Development and Performance Evaluation of a linear actuator based Wearable Assistive Device

Mohatashem R. Makhdoomi, Alala M. Ba hamid, Tanveer Saleh
Department of Mechatronics Engineering,
International Islamic University Malaysia
Jl. Gombak, 53100 Kuala Lumpur, Malaysia, Email: makhdoomimohtashim@gmail.com

Abstract—**For an assistive device to be usable in carrying out activities of daily living, it is highly important that the device be compact, light in weight and portable. It is even more important that the device be comfortable and safe to use. As different people have different hand sizes, the assistive hands must be designed considering the variety of hand sizes that can be accommodated without any compromise in safety or comfort. This can be best achieved by making use of a joint-less structure that takes the shape of the hand that wears it. This paper proposes the design of an assistive device that is lightweight, compact, safe and comfortable. This device assists the hand in gripping objects used in daily life activities. The performance evaluation of this device is carried out by measuring the grip-force exerted by the finger-tip on the object. The maximum range of grip-force exerted by this assistive hand is between 2.5 to 4.5 N. The minimum grip-force that can be applied is 0.9 N. The experiments conducted show the viability of the assistive device.**

Keywords—Assistive hand; Wearable; Linear Actuator; Force Sensing Resistor; Grip force

I. INTRODUCTION

Physical disabilities are mainly caused due to stroke or spinal cord injuries. About 80% of the stroke affected patients exhibit a partial loss of voluntary movement in their arms & hands [1]. In a five-year study conducted in an academic setup it was found out that 40 % of the injuries recorded were related to the hand, out of which 42 % had to do with the musculo-skeletal system of the hand[2]. In 2006, the total adult population of disabled people in Malaysia was 13,515 out of which 8,402 were males and 5,113 were females [3]. Hands are an important part of the interaction of a human being with the surroundings when it comes to manipulation, touching or even shaking hands. For a hand to be able to perform functions such as grasping, hook or pinching, it must be able to feel touch, possess mobility & strength [4].

With the gradual advancement in the field of allied sciences such as anatomy, physiology and bio-mechanics, mechatronics extended its sphere of influence into the medical field. This led to the development of medical robotics consisting of surgical robotics, rehabilitation robotics & assistive technology such as prosthetics & exoskeletons. Over the past few decades, the rapid advances in mechanical designs and control algorithms for electromechanical systems have resulted in a significant development of exoskeleton devices but their use is still limited to larger body areas such as the upper and the lower limbs [5]. There is an on-going research to investigate further potential roles of robotics technology in rehabilitation.

The main reason to develop assistive hands is to restore the hand functions of a patient that can enable him to carry on with day to day life activities. In order to do so, it is important to conduct a thorough study of the anatomy, physiology and pathology of the hand, to understand how it functions and about the various diseases that could lead to loss of functions. Nonetheless the points to be considered while designing an assistive device are weight, compactness, & portability. As mentioned previously, the main purpose of the designing an assistive hand is to restore hand functions. Therefore, assistive hand must be safe to wear and its mechanism should work in such a way that it does not exert unnecessary pressure on the joints of the wearer. It is for this very purpose, the centers of rotation of the finger joints must coincide with the centers of rotation of the assistive device [5]. This can be achieved by aligning the centers directly as in [6], or aligning the remote center of rotation as presented in [7], or by use of -bi-articulated mechanism as proposed in [8]. The same can be achieved by using artificial rubber muscles gloves that bend the fingers as they bend [9]. However, by making use of joint less, tendon like arrangements, the fingers can be actuated about their own joints without having to design heavy mechanisms to align the centers of rotation. An assistive device using joint less structure was designed previously using a brush-less DC motor [10]. However, the device was not sensor integrated and the force was measured by means of a load cell placed at the end of the finger. The device could perform the pinch function.

With recent advancements in linear actuator technologies, it has become comparatively easier to design assistive hands with above mentioned features. This is because linear actuators have a simple design, small size, are light in weight and save time and cost and occupy less space. This paper describes the design and performance evaluation of a wearable sensor integrated assistive hand with linear actuator as a source of actuation.

