects the middle phalanx and distal phalanx.

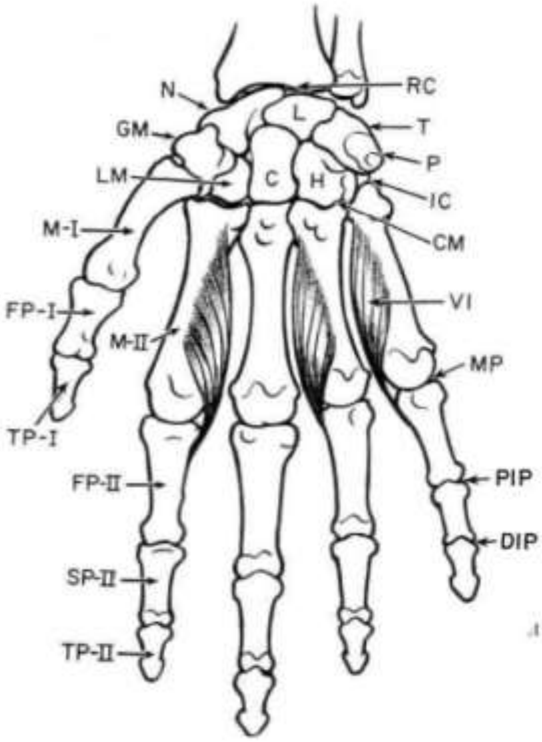


Fig. 1. Bones and articulations of the hand [1]

B. Ligaments

Ligaments are relatively strong, fibrous connective tissue bands, connecting bones to other bones. They serve to offer support and stability to the joints by restricting any movement beyond a certain degree. The ligaments are composed of collagen fibers, which provide them with strength and flexibility. The ligaments in the hand play a crucial role in stabilizing and supporting the bones and joints, allowing for precise and coordinated movements. Ligaments distribute the mechanical forces in performing various activities across the joints of the fingers, thereby reducing the risk of damage to bones and soft tissues. It permits needful bending, straightening, and slight sideways motions preventing vicious or abnormal movements that can cause injuries.

The mechanoreceptors present in ligaments constantly report the position and movement of every finger joint to the brain. Such feedback is essential for fine motor work, such as the manipulation of objects or writing. The ligaments provide information that enables the brain to quickly alter muscle activity to avoid overextension or dislocation of the joint and possible injury to the joint. They ensure smooth and controlled movement by synchronizing the action of muscle tendons with the position of each of the finger's joints.

C. Tendons

Tendons are strong, flexible connective tissues that attach muscles to bones. They serve to transfer the force created by the contractions of muscles to the bones. Unlike ligaments, which connect bones to other bones and primarily provide joint stability, tendons are primarily involved in movement. Although tendons themselves are not sensory organs, they play a role in the body's proprioceptive system: their ability to detect the position, movement, and forces exerted by muscles and tendons. This sense enables you to feel where your fingers are and what they are doing without looking at them. It is based on feedback from muscle spindles and Golgi Tendon Organs (GTO). Muscle spindles respond to changes in the rate of stretch and also to stretch level within the muscle. Golgi Tendon Organs are tendon-based receptors, located within tendons. These allow tendons to feel the tension and force produced by a muscle, which can also act as feedback.

D. Bionic Hands System

One of the most remarkable aspects of bioprosthetic hands is the variety of control mechanisms available. For basic implementation, myoelectric control is commonly used, where sensors detect electrical activity in the remaining muscles of the arm or shoulder. As the user thinks about moving their hand, the sensors pick up on the electromyography signals and send them to the microprocessor or microcontroller, which after processing the signal instructs the prosthetic hand to move accordingly. More advanced bioprosthetic hands use brain-computer interfaces (BCI). These systems include sensors in the fingers that detect pressure or texture, sending information back to the brain via electrical signals or vibrations. This feedback allows users to gauge how firmly they are gripping an object or to feel different textures, improving control and reducing the risk of accidents like dropping items.

