RECENT J. (2026), 79:030-037
https://doi.org/10.31926/RECENT.2026.79.030

Study of the Current State of Bionic Hands Development

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Abstract

The purpose of this study is to explore the field of human upper limb rehabilitation, with an emphasis on solutions for replacing or recovering their functionality through prosthetic equipment. These are designed to take over the functions of the biological hand as similarly as possible in its absence. The paper includes a detailed description of the anatomy and biomechanics of the hand, essential elements in the research and development of new robotic devices for prosthetic or rehabilitation purposes, as well as in improving solutions available on the market. The performance of different types of actuators applicable in this context is also analysed, along with the results of relevant scientific studies, which were built on previous research and generated valuable data for future developments.

Keywords

bionic hand; pneumatic actuators; rehabilitation

1. Introduction

Bionics is an interdisciplinary science that combines biology with technology, taking the functioning principles of living organisms and translating them into technical solutions aimed at improving the quality of life. Robotics, in turn, is the field that materializes this knowledge, dealing with the design and construction of mechanical systems capable of replacing humans, partially or totally, in various technological processes. It is based on biomechanics, the science that studies the application of the laws of mechanics to living organisms.

The hand is a complex segment of the human upper limb, connected by the wrist to the forearm and consisting of five fingers. Its importance lies both in its role as a manipulation organ with multiple sensory functions, and in its role as a means of expression and communication. Through gestures, the hand enriches the message transmitted in social interactions, and for people with hearing impairments it represents the only means of communication.

Existing solutions for prosthetic and rehabilitation devices are constantly evolving, with a constant need for diverse and innovative approaches to enhance the quality of products offered to users. In this context, this article centralizes data on the anatomy and biomechanics of the hand, as well as the results of recent works on the current state of knowledge in the field, with the aim of facilitating the development of future solutions.

2. Anatomy and Biomechanics of the Hand

To understand existing solutions and the current state of development, first it is necessary to know the system they aim to reproduce. The hand is a complex anatomical structure, made up of bones, muscles, ligaments, tendons and nerves, all contributing to its optimal functioning, defined by flexibility and precision.

In order to transpose the shape and functionality of the hand into a technological context, its skeleton, which constitutes the supporting framework of the entire structure, must be analysed. It is formed by the carpal bones — a set of eight bones, namely the trapezium bone, the metacarpal bones, five in number, and the phalanges, which compose the fingers. The thumb is formed by two phalanges, while the other fingers are composed of three tubular bones each.

The thumb plays an essential role in the ability to grasp and manipulate objects. It is the only finger capable of opposing the other fingers, moving in three planes. This special mobility is conferred by the trapezius bone, onto which the metacarpal of the thumb is joined.

For a 3D-analysis of the hand, its movements can be related to the anatomical position of the body (Figure 1) and to the anatomical reference planes of the hand.