II. ASSISTIVE HAND MODELLING

In this model, the human finger is represented simply as two links and a joint that aim to mimic the arrangement of the finger, the metacarpal bone and the metacarpophalangeal (MCP) joint. A wire is used to function like a tendon to help in the flexion and extension of the finger. The tension in the wire T makes an angle of θ with the horizontal. The MCP joint angle is denoted by φ. If 'L' is the length of the finger, then the weight of the finger is assumed to be centered at half the length of L. The tension T acts at a length 'r' from the MCP joint. The tension in the wire in fig. 2, denoted by T in fig. 1, is due to the pulling force generated by the linear actuator. The grip force F comes into play only when the object makes contact with the finger.

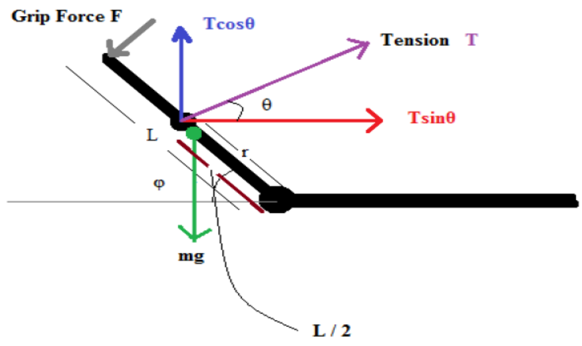

Fig.1. Representation of the finger and the metacarpal bone

At equilibrium conditions,

$$\sum M\varphi = 0$$

this implies,

$$rcos\varphi(Tsin\theta) + rsin\varphi(Tcos\theta) - mg\left(\frac{L}{2}cos\varphi\right) - F(L) = 0 \quad (1)$$

$$rcos\varphi(Tsin\theta) + rsin\varphi(Tcos\theta) - mg\left(\frac{L}{2}cos\varphi\right) = F(L) \quad (2)$$

Re-arranging the equations,

$$F(L) = rcos\varphi(Tsin\theta) + rsin\varphi(Tcos\theta) - mg\left(\frac{L}{2}cos\varphi\right) \quad (3)$$

$$F = \frac{rcos\varphi(Tsin\theta)+rsin\varphi(Tcos\theta)-mg\left(\frac{L}{2}cos\varphi\right)}{L} \quad (4)$$

$$F = \frac{Tr(cos\varphi sin\theta+sin\varphi cos\theta)-mg\left(\frac{L}{2}cos\varphi\right)}{L} \quad (5)$$

$$F = \frac{Tr(\sin(\theta+\varphi))-mg\left(\frac{L}{2}cos\varphi\right)}{L} \quad (6)$$

Thus, Eq. 6 can be used to calculate the grip force.

III. Design of the Assistive Hand

The design presented here is that of a joint-less, tendon-like mechanism which, when worn by someone takes the structure of the hand of the wearer. The wearable assistive device consists of a glove onto which small guide tubes are attached. The tendon-wire runs along the perimeter of the digit. The ends of these tendon-wires are fixed onto the mechanism that is mounted on the platform along with the linear actuator. This mechanism is made to slide through a guiding slot on the platform by the linear actuator. At the moment, the design makes use of only two digits, i.e. the index finger and the thumb to serve the purpose of gripping.

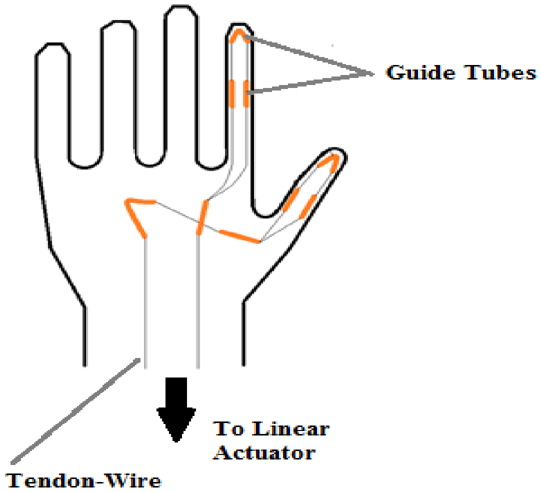

Fig.2. Joint-less arrangement on the glove

A force sensing resistor (FSR) not shown in the fig. 2, is fixed at the finger-tip of the index finger to measure the changes in the force exerted by the finger. The Firgelli L-12 linear actuator which provides a stroke of 30mm is used. The stroke of this linear actuator is translated into the tendon displacement. The linear actuator and the tendon-wire mechanism are mounted on a wearable casing made of ABS plastic. As the linear actuator pulls the wire, the tension created within the wire pulls the digits in the direction of the motion of the linear actuator's piston. This pull helps to curl the index finger around an object while gripping. The FSR located at the fingertip, measures the force exerted by the finger on the object. This force exerted acts as a feedback to control the stroke of the linear actuator.