E. Motion Controllers

The predominant method to actuate a multibody system is computed torque control. Computed torque control is a technique in robotics that involves calculating the torque required at each joint of a manipulator to achieve a desired motion. This control strategy utilizes the dynamic model of the robotic system, allowing for compensation of inertia, Coriolis forces, and gravitational forces acting on the manipulator. The technique involves both forward and inverse kinematic models, which are essential for calculating the trajectory of the manipulator's end effector. The forward model helps determine the end effector's position based on joint angles, while the inverse model calculates the required joint angles for a given end effector position. As the manipulator operates, real-time adjustments to the computed torque can be made based on feedback from sensors monitoring the manipulator's performance. This adaptability enhances the robustness of the control system, enabling it to cope with disturbances and variations in load without compromising precision.

Another relatively new method is the strain feedback method. This method utilizes the PID control technique with strain as its feedback source. To control the robot the orientation constraints can

$$\lim_{t\to\infty} u(x,t) = 0, \lim_{t\to\infty} u(x,t) = 0$$

(1)

$$\lim_{t\to\infty}\theta(t)=\theta_0, \lim_{t\to\infty}\dot{\theta}(t) = 0 \qquad (2)$$

Where $\theta_0 \in [0,2\pi)$, u is the displacement i.e. strain.

The general control torque equation can be given by,

$$N(t) = k_i k_d u_{xxt}(0,t) + (k_p - EI)u_{xx}(0,t) + k_i \int_0^t u_{xx}(0,s)ds - k_1\theta(\dot{t}) - k_2(\theta(t) - \theta_0) \qquad (3)$$

But, even in these above equations, there is a need for the current joint angle. This need could be fulfilled by converting the link's strain into joint angles. If the strain feedback method is used then the control becomes much easier with the only feedback source required being strain, used for control torque and joint error calculation.

F. Stress on a body

Stress on a body(often a beam) refers to the internal forces or reactions that develop within the body as it resists external loads. Beams are structural members that experience forces and bending moments and thus eventually distribute stresses along their cross-section. There are four major kinds of stresses in the beams. Normal stress arises from axial forces which might be tensile or compressive force, distributed over the cross-section. Bending stress occurs due to moments that cause tension and compression to opposite sides of the neutral axis, with the maximum stress at the outermost fibers. Shear stress appears for forces parallel to the cross-section, usually peaking at the neutral axis. Torsional stress occurs in beams subjected to twisting moments, causing shear stress around the beam’s axis. All these stresses are important in understanding how a beam behaves under different loads and motions.

G. Stress-Strain relation

Stress is the force applied to a material per unit area, while strain is a deformation or change in the shape of the material that results from the applied force. The stress-strain relation describes how a material deforms in response to applied stress, showing the relationship between the stress and the strain a material experiences. The phases of a Stress-Strain relationship are Proportional Limit (Elastic Region), Yield Point, Plastic Region, Ultimate Strength, and Fracture Point. Proportional Limit is the region where the stress is directly proportional to strain, following **Hooke's Law**:

$$\sigma = E \cdot \epsilon \tag{4}$$

Where σ is the stress, E is Young's modulus (elastic modulus), ϵ is the strain. At this proportional limit, the material enters into a yield point where permanent deformation starts and the stress at that particular stage is termed as the yield strength. At that point also the very small increase in stress will produce much higher strains. After reaching that yield point, the material enters into the plastic region and undergoes plastic deformation; that is, the material will not regain its original shape after removing the load. In this region, the curve is flat where stress increases without great increases in strain. The highest point on the curve is the ultimate tensile strength or UTS showing the maximum amount of stress that material can take without fracturing. After the material has reached the ultimate strength it starts at the neck and then breaks off at the fracture point where it fractures under the applied load.

H. Strain Gauge and Wheatstone bridge

A Strain gauge is a proprioceptive sensor whose resistance varies with applied force; It converts force, pressure, tension, weight, etc., into a change in electrical resistance which can then be measured. When external forces are applied to a stationary object, stress and strain are the result. The Wheatstone Bridge circuit is a basic circuit that is applied in the measurement of small quantities of unknown resistance. Resistance is measured by joining the resistor of unknown value with three resistors of known value in a quadrilateral arrangement. A strain gauge is bonded to a material. As the material deforms under an applied load, the strain gauge stretches or compresses, its length and cross-sectional area changing; thereby its electrical resistance changes. The change in that resistance is sensed using a Wheatstone bridge circuit, which includes four resistors (one or more of which are strain gauges). The output voltage is zero in a balanced Wheatstone bridge where the values of all resistances are equal. However, with strain-induced resistance changes in the strain gauge, the bridge is rendered unbalanced. This gives a measurable output voltage. The measurements of strain are accurate because the sensitivity to small changes in resistance is high as the output voltage and strain on the material are directly proportional. The sensors can be utilized as a quarter bridge, half bridge, and full bridge setup as seen in Figure 2.

