Advances in Finger Prosthetic Mechanisms

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Approximately 70% of the upper extremity amputations refers to partial hand loss with the involvement of one or more fingers. Historically, this type of limb amputation has been addressed adopting simple opposition designs that use the movement of the residual digit for grasping against a fixed device. Nevertheless, in the last few years, technological advances, and the introduction of modern computer-aided tools for the synthesis and functional design of mechanisms have led to the development of smaller, more robust systems that are constantly improving body-powered and electrically-powered prototypes.

prosthetic fingers | partial hand prosthesis | robotics | functional design | mechanism analysis | underactuation

1. Introduction

The development of a prosthetic finger or partial hand must necessarily have as its foundation the anatomical study of the human counterpart allowing the complete recovery of the natural functions of the latter's residual limb. The complexity of the hand, and consequently of the fingers, lies in the compactness and small size that it presents in front of a high dexterity, through which numerous grasping modes are allowed. These features are implemented by the human hand with tendons that transmit the motion generated by remote muscles, located in the forearm, to the various joints of the finger phalanges, as explained in more detail in Section 2. Whereas many recent reviews have been presented that refer to the design of complete robotic hands [1][2][3][4] and grasping research trends [5][6], to the best of the authors' knowledge a survey devoted specifically to the mechanisms used for finger and partial hand prosthetic or rehabilitation has not been presented in the literature. Various cutting-edge solutions that use both in body-powered and extracorporeal energy prostheses will be surveyed: the objective is to generate a solid knowledge base about the multitude of existing systems detailing advantages and disadvantages. It represents the starting point for the study and development of all prosthetic solutions that can be developed to advance the current state-of-the-art. To this aim, mechanisms derived from full prosthetic hands and that can be of interest for single finger implementations are also listed.

2. Technical Requirement Definition and Analysis

2.1. Functional Characteristics

There are three major types of bones in the hand [7][8] including: phalanges, metacarpal and carpal bones. Numerous muscles, ligaments, tendons, and sheaths can be found within the hand. The muscles are the structures that can contract, allowing movement of the bones in the hand. The ligaments are fibrous tissues that help bind together the joints in the hand. The sheaths are tubular structures that surround part of the fingers. The tendons connect muscles in the arm or hand to the bone to allow movement. In addition, there are arteries, veins and nerves within the hand that provide blood flow and sensation to the hand and fingers. The high dexterity of the hand and fingers is implemented through tendons that transmit the motion generated by remote muscles, located in the forearm, to the various joints of the finger phalanges (Figure 1). The fibrous sheaths hold tendons in position and close to the bones.

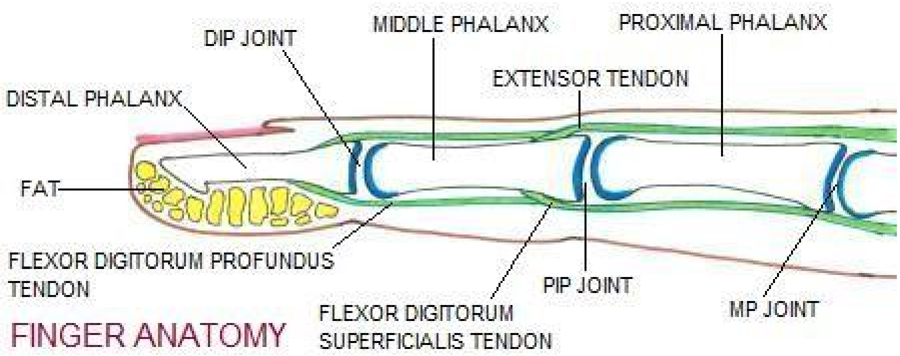

Figure 1. Finger anatomy [8].

Setting aside medical/anatomical aspects that can be found in many dedicated references, e.g., [9][10] and in the pursue of an engineering functional scheme, each of the hand fingers can be seen as composed of three phalanges, except for the thumb which has two but in addition it shows a more complex mobility solution thanks to the two dofs of the trapeziometacarpal joint. All the digits are connected to the metacarpals by five MCP (metacarpophalangeal) joints. What previously said results in a model of hand that features twenty-one degrees of freedom (dofs), without the six dofs needed to position and orientate the hand in the reference system, three of which in the wrist, since the following exposition will focus on the fingers.

