Biomimetic Design and Development of a Prosthetic Hand: Prototype 1.0

Nayan M. Kakoty, Shyamanta M. Hazarika

Abstract

This paper reports the biomimetic design and development of an extreme upper limb prosthesis. The motivation for developing a new prosthetic hand is provided by the fact that low functionality and low controllability are the most important reasons why amputees do not use their prosthetic hands. In addition, although multifingered hand prosthesis has appeared in the market, the cost is exorbitantly high and out of reach of common people, which is particularly true for developing countries like India. The paper presents an anthropomorphic design of a prosthetic hand with 15 degrees of freedom using underactuated mechanism. Control is through electromyogram signals based on support vector machine for classification of six grasp types involved in 70% of daily living activities.

Keywords: Biomimetic, Prosthetic hand, Electromyogram, Grasps

1 Introduction

Dexterous artificial hand design and manipulation is an active research area. A very interesting practical application is the field of upper limb prosthetics. Number of laboratory prototypes and commercial versions of upper limb prosthesis have been available. However, electromyogram (EMG) based control is still rudimentary, being limited to a few hand postures. Control is non-intuitive, in the sense that the user is required to learn to associate muscle remnants actions to unrelated posture of the prosthesis. Neuro-bionic hands address some of these issues. However, commercially launched variants (such as i-Limb from Touch Bionics [1]) are exorbitantly priced. Commercially available indigenous upper limb prosthesis in India is manufactured by Artificial Limb Manufacturing Corporation of India (ALIMCO) [2], Nevedac Prosthetic Centre [3] and CMC Vellore [4]. ALIMCO hand is with a cable control system. Nevedac/CMC Vellore hand works with micro-switches as an alternative to the myoelectric control. These are too rudimentary to be attractive.

For overcoming poor functionality and controllability of prosthetic devices, *biomimesis* is an opportune for investigating novel forms and functions closer to biological models [5]. Biomimesis is the understanding of nature, its models, systems, processes and elements to emulate or take inspiration from these design and processes. Yoshida et al. [6] have reported the development of biomimetic prosthetic hand sensory system. Following a biomechatronic approach, design and fabrication of an active finger with two degrees of freedom (DOF) has been presented by Carrozza et al. [7]. Development of a EMG controlled prosthetic hand mimicking the dynamic properties of neuromuscular control is reported by Okonu et al. [8]. However, the functionality of

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the proposed hand is limited to a single DOF. An advanced five fingered, multisensory biomimetic prosthetic hand controlled by an intuitive myocontrol scheme is presented by Wang et al. [9]. Reported control system is concentrated towards individual finger control instead of emulating *grasp types* used during daily living activities (dla). None of these commercial and laboratory prototypes are near to the original levels of flexibility of human hand they intended to replace.

This paper presents the biomimetic design and development of an EMG controlled extreme upper limb prosthesis to achieve the kinematics of six different *grasp types* used during 70% of dla. Except for the functionality of the skin and abduction/ adduction movement of the fingers, Prototype 1.0 implements most of the human hand characteristics.

2 Design and Development of Prototype: 1.0

Biomimetic Approach: Through careful investigation of human hand physiology and biomechanics, we develop Prototype 1.0; the biomimetic approach as shown in Figure 1 is followed. The approach comprises of four important steps. In case of design

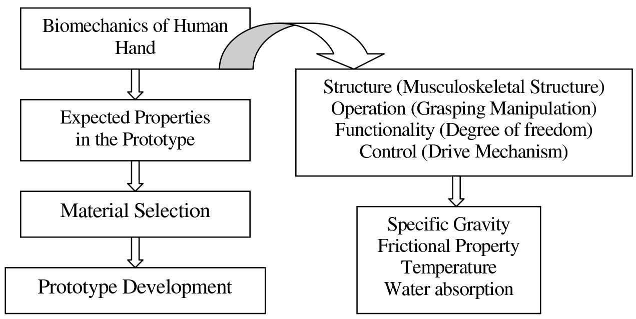

Figure 1: Biomimetic Design Approach for the Hand

of an upper limb prosthetic, it involves: a. study of biomechanics of human hand b. enlisting expected properties in the prototype c. material selection and d. prototype development. This process led to identifying the building blocks for Prototype 1.0.