IV. Simulation Studies

The mathematical equation for grip force obtained in the previous section is used in the Matlab environment to simulate the change in the grip force with change in certain parameters. The variable parameters such as the applied tension T, the distance r and the angle θ affect the grip force of the system. Every time a simulation is obtained by varying a parameter, one at a time, while others are kept constant. The simulation results are as follows:

A. Parameter variation, Tension T

Fig.3 depicts the variation in gripping force with the change in MCP angle for different values of T. As the MCP angle φ increases, the gripping force F increases and attains a maximum value at an MCP angle of φ = 60 degrees. It is also observed that for higher values of T, the gripping force F is high. With T equal to 40 N, the gripping force F reaches a maximum value of 4.6 N. For a T of 15 N, F attains a maximum value of 1.75 N approximately. For a T of 30 N, the gripping force F reaches the maximum value of 3.5 N.

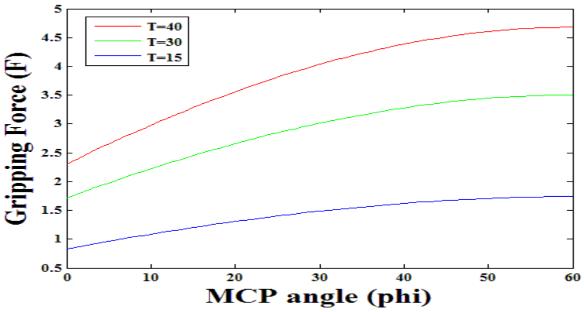

Fig. 3. Gripping Force vs. MCP angle φ with different values for *T*

B. Parameter Variation, r

Keeping other parameters constant, as r is increased from 10 mm to 20 mm, the gripping force F also increases, however, the general trend remains the same as observed for T-parameter variation. That is to mention, with increase in the MCP angle φ, F increases and attains a peak value. When r equals 20mm, T equals 40 N and θ equals 30 degrees, F reaches a maximum value of 9.4 N. With r equivalent to 10 mm, F attains a maximum value of 4.8 N. By selecting r = 15 mm, the gripping force F attains a maximum value of 7 N.

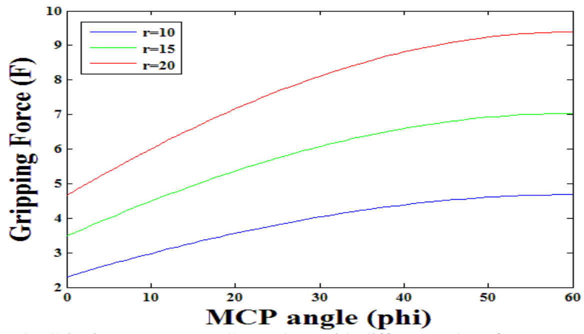

Fig. 4. Gripping Force vs. MCP angle φ with different values for *r*

C. Parameter variation, θ

On varying θ from 30 degrees to 60 degrees, the gripping force shows the same behavior in relation to the MCP angle as observed in the previous sections. However, the gripping force F attains the same maximum value at different MCP angles for different values of θ. Lower the value of θ, greater is the value of φ at which maximum gripping force is achieved. F is maximum at φ = 60 degrees when θ equals 30 degrees, but for θ = 60 degrees, F reaches the highest value at φ = 30 degrees.

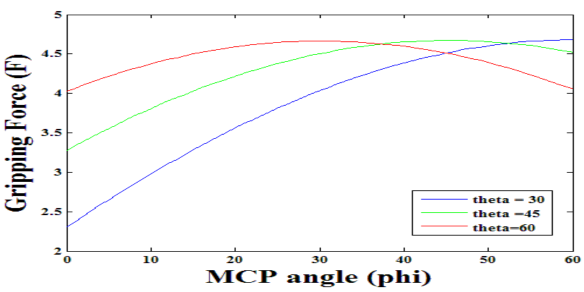

Fig. 5. Gripping Force vs. MCP angle φ with different values for θ

All the simulation results also point out the existence of the gripping force when the MCP angle φ is zero. This holds true for a sufficiently large object because the flexion will be negligible. So φ is almost zero degrees and the grip force is given by,

$$F = \frac{Tr\sin\theta - mg(\frac{L}{2})}{L} \quad (7)$$

Thus, depending on how big the dimensions of an object are, the grip-force comes into play with little or no flexion at all. This proves that, if the finger makes contact with the object, the grip-force can act on the object even when there is little or no flexion.