Amputation of a part of a hand may involve functional limitations for the amputee that are not easy to recover by orthoses or prostheses [11]. Loss of portion of hand occurs through trauma or congenital skeletal deficiencies: the former usually occurs along a straight line instead for the latter case the pattern of absence is quite variable but usually different. Patients who suffer transphalangeal amputation need no device but may desire cosmetic fingers; thumb amputation can be recovered with prosthetic thumb; distal transmetacarpal amputee search both cosmetic hands and functional devices same as proximal metacarpal amputation patients. The conventional approach to designing anthropomorphic prosthesis often involves mechanizing biological parts. This method inevitably introduces undesirable discrepancies between the human and robotic hands. The larger the level of finger amputation, the higher the extent of dexterity loss.

During manual activities, fingers are typically used to push, pull, and manipulate objects. The finger force is demonstrated to vary in a range of 30 to 110 N, respectively, from the little finger to the thumb capable of exerting the maximum force [12]. In fact, it can be estimated that the relative contribution of each finger to the total four finger force was approximately 41% (index), 32% (second), 20% (third) and 7% (fourth). In addition, a simple qualitative analysis of the hand structure reveals that the fingers are all different length and widths [13]. In addition, there is not an equal distribution of surface area on each finger and this may affect the contact stress, and subsequent force contributions of each digit.

2.2. Grasp Characteristics

- Natural motion: the prosthesis must emulate the closure as much as possible than an anthropomorphic hand. This ability is referred to as pre-shaping of the finger when contacting with an object (Figure 2).
- Shape-adaptivity: the stability of each grasp pattern greatly depends on this characteristic that is often obtained with an underactuated mechanism.
- Pinching motion: the distal phalanx remains straight or rotates in counterclockwise direction; so, the fingertips of index and thumb are in front of each other. It results in an efficient grasp for thin objects like keys or papers (Figure 3).

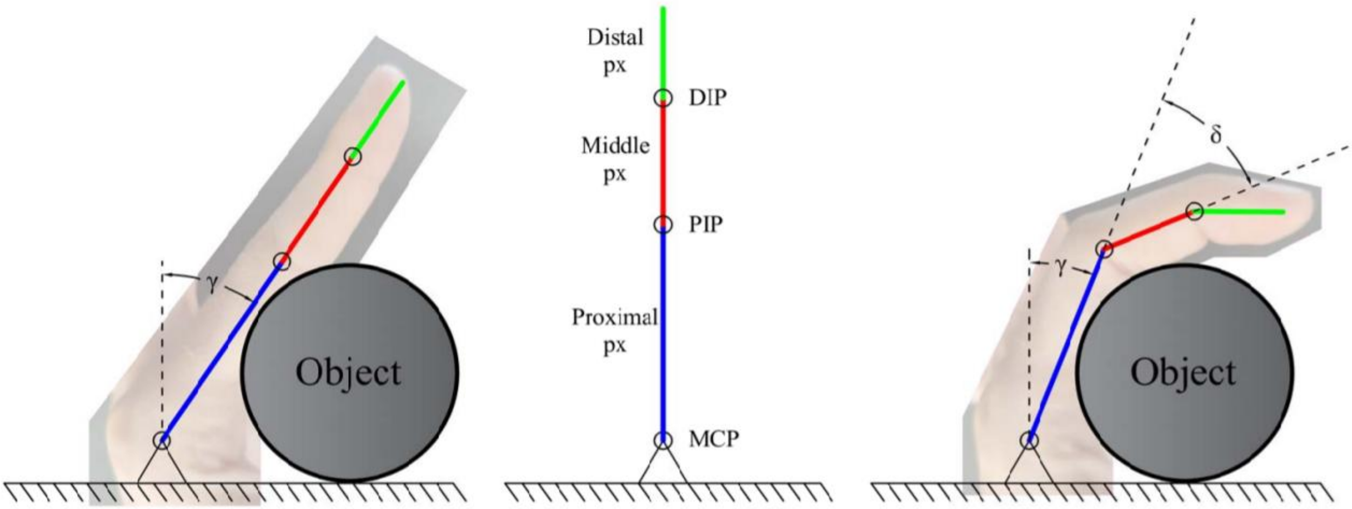

Figure 2. Prosthetic finger without (**left**) and with pre-shaping ability (**right**).