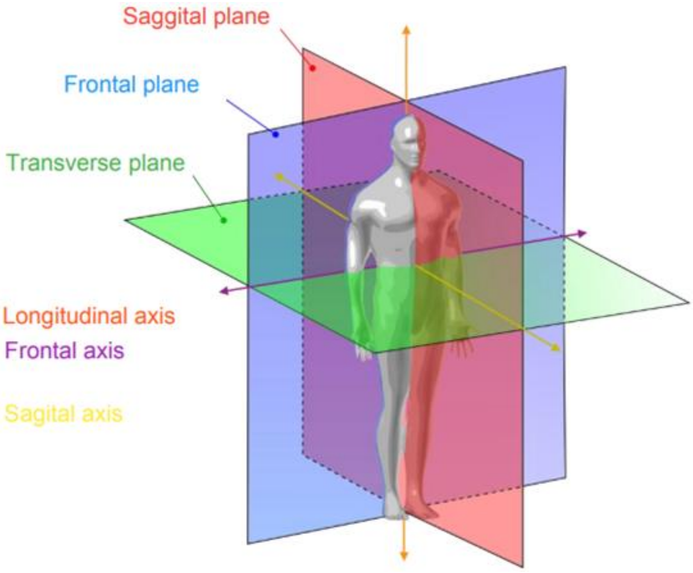

Fig. 1. Anatomical position of the body

A more in-depth analysis of finger movement considers the three anatomical planes of the hand: the medio-frontal (coronal) plane, which delimits the dorsal and palmar surfaces; the medio-sagittal plane, which separates the ulnar and radial parts; and the medio-transverse plane, which marks the separation between the proximal and distal regions, as shown in Figure 2. These planes are used to define the direction of finger movements relative to a reference point. In the case of the thumb, adduction and abduction movements occur in the sagittal plane, and flexion and extension in the frontal plane. The opposition movement conducted only by the thumb is a combination of flexion and abduction. For fingers II–V, adduction and abduction movements occur in the frontal plane — abduction representing the finger's distancing from the sagittal plane, and adduction its approach — while flexion and extension occur in the sagittal plane, with flexion being the movement toward the transverse plane, and extension the movement in the opposite direction.

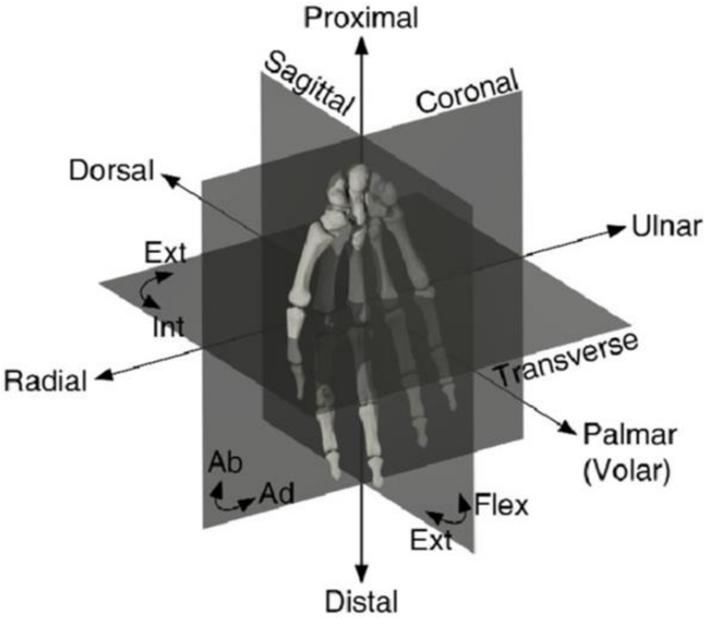

Fig. 2. Anatomical planes of the hand [1]

In order to measure the amplitude of finger movement, an initial reference position was established, namely the one in which the fingers are extended and aligned with the metacarpal bones. Movement can be active, achieved through the individual's own strength, or passive, caused by external forces.

Fingers II–V consist of four bones each: the metacarpal bone and the three phalanges — proximal, middle, and distal — interconnected by three joints. The joint between the metacarpal bone and the proximal phalanx is called the metacarpophalangeal (MCP), the joint between the proximal and middle phalanx is called the proximal interphalangeal (PIP), and the joint between the middle and distal phalanx is called the distal interphalangeal (DIP). These are represented in the image below (Figure 3).

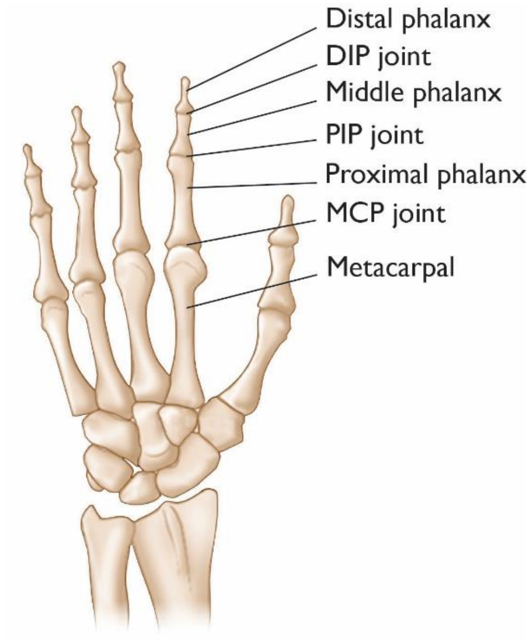

Fig. 3. Finger joints II-V

The middle phalanx is absent in the thumb, and therefore the proximal interphalangeal joint is also absent. The amplitude of active flexion of the MCP joint for fingers II–V increases progressively, from approximately 90° at finger II (index) to 110° at finger V (little finger), extension being achieved by returning the finger to its original position. Abduction-adduction movement is possible exclusively at the MCP joint, and its amplitude varies depending on individual joint flexibility; the average value of abduction is between 30° and 40°, adduction representing the return of the finger to the reference position. Flexion of the PIP joint has an average amplitude of approximately 100°, and that of the DIP joint of approximately 70°. Passive movement can increase the amplitude of certain movements by approximately 10°.