These simulations are of significance because they help in finding out the instances where the gripping force is maximum. This in turn would help identifying the exact angle required by the assistive hand to generate a maximum force by providing the correct displacement in the tendon.

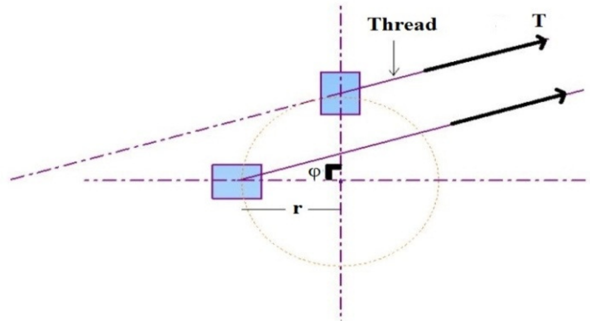

Fig. 6. Relation between tendon-wire displacement *l* and MCP angle φ

In fig. 6 above, the blue rectangle represents the part of the finger where the tendon wire is connected. At full extension of the linear actuator, the finger is in line with the horizontal axis. At full retraction of the linear actuator the finger is pulled such that the metacarpophalangeal angle becomes a right angle. If *r* is chosen to be constant, then for a particular value of φ, the required displacement *l* in the tendon-wire can be obtained. The mathematical equation describing this relation is:

$$l = r\varphi \quad (8)$$

In this design of the assistive hand, this displacement will be provided by the linear actuator. This displacement is provided by the linear actuator.

V. Controller Block Diagram

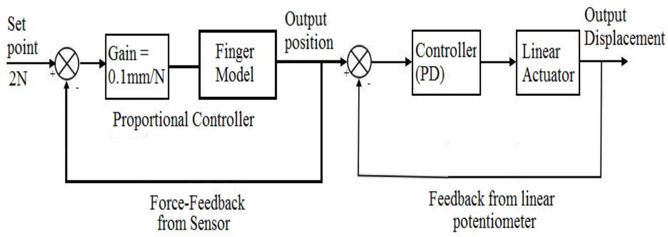

Fig. 7 Block Diagram of the Sensor-integrated Assistive Hand

Fig. 7 shows the block diagram of the sensor integrated assistive hand. The force set as the threshold or the set point is 2 N. The feedback obtained from the force sensing resistor is the actual grip-force measured at the tip of the finger. The error signal obtained is multiplied by a proportional gain of 0.1 mm/N which acts as a set-point for the linear-actuator responsible for the displacement of the tendon-wire. The linear actuator has its own driver which houses a PD-controller. It also has an in-built linear potentiometer for feedback position control. The linear potentiometer, at all times records the position of the piston. Thus, every time, the change in force results in the change in the input to the linear actuator, the error signal given to the controller of the linear actuator is obtained as a difference of the change in the input and the previous value. Thus, when the feedback force equals the threshold value, the value of the error signal is zero, which means that the input to the linear actuator becomes zero, this when subtracted from the previous value of the linear actuator yields the same value as the previous value. Practically, it means that there is no change in the displacement of the piston, and hence the tendon-wire, and therefore, no change is shown in the position feedback. At this value of gripping force, the object has already been gripped and without any need to exert any more force by pulling the tendon-wire.

