Design of a portable anthropomimetic upper limb rehabilitation device for patients suffering from neuromuscular disability

Vinay Chandrasekhar[1], Vikas Vazhayil[2], and Madhav Rao[1]

Abstract—**An upper limb anthropomimetic rehabilitation device has been designed for patients suffering from a neuromuscular disability. The developed device has been designed as a wearable device and attempts to supplement all known functions of the human hand and fingers. The actuation of individual joints of the hand and wrist has been implemented by using DC motors interfaced to a control system. A pulley system was adopted to ensure a low device profile with the aim of maximising functionality in the affected hand. Both actuators and the electronic assembly are sited in the forearm assembly for this purpose. The device is designed to fulfill multiple roles. At its simplest instance, it is designed as a device for providing resistance training in patients suffering from reversible neuromuscular weakness. The device also aims to provide support as an exoskeleton device in patients suffering from partial but permanent neuromuscular weakness. The measurement of finger and wrist bending in axial and radial directions were investigated by an array of potentiometers mounted around the wearable device covering different joints of the fingers and wrist, and were further analyzed to characterize the range of the device. The system is a composite device with diverse functions fulfilling all the requirements of an upperlimb orthotic device. The device is planned to be part of a comprehensive exoskeleton device for quadriparetic patients in the future.**

Index Terms—**upper limb, rehabilitation, exoskeleton, physiotherapy device**

I. Introduction

A large number of neuromuscular diseases cause hand weakness. Neuromuscular weakness does not cause anatomic disfiguration, but causes functional impairment. With long standing impairment, anatomic changes set in. In such cases, even recovery of the primary illness there is residual dysfunction. Patients suffering from neuromuscular weakness require meticulous physical rehabilitation measures requiring long hours of work with trained personnel. Very often many of these patients do not receive the dedicated and meticulous attention they deserve and the rehabilitative measures are often found wanting [1]. Due to motor impairment, the stroke patients have minimum ability to get independently involved in daily chores and activities, leading to other physiological and psychological problems. Only about 18% of patients [1] with upper limb motor impairment attain complete recovery which is attributed to a limited number of therapy centers, outdated devices in usage, and limited availability of rehabilitation devices in the approved centers. In essense physical therapy mandates repetitive movements of the dysfunctional limb under controlled conditions. In view of the limited number of centres with dedicated physical therapy devices and services, the need of the hour is home based rehabilitation devices which can be used by the patient and attendants with minimal technical support [2]. A feasible option in this direction is for the patient to be able to rent or lease a portable device to use the device domestically at their convenience under supervision of the care taker [3].

Previously, an assistive upper limb domestic device for the elderly patients has been described and mentioned in [4], however the device showcased limited degree of freedom and was not suitable enough to imitate complete activities of the upper limb device. A soft assistive device using pneumatic artificial muscles was designed only for elbow movement [5]. Similar elbow, arm, and shoulder based rehabilitation device is stated in [6], [7], however the same design principles does not suit the upper limb finger movements. A stroke rehabilitation monitoring system is discussed in [8], as an improvement from [9], however the designed static system is non-portable, thereby limiting the scope to a specific place in either rehabilitation centers or physiotherapy departments of hospitals. A study on separately integrating sensory system as a feedback module to the existing trans-humeral prosthetic upper limb device is shown in [10], however the device was limited to a prosthetic version and hence not applicable as a rehabilitation device for patients with partial impairment of upper limb function.

The high profile of the actuation system in the work described in [11], is suitable for a single finger actuation. However, using a similar model for multi finger actuation is difficult in terms of space and placement. Hence, the design with low footprint profile that allows increased number of actuators per unit area is needed for clinical use. In the work stated in [12], the system is majorly placed on the palmar side of the arm, thereby disabling any sensory feedback to the user. Hence a much needed rehabilitation device to minimize the system footprint on palmar surface is essential. The design proposed in the work [13] has a large mechanical profile on the dorsal side, making the device bulky and inconvenient for routine clinical use. Use of soft robotics for actuation mentioned in the recent past [14], [15] requires

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[1]International Institute of Information Technology, Bangalore, Bangalore-560100, India vinay.chandrasekhar@iiitb.org
[2]NIMHANS, Bangalore-560029, India

heavy systems support to aide in the movement of upper limbs.