The movements of fingers II-V are shown in Figure 4.

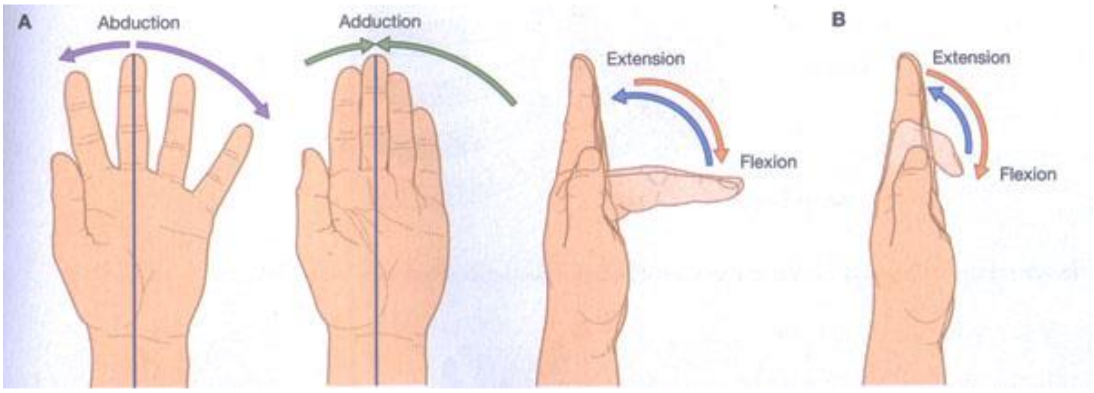

Fig. 4. Movements of fingers II-V [2]

The amplitude of thumb movements can be determined by measurements related to two reference axes (Figure 5). The abduction-adduction movement, through which the thumb moves away from or towards the index finger, is measured relatively to the anteroposterior axis, its amplitude being approximately of 35°–40°. With respect to the radioulnar axis, the opposition-reposition movement is measured, which consists of the thumb approaching or distancing from the other fingers and involves a 90° rotation combined with flexion of the MCP joint.

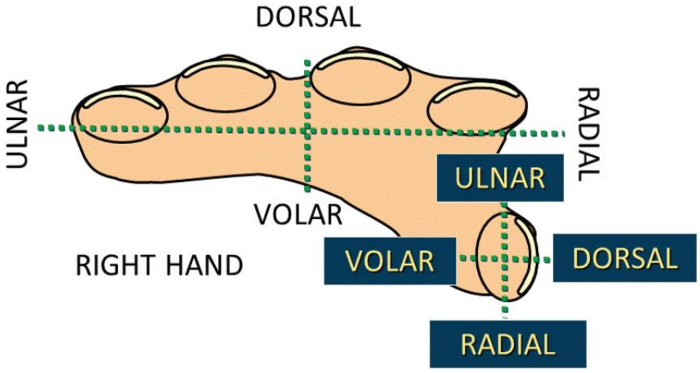

Fig. 5. Thumb axes [3]

Fig. 6. Thumb movements [4]

3. Bionic Hands

Being a subject of continuous interest for researchers, numerous bionic hands have been designed over time, both for prosthetic and rehabilitation purposes. The main factor influencing their performance is the actuation mode, since, depending on the targeted application, actuators may have well-defined limitations.

The most widely used actuators in robotics are electric and pneumatic, due to their affordable production and acquisition costs, as well as their continuously improving technical performance. In the design phase of robotic hands, anthropomorphic characteristics — such as dimensions, weight, influenced by the materials and components used, and the control system, which must ensure the necessary force and precision of movement — must be correlated with the needs of the users.