Human Hand Physiology: The human hand has a complex anatomical structure consisting of bones, muscles, tendons, skin and the complex relationships between them. It consists of five digits: four fingers and one thumb. The fingers constitute of three interlinking segments: proximal, intermediate and distal phalanges. The thumb is made up of only the proximal and distal phalanges. The first phalanx is connected to the metacarpal bone. The metacarpal bones constitute the palm and are connected to the carpal bones. The movements of the carpal bones allow the hand to rotate with respect to the arm. The joints on the hand are named: distal interphalangeal (DIP), proximal interphalangeal (PIP), metacarpo phalangeal (MP) joints. Figure 2 shows the bones and joints of the hand.

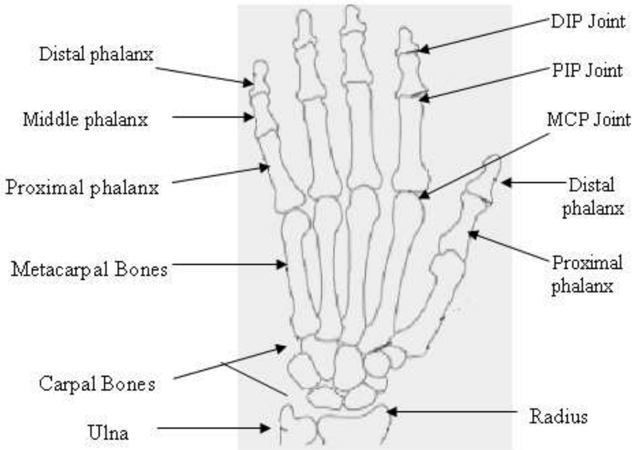

Figure 2: Bones and Joints of Hand

Each joint is characterized by the geometry of the contacting surfaces and by an angle of movement as illustrated in Table 1. The movements of the hand are of different kinds: each finger can move in the hand plane to go closer to the medial axis (adduction), can move far from the axis (abduction), can flex and extend. The thumb is able to move in opposition with other fingers along with abduction and adduction. All digits except the thumb has 3 flexion/extension and 1 abduction/adduction. The thumb is missing one joint therefore that makes a total of (4*4 + 3)= 19 DOF excluding the wrist. The wrist has 3 rotational DOF, hence the human hand have 22 DOF in total.

Table 1: Finger joint range of motion of Human Hand (in degrees) [10]

	Thumb	Index	Middle	Ring	Little
MCP (Abduction / Adduction)	0 to 90	-30 to 30	-20 to 20	-30 to 30	-30 to 30
MCP Flexion	0 to 100	-30 to 90	-30 to 90	-30 to 90	-30 to 90
PIP Flexion		0 to 110	0 to 110	0 to 110	0 to 110
DIP Flexion	0 to 90	0 to 70	0 to 70	0 to 70	0 to 70

Grasping and Daily Living Activities: Study of human *grasping strategies* to understand *cognitive* underpinning of constructing grasps based on *qualitative* abstractions have been undertaken [11]. Grasping strategies have been observed within different subjects and common *practices* identified. Six grasp types as shown in Figure 3 is sufficient for grasping strategies in 70% of dla [12]. Prototype 1.0 is designed to execute only the above six grasps.