In general, previous work do not incorporate all the features including simultaneous flexion and extension actuation so as to be able to lock the finger in place and hold position which is important for tone and posture. Also not described are devices with the ability of abduction and adduction of hand and fingers. An ideal assistive device should incorporate these features and should be able to actuate different parts of the upper limb including hands, fingers, and wrist independently.

II. Design of the anthropomimetic upper limb device

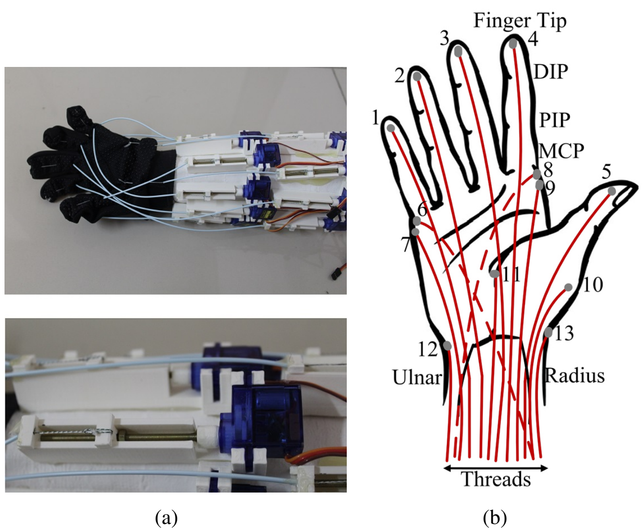


Fig. 1: (a) Pictures of the 3D printed anthropomimetic upper limb assistive device. (b) Schematic representation of anthropomimetic upper limb device showing threads of pulley system, connecting to different parts of glove covering human hand.

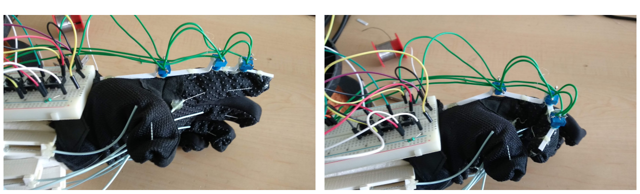
The design of the upper limb device includes wearable glove with gorilla fishing thread (Berkley Gorilla Tough. Model No. GTQS35-14) of 0.2 mm diameter, connecting pulling points in the glove to DC motors, thereby forming an array of pulley systems. The thread is driven by the DC motors extended bolted joint system which are encased in the 3D printed grooves as shown in Figure 1 (a). In the groove, an assembly comprising of 6 cm long bolt with a pair of hexagonal shaped nuts was designed to efficiently pull and release the threads of the pulley system, as shown in the Figure 1 (a). The pair of hexagonal threaded nuts were capped by a flattened plastic head, which moves smoothly along the grooves, when the nut moves along the bolt. A thread is pinned to the plastic head of the assembly on one side, and stitched to glove on the other side to complete assisted pulling mechanism design. An array of stacked pulley system is shown in Figure 1 (a). The threads, with the programmable DC motors form the pulley system to control movement of various parts of the hand. Multiple threads are attached at optimal points of the glove as shown in the schematic drawn in Figure 1 (b), to assist in bending of individual fingers, and wrist with minimum disturbance from other movements. The figure shows array of threads stitched to 13 different points in the glove to generate 12 different assisted movements including flexion, and radial abduction and adduction of fingers and wrist. For completing extension action for fingers and wrist, similar thread based pulley assembly are designed on the dorsal side of the hand. Through this pulley system assembly design, the rotational movement of DC motor was translated to the linear motion. A pair of pulley systems were assembled for each finger, with the threads running through the dorsal and frontal region of fingers, and attached to the plastic head of the assembly. The design was repeated for every finger except thumb to offer axial flexion and extension functionalities. Similarly pulley system setup including threads, nut-bolt assembly module, and DC motors were designed for wrist and thumb with thread attached to the wearable glove covering these regions to complete the finger operational design. The thumb portion was driven by four pulley systems to offer flexion, extension, abduction, and adduction. The upper limb device was designed with four pulley systems to offer radial abduction and adduction motion for fingers. Two motors were designed to pull fingers radially away and the other two motors were configured to push the fingers together. The pulley systems were installed near the metacarpophalangeal (MCP) joints of little and index fingers, that enabled the stretching of four fingers radially away and together. No pulley systems were needed for middle and ring fingers, since the radial movement of these fingers were involved when the other two fingers were radially displaced. All the DC motors were staggered and encircled around the enclosure covering the forearm, along with the grooves to hold the movable nut and bolt assembly.