The current limitations that prevent the widespread adoption of robotic hands mainly concern the difficulty of compactly integrating actuators and sensors, as well as the high cost of devices available on the marketplace, which restricts their use predominantly to experimental studies. Numerous experiments have been conducted to reproduce hand movements, embodied in anthropomorphic structures with different degrees of freedom. Their actuation has been achieved by various methods: pneumatically actuated soft elements, tendons and ties actuated electrically by linear motors or pneumatically by pneumatic muscles, as well as structures directly actuated by electric motors [5].

Tendon actuation involves the use of wires made of materials with high tensile strength and high flexibility, inserted into the structure of the finger to simulate the function of the natural tendon. By actuating them, the finger performs the flexion movement, imitating the fine movements of human fingers. The main advantages of this method are its relatively simple implementation and the ability to reproduce the kinematics of the fingers almost identically. The disadvantages consist in the accelerated wear of the tendons due to their being pretensioned for correct operation, as well as in the high maintenance costs due to the complexity of the structure.

The actuation by means of linkages is achieved through rigid elements made of metal or polymers resistant to mechanical stress, which transmit the movement from the motor to the finger. The advantages of this solution consist in the ease of manufacturing and maintenance, while the main disadvantage is the difficulty of obtaining movements with many degrees of freedom, the dimensions of the components leading to an increase in the overall dimensions of the assembly.

In the case of direct actuation by a motor, micromotors are integrated into the structure of the bionic hand, which allow individual control of each finger, offering a high degree of precision and autonomy. The disadvantages are related to the fact that both the dimensions and the performance of the assembly directly depend on the motors used, whose own weight can generate high inertia, affecting the control of the robotic hand. At the same time, using quality motors comes at significant costs, which makes it difficult to achieve an affordable assembly.

Pneumatic actuators can be of pneumatic motor or pneumatic muscle type, both categories using a compressor as a power source. This represents the main disadvantage in robotic hand applications, due to the considerable size of the equipment. Pneumatic muscles are frequently used in both robotics and medical applications due to their special feature known as compliance; this allows conducting linear movements similar to those generated by human muscles. Muscles are also efficient, non-polluting pneumatic consumers with a remarkable power-to-volume ratio. Disadvantages include the relatively large volume, limited stroke — maximum 25% of the muscle length — and the need for expensive additional equipment to increase control precision.

Further on some of the analysed applications are presented in order to illustrate the information presented above.

3.1. Applications using electric actuators

A relevant example is an underactuated finger where the number of degrees of freedom exceeds the number of actuators [6]. The finger shown (Figure 7) is composed of four rigid bodies and three joints (Metacarpophalangeal joint - MCP, Proximal Interphalangeal joint - PIP and Distal Interphalangeal joint - DIP). The entire system is underactuated, the motion being generated from a linear electric motor. The PIP and DIP joints operate dependently through two four-bar mechanisms.

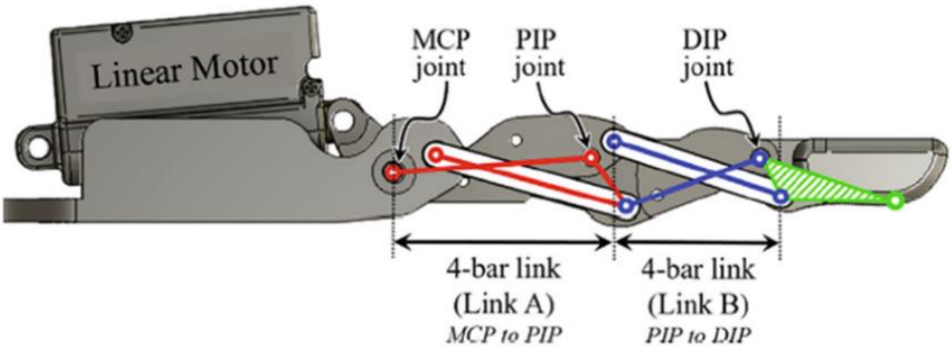

Fig. 7. Electric underactuated finger (with linkages) [6]

Savic et. al. [7] proposed a robotic hand adaptive to the shape of the object to be grasped (Figure 8). This is possible due to a mechanism actuated by tendons and torsion springs located in each finger joint. The flexion mechanism of each finger is driven by a direct current (DC) motor, which constitutes the active actuator. The extension function is ensured by torsion springs operating as passive antagonist elements. This hybrid architecture, based on tendons and elastic elements gives the system a passive compliance, facilitating morphological adaptation to the geometry of the manipulated objects.