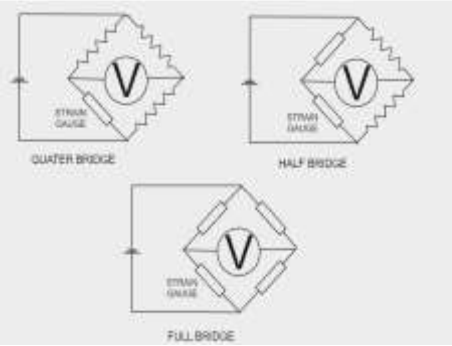


Fig. 2. Configurations of Strain Gauges

The strain gauge factor, G.F can be found using the formula:

$$G.F = \frac{\Delta R/_{R}}{\Delta L/_{L}} = \frac{\Delta L/_{L}}{\varepsilon} \qquad (5)$$

3. STRAIN SENSING METHODOLOGY

A. Kinematic Model of a Human Digit

The Kinematic model of the human digit consists of revolute joints that represent Interphalangeal joints. The MCP joint can be represented as a planar joint. In a bionic hand it is simpler to represent the planar MCP joint as a revolute joint as well. (see Fig 3.)

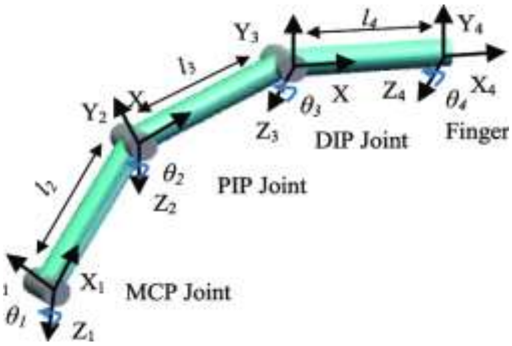


Fig. 3. Kinematic Model of Human Digit [2]

B. Simscape Model of a Human Digit

The links were modelled in this environment with the General Flexible Beam block. This block automatically computes the beam's cross-sectional properties, such as the axial, flexural, and torsional rigidities, based on the geometry and material properties. Weld joints were placed in the midpoint of these links to record the internal forces of the link (F_tensile in Fig 4.). The Rigid Transforms were placed to interface the flexible links with revolute joints present outside the digit subsystem.

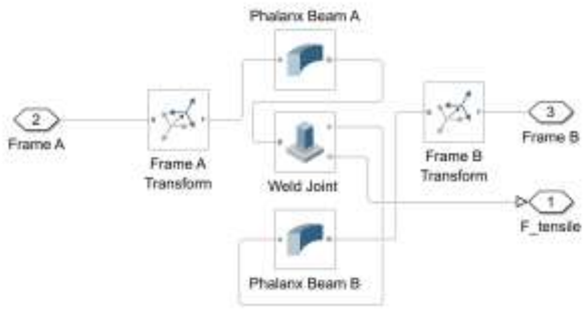


Fig. 4. Flexible Link Subsystem

C. Simulink Model of Ideal Stress Sensing

The tensile force from the flexible link subsystem gives three outputs, F_x, F_y, and F_z respectively. For this model the tensile force is in the F_x direction, therefore a simulink demux is used to separate the signals (see Fig 5.). Due to the high frequencies of oscillations produced by the model solver, a mean block is used to extract the mean value of signals. This force is converted to stress using a gain value which is the cross-section area of the link.