The device supports flexion and extension motion of wrist with four cables, forming pulley systems, that are attached to the glove covering the radius and ulnar sides of the wrist. Similar to the finger actuating pulley system, the threads terminate at the movable plastic head, which is sequentially displaced by the movable bolt connected to the DC motor shaft. The two motors on the palmar side, drive to attain flexion motion of the wrist, and the other two motors at the dorsal side operate to achieve extension motion for the wrist. Again, to minimize any contention issues among the pulley systems, only two motors on the same side were made to operate, whereas the other two motors were logically switched off from the power supply. The motors were configured to drive in forward mode to pull the wrist on either side, and complete flexion and extension motion of the wrist. During the reverse mode of DC motors, the pulley system releases the thread to attain a relaxed wrist position. The abduction state of the wrist was achieved when the motors positioned on radius side of the wrist were operated and motors placed on ulnar side were switched off, and vice versa operation achieves adduction motion for wrist.

The complete upper limb device was designed in a view to not only have minimum electronic components around the palm space, but also to provide maximum range of natural motion without any external impedance. The device was designed to develop a complete upper limb exoskeleton device in the future, including the rehabilitation module which is discussed in this paper.

III. Experiments and Results

For experimental validation, a set of sensors were placed at different positions of the glove to measure the range of motion of individual assisted movement. The upper limb anthropomimetic device was investigated by measuring bending angle during the individual assisted mechanism of fingers, and wrist. In addition, the maximum force generated by the designed system was measured using a force sensor while the device is operating, to ensure successful actuation of upper limb. An array of potentiometers as sensors were designed along the index finger of the left hand to measure the range of motion involving bending action. Potentiometers as a sensor was preferred over flex sensor to obtain precision on the finger bending measurements. Flex sensors showed resistance changes due to the finger movement, also the large area coverage of the flex sensor does not allow for individual finger joints measurement. Three potentiometers, each were fixed on the side of the index finger along the three joints namely, metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joints, as shown in the Figure 2. The assisted finger actuation ranging from flexion to extension state was measured accurately by the potentiometer sensors at each of the three joints: MCP, PIP, and DIP. Note that a single pulley system in the form of a thread was pinned to the wearable glove covering the finger tip, which induces movement in three joints specified. Similarly the range of abduction and adduction, referred for lateral movements of the fingers, was measured by the potentiometers, fixed close to the MCP joints on the palmar side. Similar actuation result was expected on other fingers including thumb by the device.



(a) (b)

Fig. 2: Pictures of potentiometers interfaced to the upper limb anthropomimetic device to measure finger bending (a) during an extension, and (b) flexion actions.