Another application that demonstrates the potential of innovative solutions based on electrical components is a study dedicated to a bionic hand controlled by electromyographic (EMG) signals [8]. These signals are generated by the electrical activity of muscles during movement and are captured using electrodes fixed to the skin surface. Characterized by frequency, amplitude and duration, the recorded signals were used to control a bionic hand built from 3D printed components, which successfully reproduced the recorded movements (Figure 9).

Fig. 8. Hand and finger structure [7]

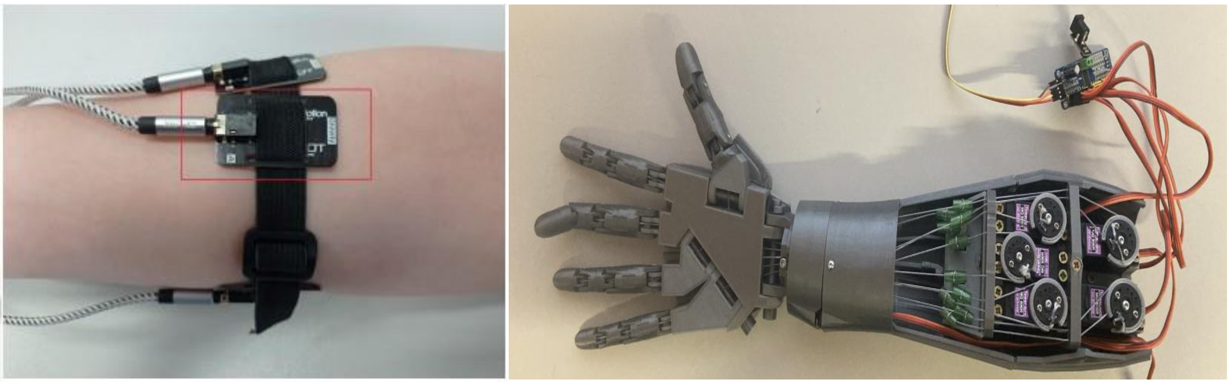

Fig. 9. Electrodes (left) and bionic hand (right) [8]

This study concluded that data acquisition and the establishment of extensive databases involve a considerable financial effort, while the quality of the recorded signals depends largely on individual physiological characteristics, such as the size of muscle fibres, which vary from one person to another.

In conclusion, electric actuators offer significant advantages in terms of control accuracy and signal processing capacity, but have disadvantages related to the high acquisition costs of components, equipment and databases, as well as to their sensitivity to external factors.

3.2. Applications using pneumatic actuators

The first presented example (Figure 10) is an exoskeleton glove powered by pneumatic muscles and tendons, designed to reduce tremor amplitude [9]. It is equipped with one pneumatic muscle for each finger and with caps equipped with tactile sensors at the fingertips. The sensors are designed to determine the dominant frequency of the tremor through a signal acquisition device, after which the pneumatic muscles are activated depending on the amplitude of the movement, in order to attenuate the detected tremor.