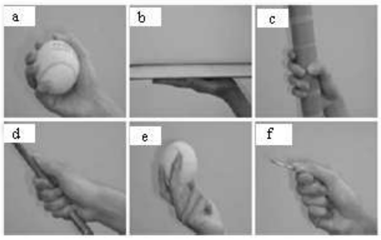

Figure 3: Grasp types: a. Power b. Palm-up c. Hook d. Oblique e. Precision f. Pinch

2.1 Proposed hand architecture

The proposed hand consist of five digits: four fingers and a thumb. Each finger consists of three links replicating the distal, middle and proximal phalanx. The links are connected through hinge joints corresponding to DIP, PIP and MCP joints. Thumb consist of two links. An extended knuckle structure at each link is provided to prevent the backward movement of the succeeding link. Extensor and flexor tendons are placed on the dorsal and ventral side of each finger and connected to individual actuation unit (a DC geared motor) embedded in the palm. All digits of the prototype can flex and extend in the joint range of the corresponding human digit as illustrated in Table 2.

Table 2: Finger joint range of motion of Prototype 1.0 (in degrees) measured using Jamar Plastic Goniometer

	Thumb	Index	Middle	Ring	Little
MCP Flexion	0 to 100	0 to 90	0 to 90	0 to 90	0 to 90
PIP Flexion		0 to 110	0 to 110	0 to 110	0 to 110
DIP Flexion	0 to 90	0 to 70	0 to 70	0 to 70	0 to 70

The palm is *two piece* and can move inward and outward to form grasp modes. Abduction and adduction is not implemented in Prototype 1.0. The wrist of the prototype is actuated though three DC motors placed in mutually perpendicular axes to produce three DOF. Index, middle finger and the thumb are driven by independent actuators. The ring and little finger are driven by a single actuation unit. The developed prototype possess a total of (3*3 of fingers + 3 of thumb + 3 of wrist) = 15 DOFs. CAD model of the prosthetic hand is shown in Figure 4; arrangement of the actuators and tendons as well as the digits of the prototype is seen in Figure 5.

Material Selection: Four materials: nylon, teflon, steel and aluminium are studied to build the skeletal structure of the prosthetic hand. Comparison has been done based on characteristics detailed in table 3 required to replicate the properties of the human hand [10]. From this tabular study, nylon and teflon are found to be bearing properties close to that of human hand. Finally, nylon is selected as a function of specific gravity and cost of material (Cost of nylon is five times lesser than that of teflon).

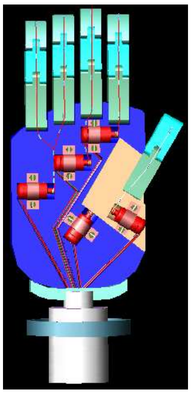

Figure 4: CAD model of Prototype 1.0

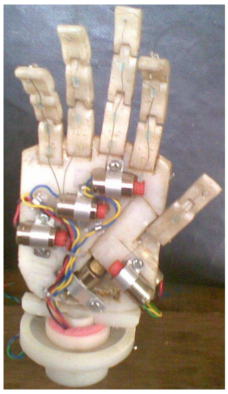

Figure 5: Ventral view of Prototype 1.0

Table 3: Characteristics comparison of the material under study

	Nylon	Teflon	Steel	Aluminium
Specific Gravity	1.13	2.15	7.85	2.64
Load bearing capacity	5800 psi	3400 psi	-	-
Frictional property	Low	Low	Medium	Medium
Water absorption	No	0.01%	-	-

3 Prototype 1.0

The building blocks of the human hand and that of the prototype are illustrated in Table 4. Table 5 shows the performance of a human hand and Prototype 1.0. [1]

3.1 EMG based control of prototype 1.0

Figure 6 shows the schematic diagram of EMG based control architecture. The fundamental units are the EMG Unit, Maximum Voluntary Contraction (MVC) unit, Normalization Unit, Feature Extraction Unit, Classifier Unit followed by the Driver circuit Unit. The EMG unit comprises of the amplifier, band pass and notch filter. The raw EMG signals extracted from the subjects [2] required processing to accurately record, display and analyze. The EMG signal obtained after filtration and amplification is the *Integrated* EMG (IEMG) signal. The Normalization unit applies MVC normalization on IEMG signals reproducing normalized IEMG signal (nIEMG). The feature vector is derived in the Feature Extraction unit using principal components of discrete wavelet transform derived features [For more details, see [13]]. The feature vector is fed to

[1] The volume of the prototype is measured dividing its weight by specific gravity of nylon.