The bending of finger movement to realize axial flexion and extension motion by the upper limb anthropomimetic device was investigated. Assuming the joint angles to be

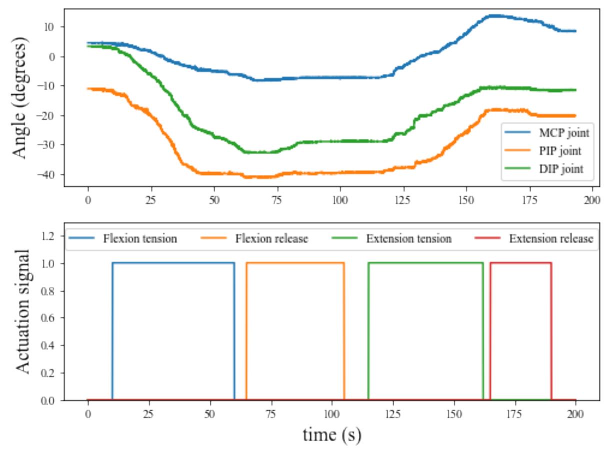


Fig. 3: Transient index finger movement, driven by upper limb anthropomimetic device, showing a complete range from extension to flexion state, as measured by the potentiometers arranged on the joints.

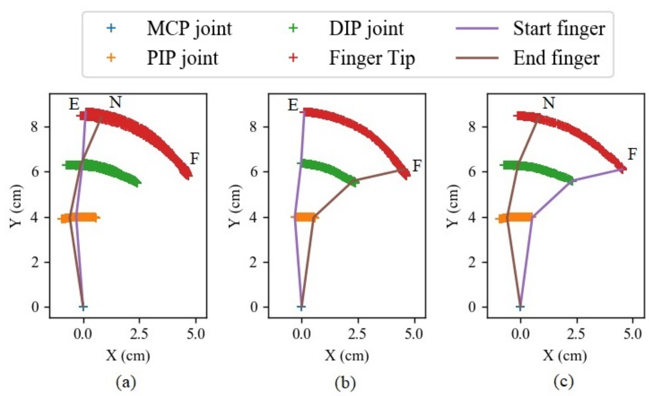


Fig. 4: Upper limb anthropomimetic device actuated finger trajectory showing (a) complete cycle ranging from flexion to extension, (b) flexion action, and (c) extension action.

zero when in the palmar plane and negative during flexion, Figure 3 shows transient response of three joints of index finger, when actuated from flexion to extension state, by four programmable signals controlling the pulley systems. The pulley systems comprising of DC motors were configured to rotate in forward direction to attain flexion, and extension state of the finger. In the forward mode, the DC motor applies a maximum force of 20 N to pull the thread and finger, whereas in reverse mode, the motor releases thread, to return to the original position. The two motors and its modes were operated exclusively to enable smooth working of the motors. The experimental results indicated in Figure 3 reflects flexion action of the index finger, returning to the original position, then driving to the extension range and finally returning back to the released finger state. The response time to reach finger flexion and extension state for a constant 20 N pulley force, as extracted from the Figure 3 was 37 seconds, and 29 seconds

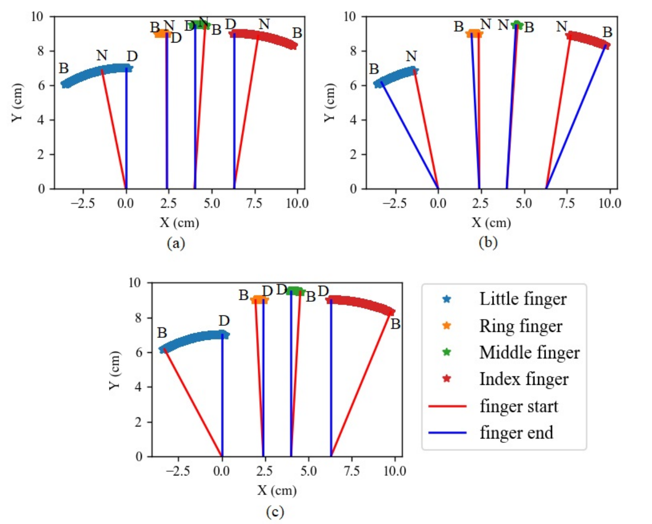


Fig. 5: Upper limb anthropomimetic device driven radial trajectory of four fingers of right hand showing (a) complete cycle ranging from abduction to adduction, (b) abduction motion, and (c) adduction motion.

respectively, indicating slow and safe assisted movement of the finger under actuation.