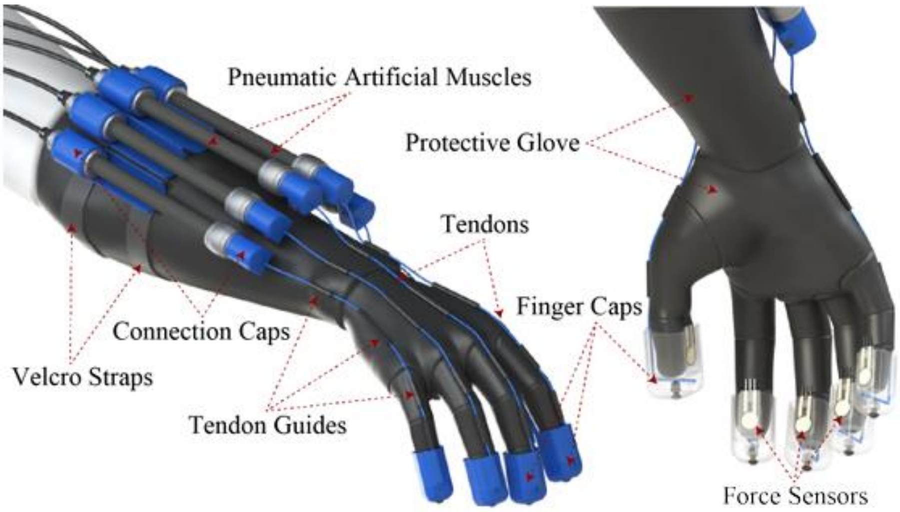

Fig. 10. Exoskeleton glove [9]

Another example of a robotic hand powered by pneumatic muscles and tendons is a device of a similar construction to the human hand, in which each finger is individually powered by a pneumatic muscle, via a steel wire (Figure 11) [10].

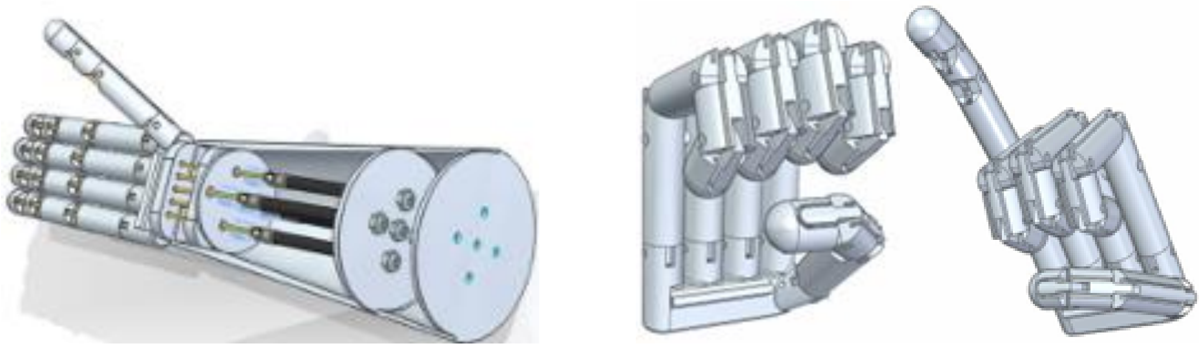

Fig. 11. Construction of the robotic hand (left); examples of gestures performed (right) [10]

Soft actuators work similarly to pneumatic muscles, having a flexible tubular body with varying sections depending on the desired movement. They are known for their adaptability and dexterity in interacting with the environment, being able to perform varied and reversible movements. The main disadvantages are their nonlinear behaviour, which makes precise control difficult, as well as their low load capacity, which makes them unsuitable for handling heavy objects.

The operating principle of soft actuators can be illustrated by the example of a soft finger (Figure 12), made by combining flexible and elastic elements with rigid ones, in order to control the direction of movement [11]. The flexible joint consists of multiple air chambers, the layer of material that is oriented in the direction of flexion being non-deformable. The assembly bends in the desired direction proportional to the pressure of compressed air applied.

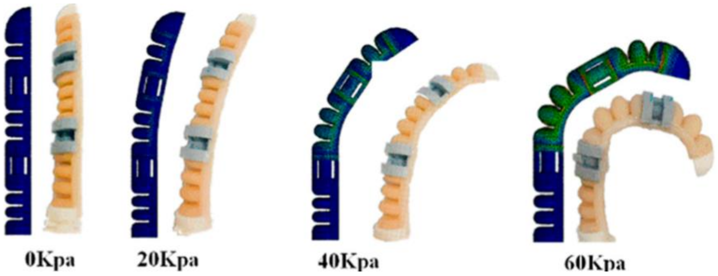

Fig. 12. Soft finger [11]

4. Conclusion

The bionic hand has been and continues to be a topic of interest for researchers concerned with the design and construction of prostheses and/or rehabilitation devices similar to the human upper limb. Although numerous studies and experiments have been carried out in order to develop robotic hands with an optimal structure, there is still a need to improve existing solutions, especially in terms of reducing manufacturing costs, while respecting anthropomorphic characteristics adapted to the needs of users.

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