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Research paper

Design and synthesis of a 2 DOF 9-bar spatial mechanism for a prosthetic thumb

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ABSTRACT

In the last two decades, different prosthetic hands have been developed. However, little attention has been given to thumb designing. This paper presents the design and kinematic synthesis of a new 2 DOF 9-bar spatial mechanism that can be used as a prosthetic thumb focused on emulating the 5 movements of human thumb joints. The mechanism replicates the movements of the interphalangeal (IP), metacarpophalangeal (MCP) and carpometacarpal (CMC) joints, with the limitation that only the movements of the CMC joint are independent and the movements of the remaining joints are dependent on CMC movements. All the links of the mechanism are contained within an anthropomorphic shape, and its tip is capable of generating a 3D surface as working envelope. These features are the result of combining the mathematical representation of a deep knowledge of the kinematics and anthropometry of the thumb with techniques of optimal synthesis and spatial mechanisms design.

1. Introduction

The thumb plays a key role in the function of the hand. Thumb opposition and the amplitude of this movement enables the hand to execute its essential function: prehension. Without the thumb, the hand loses most of its capabilities [1]. Prosthetic thumbs play an analogous role in prosthetic hands. In [2], prostheses that featured a high number of joints, thumb circumduction and flexion, achieved more kinds of grasps in comparison with those that did not have these characteristics. A similar result obtained in robotic hands field is observed in Robonaut Hand [3,4]. An increase from 50% to over 90% in its capacity to emulate Cutkosky's grasp taxonomy [5] was the result of an increment in the number of joints and Degrees of freedom (DOF) in its thumb. In summary, artificial or not, a thumb plays a key role in the performance of a hand.

Anatomically correct hand kinematic model, low weight, human-like appearance, and high grasping function are goals in mechanical design of prosthetic hands. Because of the size and weight for practical prosthetic hands are limited, usually there is a trade-off between the goals. In this context, thumb's structure can be modelled as a spatial 5R serial chain with 5 DOF [6,7], a prosthetic thumb with the same number of DOF than its human analogue would be desirable. In order to actuate each DOF at least one actuator would be necessary. However, as shown in [2], prosthesis weight is associated with the number of actuators. In consequence, a trade-off between an anatomically correct thumb kinematic model and a low weight prosthesis arises. If the number of DOF is simplified, then the kinematic model must be simplified in its number of independent movements, number of joints or in the direction of its joints rotation axes. According to [8], 2 DOF is the

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Nomenclature

x_{lm}	Distance from the origin of the basis $\{i_l, j_l, k_l\}$ to the origin of the basis $\{i_m, j_m, k_m\}$ along the i_m axis
y_{lm}	Distance from the origin of the basis $\{i_l, j_l, k_l\}$ to the origin of the basis $\{i_m, j_m, k_m\}$ along the j_m axis
z_{lm}	Distance from the origin of the basis $\{i_l, j_l, k_l\}$ to the origin of the basis $\{i_m, j_m, k_m\}$ along the k_m axis
β_{lm}	Angle of rotation from the basis $\{i_l, j_l, k_l\}$ to the basis $\{i_m, j_m, k_m\}$
$\mathbf{T}_{lm}$	Homogeneous transformation matrix between the basis $\{i_l, j_l, k_l\}$ and $\{i_m, j_m, k_m\}$
$[\mathbf{D}_{1j}]$	Relative displacement matrix from the $1st$ position to the $j-th$ position of the mechanism

minimum necessary to perform a range of prehensile tasks, by replicating the combined mobility of the CMC and MCP joints.

Movements of human thumb's kinematic model can be maintained with few DOF by making some of the movements dependent on others and by linking these movements through a mechanism. Although the advantage of maintaining the movements with few DOF is valuable, a challenge arises when trying to contain the mechanisms inside an anthropometric shape. The idea of coupling movements of finger joints has been adopted by various researchers to design mechanical fingers [3,9,10] and finger exoskeleton [11,12] based on planar kinematic chains. Although thumb's structure can be modelled as a spatial 5R serial chain with 5 DOF, the design of a prosthetic thumb based on a spatial kinematic chain has not been addressed. To date, the design of prosthetic thumbs is based on planar kinematic chains with inaccurate directions of circumduction axis and 1 or 2 DOF either passive or active [2,8,13–15].

To summarize, since the simplifications in the kinematic model, the number of actuators, the DOF and the number of joints determine the type of grasps that the prosthesis can achieve, the big challenge in prosthetic thumbs designing is to achieve a balance between these characteristics.

Seeking to preserve thumb's spatial nature, and to achieve a balance between simplifications in thumb's kinematic model and its number of DOF, this paper presents the design and kinematic synthesis of a new 2 DOF 9-bar spatial mechanism that can be used as a prosthetic thumb focused in emulating the 5 movements of the human thumb.

2. The structure of the thumb

As indicated by Kapandji, Bullock et al., and Santos and Valero-Cuevas [1,6,16], the structure of the thumb is composed of the carpal and metacarpal bones, and the distal and proximal phalanges. The structure features 5 DOF: 2 in CMC, 2 in MCP joint and 1 in IP joint, Fig. 1a. CMC and MCP joint can perform abduction-adduction and flexion-extension movements, IP joint can only perform extension-flexion movement, Fig. 1b. According to [6,16], flexion-extension axis of the three joints are not parallel, and abduction-adduction and flexion-extension axes of CMC and MCP joints are non-orthogonal and non-intersecting.

3. Methodology

In this section, the simplifications made over thumb kinematic model to develop the prosthetic thumb are described. After, the proposed RRSSRRSSSRS mechanism and its mathematical model are introduced. And finally, the optimal kinematic synthesis of the RRSSRRSSSSRS mechanism is established.

3.1. Simplifications

Next simplifications were taking into account for developing the prosthetic thumb: CMC and MCP abduction-adduction and flexion-extension axes were considered orthogonal and intersecting, CMC and MCP flexion-extension axes could be contained by a plane and, finally, IP and MCP flexion-extension axes were considered parallel to each other. With the purpose of using only two actuators and to link the movements of the joints, CMC movements are considered independent and movements of IP and MCP joints were considered dependent on CMC movements.

3.2. Proposed mechanism

Different technologies or kind of transmissions are available to link movements of prosthetic fingers and thumbs. To date, all of them are based on planar linkages or planar tendon-driven mechanisms [2,8–10,13–15]. In this work a 2 DOF 9-bar RRSSRRSSSRS spatial mechanism was proposed to be used as a structure and transmission element of a prosthetic thumb Fig. 2. The RRSSRRSSSRS preserves human thumb spatial nature and is able to emulate the movements of CMC, MCP and IP joints.

Carpal and metacarpal bones are represented by links 1 and 4, while proximal and distal phalanges are represented by links 7 and 9. MCP and CMC joints consist of two sets of universal joints, whose axes can be orthogonal or non-orthogonal and intersecting or non-intersecting. IP joint consist of a revolute joint. IP and MCP flexion-extension depend mainly on