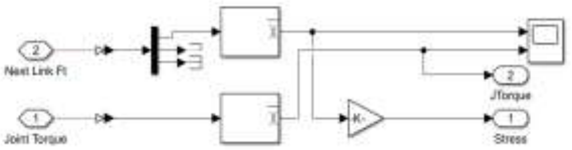


Fig. 5. Ideal Stress Subsystem

D. Simscape Model of Strain Gauge

A Simscape strain gauge is the virtual model applied in MATLAB's Simulink environment to simulate the physical strain gauge sensor in a quarter bridge configuration. It is mainly used for measurement purposes in any material deformations caused by stress with the conversion of mechanical strain into electrical signals that can be further processed for various analyses. In this subsystem (see Fig 6.), the ideal stress developed from the tensile force is converted to ideal strain by a gain of the inverse of E (Young's modulus) and is given as input to the strain gauge block. The rest of the sensor model resembles a quarter Wheatstone bridge. The model also uses an operational amplifier, to amplify the Wheatstone bridge signal which increases its accuracy, and a voltmeter to sense the output voltage from the Op-Amp.

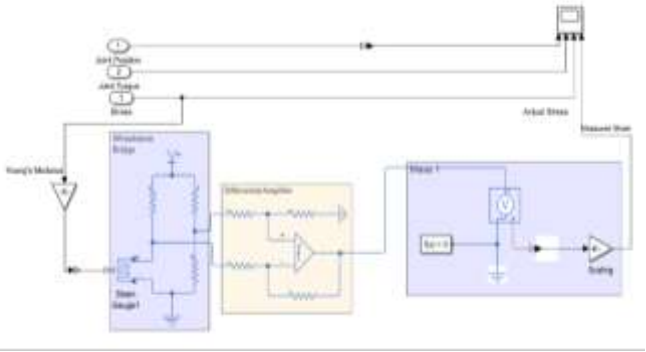


Fig. 6. Strain Gauge Sensor Subsystem

E. Interfacing Simscape Subsystems

The modelled flexible link subsystem is interconnected with revolute joints whose motions are taken from an input signal. The joints give their position and actuator torque data (see Fig 7.).This is routed to different subsystems for observation and comparison. The tensile forces signal is inputted into the ideal stress subsystem. From this subsystem, the stress is given to the Strain Gauge Subsystem. The outputs are converted to Simulink signals and visualized through the scope block in Simulink.

F. Joint Actuation

Each digit can rotate up to 90° in one direction. To observe the strain of the links through all possible orientations the digit's joint can take, the joints were given an interpolated signal that starts at 0° and ends at 90°. This resembles the finger's motion when closing the fist to observe the strain through all possible orientations.

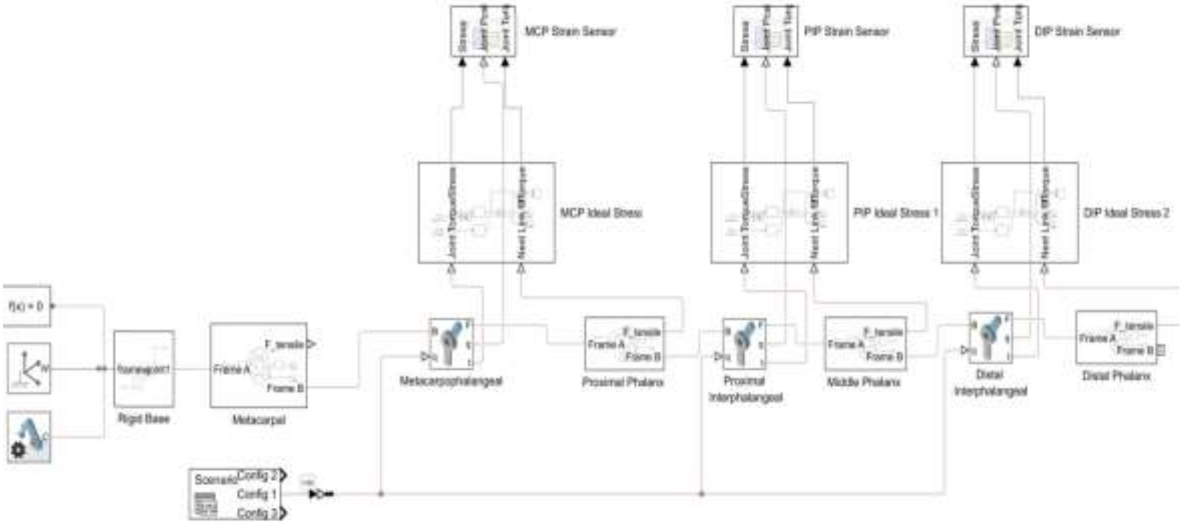
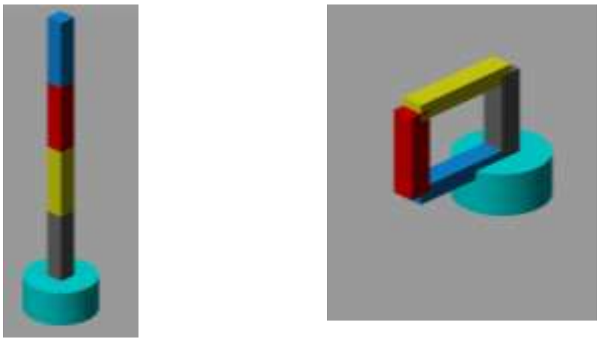