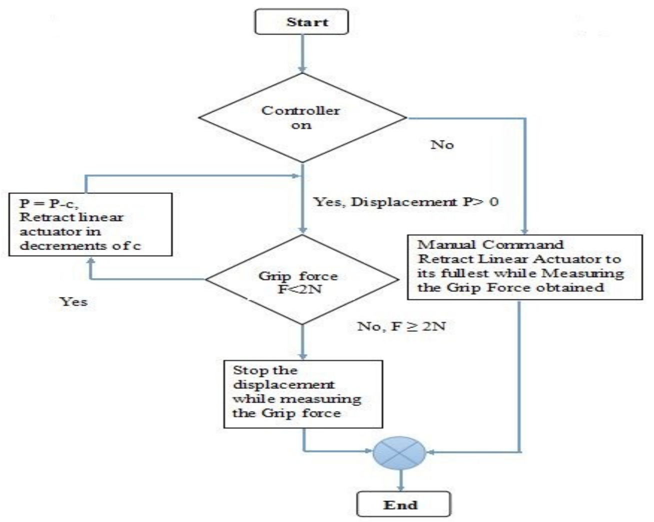

Fig. 8 Flowchart describing the performance evaluation operation

Fig. 8 describes the mode of operation and the steps involved therein. The operation is conducted using LABVIEW. To start with, one decides whether the device is to be operated in open-loop configuration or close-loop configuration. If the controller is turned “OFF”, the device has to be operated in the open-loop configuration by giving the displacement commands of retraction and extension. However, if the controller is turned “ON”, the device performs the gripping along with the feedback. In this mode, if the device is positioned at a value greater than zero, and the grip force is less than the threshold value of 2 N, the piston keeps on retracing till the force increases up to a threshold value. Once the threshold value is attained, the piston stays in its position and maintains a tension in the tendon-wire, thereby keeping the grip on the object.

VI. Experimental Setup and Results

Fig. 9 shows the complete assistive hand system. Two phases of experiments were conducted to measure the grip force exerted on the objects as shown in fig. 10**.** Phase 1 of the experiments involved simple extension and retraction of the linear actuator and measurement of the grip-force exerted thereof. Phase 2 of the experiments involved a force-feedback control. Three rigid, cylindrical objects of different diameters were used as the test subjects in these experiments.

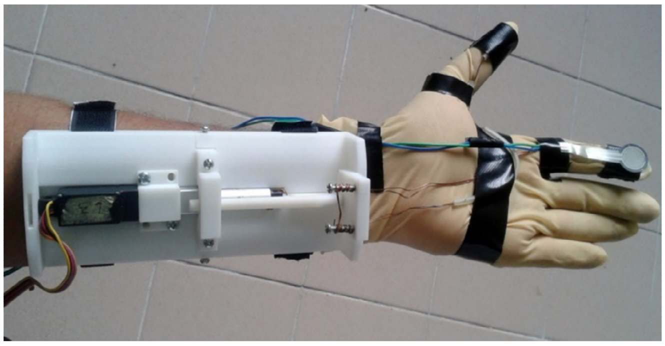

Fig. 9 Assistive Hand Assembly

The experimental studies were carried out only to measure the force while the object is being gripped.

Fig. 10 Object being gripped by the thumb and sensor-integrated finger-tip.

Both the experiments were conducted using the LABVIEW environment. The objects and diameters are shown in Table 1.

TABLE I. DIAMETERS OF THE TEST SUBJECTS

Object no.	**Diameter (mm)**
1	69
2	92
3	115

Both the phases have been described as under:

A. Open loop Grip-Force measurement

In these experiments, the grip-force existing on the tip of the index finger was measured simple by giving a displacement command to displace the piston by a length of

30 mm, directly from the program in LABVIEW. As no force feedback controller was involved, the displacement that took place was 30 mm. The plots of Force and Displacement versus time of Object no. 1, Object no.2 and Object no. 3 have been described in fig. 11, fig. 12 and fig. 13 respectively.