[2] Two channel forearm surface EMG is collected from extensor digitorum, flexor digitorum, extensor carpi ulnaris and extensor carpi radialis longus muscle following the protocol detailed in [13].

Table 4: Building blocks of Human hand versus Prototype 1.0

Human Hand	Prototype
The skeletal of the hand	Links made of nylon as virtual skeletal of the hand
Set of muscles, which are embedded in between the skin surface and the skeleton	A set of DC geared motors embedded in the palm
Mass-spring system, inter-linking the skin, skeleton and muscle	A system of strings as tendons interlinking the joints
Joint hierarchy which matches the structure of the skeleton	A joint hierarchy which matches the structure of natural hand
Complex skin for the surface	Natural latex as virtual skin for aesthetic look only

Table 5: Performance of Human hand and Prototype 1.0.

Performance	Human Hand	Prototype
Number of DOF	22	15
Wrist Mobility	03	03
Total Volume	50 cc	47cc
Each finger length	92 mm	96 mm
Each finger diameter	14 mm	14 mm
Wrist width	65 mm	65 mm
Palm width and thickness	90 mm and 45 mm	90 mm and 45 mm
Total number of sensors	17,000	Not implemented
Total weight	400 gram	520 gram

the classifier, which comprise of a radial basis function kernel support vector machine with a 10-fold cross validator; clustering six grasp types in a single step. An average recognition rate of 97.5% is achieved. The 8-bit microcontroller in the driver circuit maps the actuation of motors reproducing the grasping operation. Figure 7 shows the Prototype 1.0 performing a *precision* grasp.

4 Final Comments

Design and development of a prosthetic hand which mimics the human hand both in geometry and function is presented. The prototype exhibits all the functionality except the abduction/ adduction movement of the digits. Replicating the complex skin structure with almost 17,000 sensors was not implemented. The extension and flexion of finger in the human hand is accomplished through a complex structure of mucous sheaths of the tendons on the front and back of the wrist. The prototype replicates these through two tendons (one for extension and one for flexion) connected to the

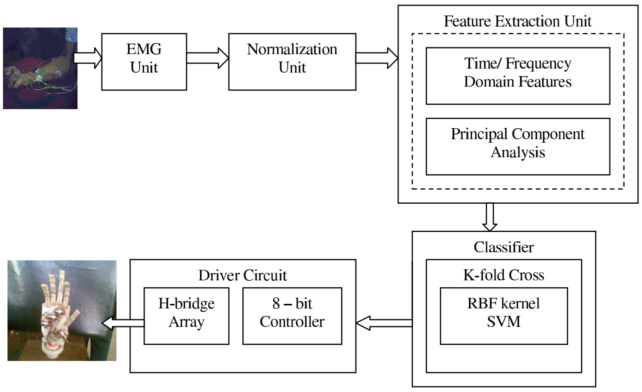

Figure 6: EMG based Control Architecture of Prototype 1.0

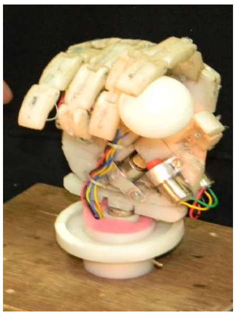

Figure 7: Prototype 1.0: performing precision grasp

actuators independently. During grasping operations by human hand, objects are hold firmly because of the palm prehension; which is achieved in the prototype by making the palm a two piece structure in order to have proper grasp modes. The human wrist is a complex structure with eight carpel bones of semicircular surface giving three DOF. This is achieved in the prototype by arranging three motors in mutually perpendicular axes attached to three concentric cylinders. The thumb mechanism in the prototype is a simplified version of the human thumb without implementing the abduction/ adduction which is necessary for most of the proper grasp modes.

Following an EMG based control architecture, the prototype reproduce the grasping operations involved during 70% of daily living activities with 97.5% accuracy. Embedment of the control circuit of the prototype is part of ongoing research.

Acknowledgments

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