Fig. 7. Complete Model

4. SIMULATION RESULTS

A. Initial and Final Positions of Digit

The mechanics explorer displayed the animation of the motion of the model, whose initial and final positions are shown in Figure 8. The collision of textures of the flexible links is a visual artifact of rendering the general flexible beam block in Simscape Multibody.



(a) (b)

Fig. 8. (a) Initial Position and (b) Final Position of Digit

B. Actuator Torques on Joints

The torque of link 2 and link 3 at 10 secs is 0.5 Nm in the counterclockwise direction. The torque of link 1 is in the clockwise direction at 0.21 Nm. There is a sudden dip in torque of all three links at 8 secs (see Fig 9.), which can be due to the increased motion signal given to the joints from t=8 secs to t=10 secs.

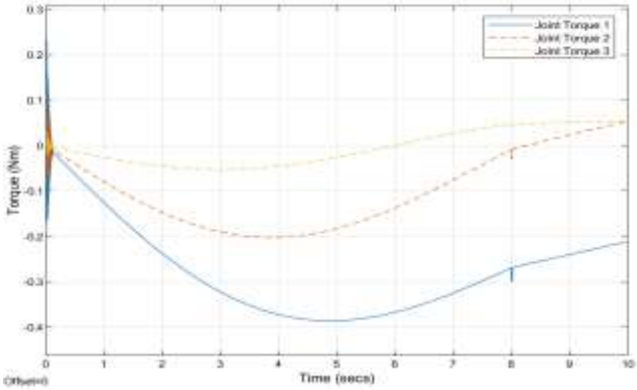


Fig. 9. Torque Developed on Joints

C. Stress on Links

The stress at link 3 transitions from compressive to tensile at 6 secs and attains the final stress of 13.24 Pa. The stress at link 2 remains compressive and reaches 0 Pa after the motion has ended. Link 1, stress remains compressive throughout the motion, as its stress is in the negative region (see Fig.10). This could be due to being attached to a rigid base (the wrist section is considered stationary).