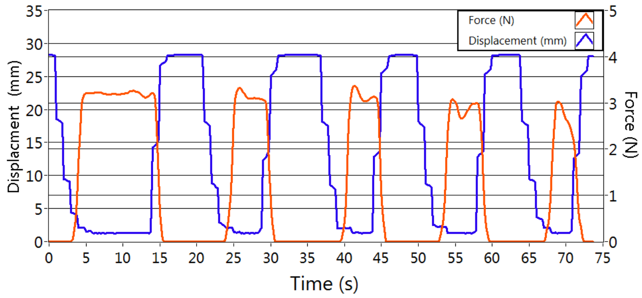

Fig. 11 Force and Displacement versus time for Object 1

Fig. 11 describes the cycle test performed with Object 1 as the test subject. The decrease in the displacement corresponds to the retraction in the piston of the linear actuator from 30mm to zero. The tendon-wire is displaced a length equal to the length of retraction. It is observed that for every cycle, as the displacement changes, there is no increase in force for a certain time. This is because, when the displacement starts, the hand is completely open. As soon as the finger-tip makes touches the object, the gripping force starts to act and is detected by the force sensing resistor. This holds true for all the experiments conducted, whether open-loop or closed loop. The range of grip-force for this cycle test is between 3N to 3.3N. Although the linear actuator was required to give a displacement of 30mm, it is not imperative that an exact magnitude of displacement will be provided as the finger to which the wire is attached cannot move any further because it is blocked by the object. It is also to be noted that during this cycle test, the command for displacement is not given at regular intervals, as is obvious from the graph, but it does not affect the behavior of the system, as the force-displacement relationship remains the same. The relationship between the force and displacement for Object 2 as indicated in fig. 12 has the same trend as Object 1. The range of force for the cycle of tests conducted in this case is 3 to 3.4 N.

In the experiment conducted for Object 3, again an increase in force is observed as the piston retracts, thereby displacing the wire, however, in this case, both the displacement and the grip force have lower values than what is observed in fig. 11 and fig. 12. The range of gripping force for this object is between 0.9 N to 1.5 N. As Object 3 is of a bigger diameter as compared to Object 1 and Object 2, the finger curls around the object fairly quicker as compared to other test objects. The low values of grip force can be explained on the basis of the behaviour of the linear actuator.

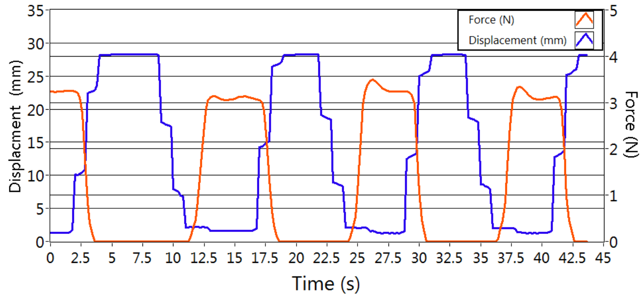

Fig. 12 Force and Displacement versus time for Object 2

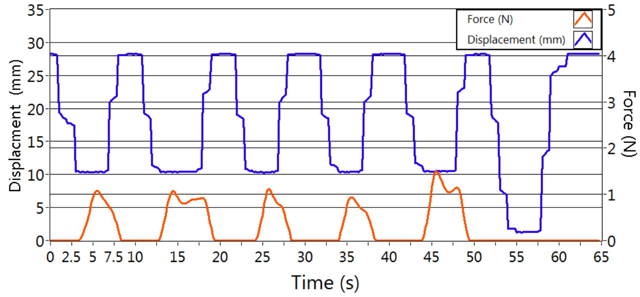

Fig. 13 Force and Displacement versus time for Object 3

When the piston of the linear actuator is unable to perform a required displacement, it is no longer able to pull. At that moment, it draws a high current before the internal circuit breaks. As there is no pulling action, no external force is exerted. During the last cycle, the object is removed from the hand, thereby allowing a full retraction without any force reading being recorded.

In all the plots so far, it is observed, that the peak values are uneven. As the maximum displacement is achieved, the linear motion becomes jittery and tends to oscillate back and forth before it stops. Due to this oscillating behavior of the actuator, the tendon-wire is pulled and released alternately, which is reflected in the grip-force exerted. Same behavior is observed during the closed-loop experiments which shall be discussed in the next section.

B. Force-Feedback Grip-Force Measurement

In these experiments, the displacement of the tendon-wire was controlled by a feedback signal obtained from the force sensing resistor. The controller implemented through a code written in LABVIEW required the linear actuator to stop the displacement when the force measured exceeded the threshold value of 2 N. This displacement was measured by an internal linear potentiometer within the linear actuator. Fig. 14 shows the plot obtained for a cycle test conducted on Object 1. When the linear actuator is fully extended, a distance of 30 mm is depicted on the potentiometer, as the piston retracts from 30 mm towards zero the wire is displaced by a length that equals the change in the length. As soon as the fingertip makes contact with the object, the force starts to increase. As soon as the force reaches a threshold value the piston stops, thereby holding on to a certain value of force at a certain displacement.