Figure 4 shows the trajectory profile of three joints, and tip of the index finger, as measured from the potentiometers arranged on MCP, PIP, and DIP joints. Note the labels E, N, and F indicates the position of the finger under test in extension, relaxed, and flexion states, respectively. Figure 4 (a) presents the path of a complete flexion-extension cycle showing displacement of the joints and finger tip. Figure 4 (b) shows the path and trajectory for assisted flexion, and similarly Figure 4 (c) demonstrates the same for an extension event. Post actuation cycle, the device switches off the power to all pulley systems, leaving the finger to a relaxed position. The maximum trajectory range for DIP joint, PIP joint, and tip of the index finger in completing a cycle from extension to flexion was found to be 3.45 cm, 1.45 cm, and 6 cm respectively.

Figure 5 (a) shows the trajectory of four finger tips during a complete cycle ranging from abduction to adduction motion. Note that labels B, N, and D represents the position of the fingers in abduction, normal, and adduction states respectively. The maximum range of radial motion for each finger as observed from the Figure 5 (a) is 3.5 cm for index finger, 0.9 cm for middle finger, 0.8 cm for ring finger, and 3.7 cm for little finger. Figure 5 (b) and (c) shows separate trajectories for abduction and adduction events. Note that the middle and ring finger has minimum movement in the overall abduction and adduction event, as expected. The total span of fingers from little finger to index finger during adduction event was observed to be 7.2 cm, whereas post abduction motion, 13.7 cm was observed. The response time to achieve abduction and adduction state, were reported to be 39 seconds, and 31 seconds respectively, which confirms safe and slow assisted radial motion.

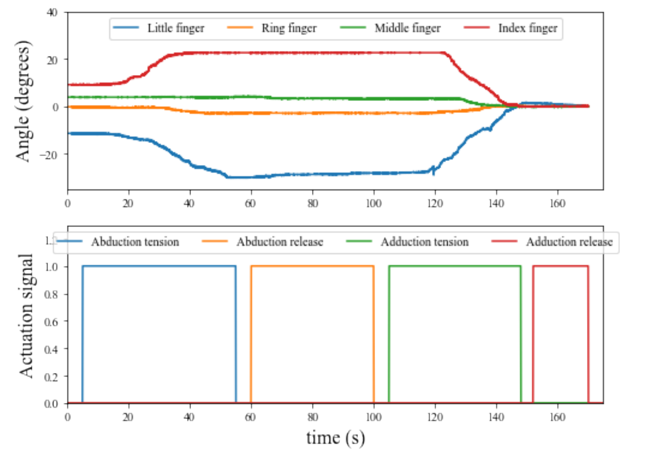


Fig. 6: Anthropomimetic upper limb device generating transient displacement of four fingers during the radial abduction and adduction motion is shown.

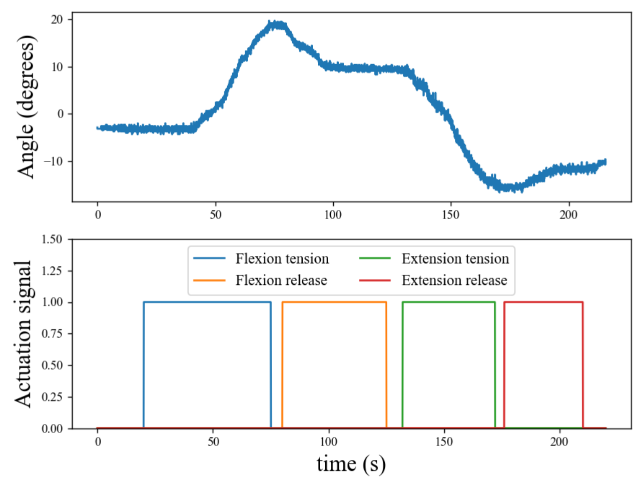


Fig. 7: Transient response of wrist movement, driven by upper limb anthropomimetic device is shown.