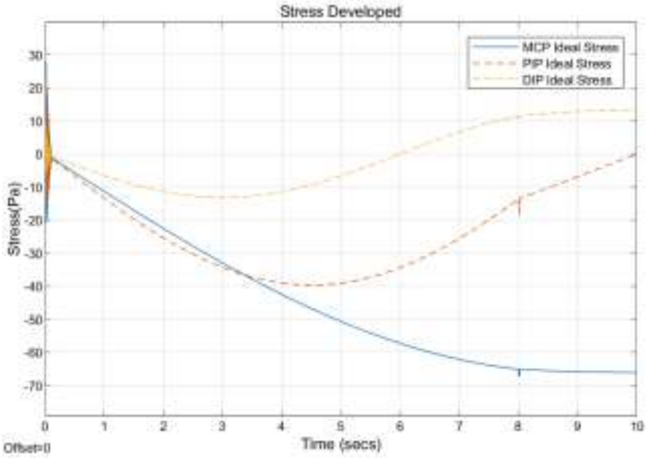


Fig. 10. Stress on Flexible Links

D. Strain Gauge Observation

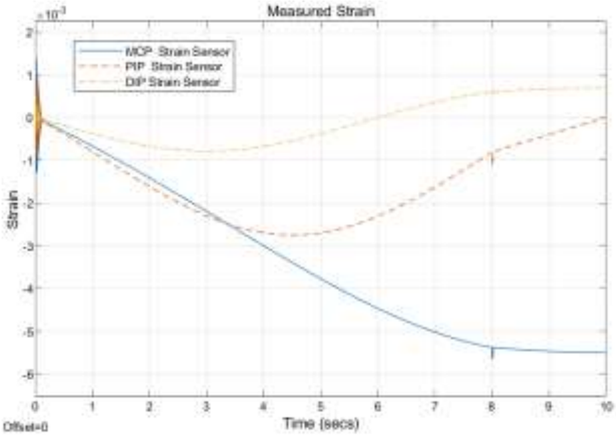
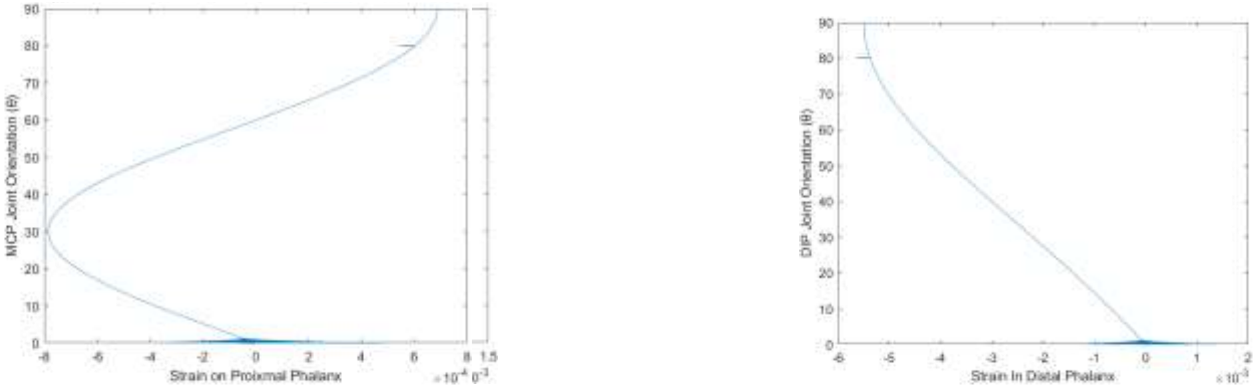


Fig. 11. Strain Gauge Reading

As seen in Figure 11, the strain at 10 secs for links 1, 2, and 3 are -5.49×10^{-3}, 0, and 6.84×10^{-4}. Since link 2 (Middle Phalanx) is constrained by 2 rotating joints the strain is 0 when there is no motion on these joints. The first link (Proximal Phalanx) is constrained by a non-moving base (Metacarpal) the strain is compressive, and since link 3 (Distal Phalanx) is free on one end its strain is tensile.

E. Discussion.

The results show that the strain of the subsequent link can be used as feedback instead of joint orientation for controlling bionic systems. The strain and joint orientation are also plotted for each joint-phalanx pair in Figure 12.



(a) (b) (c)

Fig. 12. Strain and Joint Orientation Relations

These plots show that the joint angles relate to the strain, similar to the strain vs time graph (see Fig 11). This implies that the strain data can be converted to joint angle data and used as the current joint orientation to calculate the joint error in the computed torque control or strain feedback controller. The initial strain oscillations from t=0 secs to t=0.005 secs can be ignored and subsequent values can be used for the above purpose. This eliminates the need for complex rotary encoders to give feedback to the motion controller.

5. CONCLUSION

This study proposes a new methodology to obtain joint parameters of a bionic system, or any system having spatial constraints, by measuring the link strain using a strain gauge sensor. The model was done using MATLAB Simscape Multibody and results were observed through MATLAB Simulink. Due to computational limitations, only one of the digits was considered. The results show an observable correlation between joint torque, orientation, and link strain. This relation can be used as lookup data in a cybernetic controller, to design a robust controller that doesn’t rely on complex algorithms and wireless technology to interface human EMG or EEG signals to robotic actuation. The future scope of this study is to develop a controller that could provide a rest-to-rest control of human digits. This controller could be tested with the existing prosthetics to compare its efficiency with other control techniques. Such a controller could decrease the cost of manufacturing bionic devices and aid in Amputee rehabilitation.

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