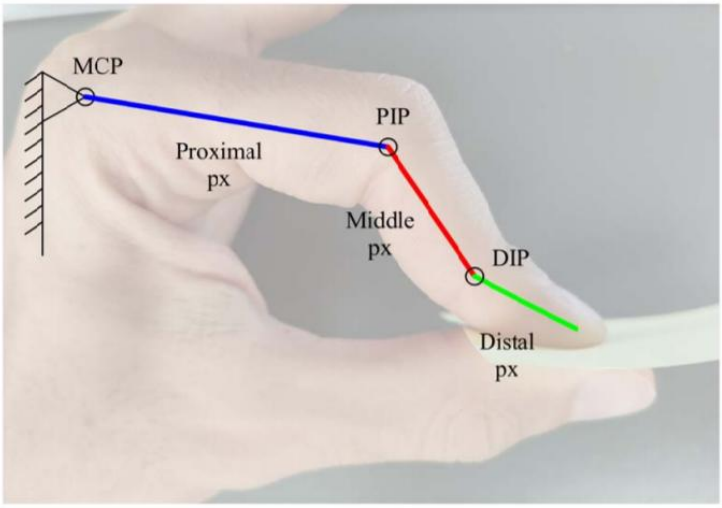

Figure 3. Pinching grasp modality.

- Stability: objects need to be grasped and manipulated safely with different shapes and surfaces without failures, avoiding the ejection phenomenon (i.e., negative contact forces).
- Force isotropy: grasping should be fulfilled with a uniform distribution of forces, which allows for example a light and stable grip of fragile objects. It is a significant feature for the prosthetic finger mechanisms that adapt to the shape of the object's body.
- Workspace: it depends on the number and length of the phalanges with which the prosthetic finger is modeled. Most prostheses show a planar movement.
- Stiffness: it is the relationship between the actuation torque and the phalanx movement considering the forces exerted by the object.
- Bond and adjustment (for body-powered devices): the residual finger must be wrapped effectively by the prosthesis and be able to drive the prosthetic finger as a natural extension with an efficiency ratio as close as possible to the unit.
- Accuracy in the required tasks.
- Time of extension and bend motion.

2.3. Physical Characteristics

- Weight: the lighter the better.

- Number of phalanges: it results from a trade-off between the increase in the number of components making up the prosthesis, the improvement of the setting performance and the increase in complexity.
- Compactness: it is defined as the ratio between the width and length of a finger. It is ideal to achieve a ratio like human finger.
- Design flexibility: it is recommended versatility to the uniqueness of the user (finger size, size of components making up the prosthesis).
- Biocompatible materials that avoid irritation due to prolonged use.
- Appearance: the amputation of the upper extremities involves a change in the external appearance that can lead to psychological problems in the acceptance of one's condition.
- Manufacturing process: it provides a prosthesis with the best values of the above parameters at the most competitive cost considering the various production processes.
- Noisiness: the purpose of all prosthesis is to provide the functional result without attracting undue attention to the user.

3. Conclusion

In conclusion, future research should be devoted to develop new body-powered prototypes that can outperform existing state-of-the-art solutions. One notable example is that developed by Y. Choi e D. Yoon [14], showed in the first row of Table 7, that is the only one-dof body-powered prosthesis, which ensures both a natural motion and a shape-adaptive grasp thanks to its underactuated mechanism. However, the patent results in a bulky, asymmetrical solution, and it is not suitable for manipulate fragile objects. As matter of fact, the success of grasping largely depends on the bearable critical load of the torsional springs before they compress and permit curling motion.

The second prototype family of interest is that developed by Naked Prosthetics, which provides a different solution for what concerns the number of digits, price, drive joint, aesthetic appearance, and anchoring. They are not as complex as the one strengthened by Y. Choi e D. Yoon even though they permit natural motion with a lower number of components, earning in compactness and lightness. These devices try to solve the wrap problem of residual fingers with the use of circular shims that represents a potential weakness and a field for future improvement. All Naked Prosthetics devices comprise a linkage system, tip pad for interaction with touch screens, nails for both aesthetic appearance recovery and rehabilitation of scratching and peeling functionalities.

Shape-adaptability in [14] is achieved via underactuation using springs. The set of solutions to achieve the same goal is wide. An alternative and maybe better proposition could be the use of different type of passive elements that overcome the disadvantages of springs or adopt an hybrid solution like the DPGS by Koganezawa [15] or the one by MacDuff [16][17] that integrate tendon-cables to improve curling motion. Furthermore, only few prototypes have implemented a precision pinching grasp [18][19] but all of them are externally powered.

Therefore, future prostheses will have to face the challenge to design a solution that addresses all the above-mentioned aspects.

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