Experiments were performed to bend the wrist in axial and radial direction by the wearable upper limb device. Figure 7 shows the investigated response time, and range of actuation for the device. The control signals interfaced to a pair of DC motors triggers the pulley mechanism to actuate wrist in either direction. For attaining extension state, the control signals were triggered to operate the dorsal side of DC motors in forward mode, and extension release event was achieved when the same DC motors were running in reverse mode. The response time for achieving flexion and extension state was found to be 34 seconds, and 42 seconds respectively, indicating safe assisted movement for rehabilitation. The maximum flexion and extension range of 20 °, and 17 ° respectively was established from the device. The motors were positioned to offer sideways actuation for the wrist, and experimentally the maximum range for radial abduction and adduction motion were recorded to be 7 °, and 6 ° respectively.

IV. Discussion and Conclusions

Technological innovations have changed the management of disability. Prosthetic devices have changed the lives of amputees and allow them to lead near-normal lives. However, in the case of neuromuscular disability, progress in orthotic devices has been relatively tardy. This is due to the added complexity of these devices to account for form and physiology of the affected limb. In particular, upper limb device development has been lagging compared to progress in lower limb orthotic devices The major challenge in upper limb orthosis is in mimicking and assisting hand function. The hand is one of the most complex organs of the human body. The versatility of hand functions makes it difficult to implement using sets of actuators. Added to it, the technical challenges of having a compact device with a small device profile adds on the complexity of the design. The design proposed incorporates all the features which are required for implementing all functions of the human hand. The assembly of actuators and the control systems within the forearm component is an attempt to enable the hand to have a full range of movement. The design is thus anthropomimetic in that it mimics natural design wherein a substantial number of muscles actuating the hand are sited in the forearm. Each set of pulleys attempt to mimic the tendons which actuate fingers individually. The form factor of each finger is too complex for single sets of actuators to replicate finger function. Hence, multiple strategically placed pulley systems are used for this purpose. Hand function is complex. A simple action such as object grasping involves multiple fingers, palm and wrist actions. These actions are combinations of movements at individual joints. Fingers have to flex, abduct or adduct to grasp an object. Replicating these movements in an orthotic device is a challenging task. The design proposed attempts to address several of these challenges in a unique way. Sets of actuators ensure that a given joint movement is faithfully reproduced whether it be interphalangeal flexion or finger abduction. Combination of actuators thus can be activated in a temporal sequence to replicate the complex function desired in the hand. The experimental results shown in the paper are steps in this direction. Opposing actuators are used in the design. This is a method to replicate the phenomenon of tone. The tone in the human body is produced by a continual state of neurological activation of a skeletal muscle. The phenomenon is complex and difficult to replicate in an orthosis. Disorders of tone are also known to occur in the disabled limb. The current design uses opposing sets of actuators to produce static positions of the hand and fingers effectively attempting to replicate tone. This is a unique feature of the device. The device is thus designed to work along with the tonic state of the limb whether it be hypotonia or hypertonia which in turn depends upon the disease condition. Thus, the overall design fulfills the nomenclature of being anthropomimetic in the anatomic and physiological sense. The next step in the development of the device is in testing in an actual clinical setting which will validate the experimental results which have been demonstrated. The design proposed can also be extended to incorporate actuation at shoulder and elbow joints also and are part of ongoing work.

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