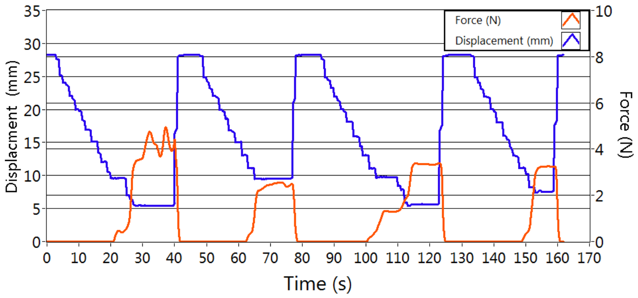

Fig. 14 Graph depicting Force and Displacement vs. Time for Object 1.

The grip force exerted on the object ranges between 2.5 N to 4.5 N. The tendon wire undergoes a displacement that ranges between 20 mm to 25 mm.

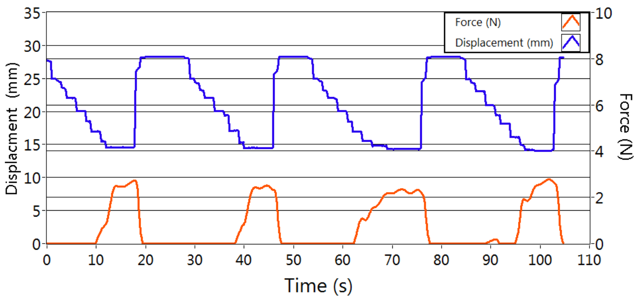

Fig. 15 Graph depicting Force and Displacement vs. Time for Object 2.

In fig. 15, the displacement for the tendon-wire in case Object 2 is about 15 mm. In this case, the range of force recorded at the mentioned displacement is between 2.2N to 3N. The tendon wire undergoes a lesser displacement as compared to the values in Object 1 as it has a higher diameter and therefore a greater circumference that Object 1. For Object 3, the maximum displacement that the tendon-wire undergoes is 10 mm (as the piston retracts from 30mm to 20mm). The grip force ranges between 1.9N to 3.1 N as can be seen in fig. 16. The lower values of displacement attributed to the same reason as explained for Object 2 with respect to Object 1.

In all the plots for closed-loop experiments, it is clearly visible that the gripping force obtained is greater than the threshold value. This is due to the fact that the proportional constant in the P-controller is very small, i.e. 0.1mm/N. This results in a high steady-state error. Due to this time lag the tendon-wire is displaced a little more than what it should at the threshold value This extra displacement results in some additional grip force being exerted on the object. It is also due to this that the closed-loop system is very slow. If the piston and hence the tendon-wire is displaced by larger increments (by using high values of proportional constant), maximum displacement is attained very fast, and the system does react well to the force-feedback. Thus, there appears to be a trade-off between the lesser steady-state error and the optimal time taken to execute the retraction operation.

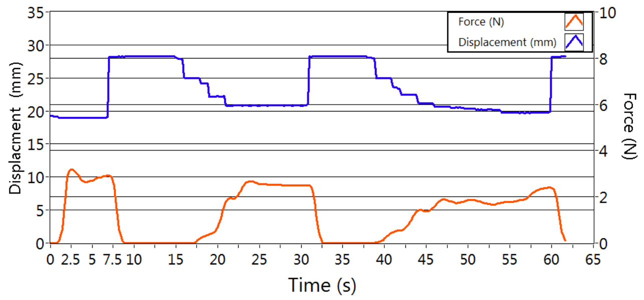

Fig. 16 Graph depicting Force and Displacement vs. Time for Object 3.

VII. Conclusion

In this paper, the design for a linear actuator driven, jointless and lightweight assistive hand was presented. This device can be used for assistive and rehabilitative purposes. Both open-loop and closed loop experiments were conducted to measure the grip force. From the results, it is clear that the gripping force is good enough to grip objects used in activities of daily living. The minimum grip force obtained was 0.9 N. However, the proportional controller developed for this device had a high steady state error, was slow in response, and time taken to grip an object during closed loop experiments was fairly long as compared to that of the open-loop experiments. Although the actuator provides a good linear displacement and is light weight and compact, it is also responsible for some oscillation in the piston as it approaches the maximum attainable value. The design proposed has a potential for application and further research is encouraged.

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