Design methodology for a multifunctional hand prosthesis

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Abstract—The first part of this paper reviews different approaches to define the motion of the fingers and the thumb in order to obtain prehension. The last part presents the design of a hand prosthesis based on a new plane of action for the thumb and on proposed design specifications and functional characteristics. The design methodology consists of two steps: the morphology design of the hand prosthesis and the 4-bar mechanism design for each finger. A 3-D computer-aided design (CAD) interactive program was used as a design tool to obtain the hand morphology. This CAD technique was also used to check the geometry, the relative motions of the fingers, and the possibility of interference for the proposed model with two prehension patterns (tridigital and lateral). It is noted that identical flexion angles of the finger joints were obtained for these two prehension patterns, the difference being in the inclination angle of the thumb's plane of flexion. This finding greatly simplified the design of the internal mechanisms of the fingers. CAD was a powerful tool in the design process of this hand prosthesis and will be more and more useful in the future.

Key words: *biomechanics, computer-aided design (CAD), design methodology, hand prosthesis, prosthesis.*

INTRODUCTION

The aim of this joint project of the École Polytechnique de Montréal and the Institut de Réadaptation de Montréal is to attempt to overcome the major functional prehensile weaknesses generally associated with the "pincer type" conventional hand prosthesis (1). We believe that these weaknesses are related to their pattern of prehension, which requires a great amount of body and arm compensatory movement and prevents a proper orientation and stabilization of the object being held.

Results of a study conducted at the Institut have shown that these weaknesses can be greatly reduced if the hand is designed around the most essential movements of the thumb. It was shown in an ergonomic analysis of prehensile activities with daily used objects that, despite its five degrees of freedom, the natural thumb uses a preferred plane of motion. As shown in **Figure 1a**, this plane of motion intersects the plane of flexion of the middle finger in the plane of the palm, with an angle ranging from 45 to 55° (2). In this design, an angle of 45° has been selected.

With conventional pincer type prostheses, such as the Otto-Bock hand, as well as with multifunctional hand designs such as the SWEN hand (3), the Belgrade hand (4), or the Northern Electric Hydraulic hand (5), the tridigital grip or the opposition of the thumb with the first and second fingers has traditionally been obtained from their motions in parallel planes (**Figure 1b**). An exception to this trend is the cable-operated hand, called the OBEU Hand, developed by Davies et al. of the Orthopaedic Bio-Engineering Unit, Edinburg (6). Within the OBEU, all fingers are flexed at a single

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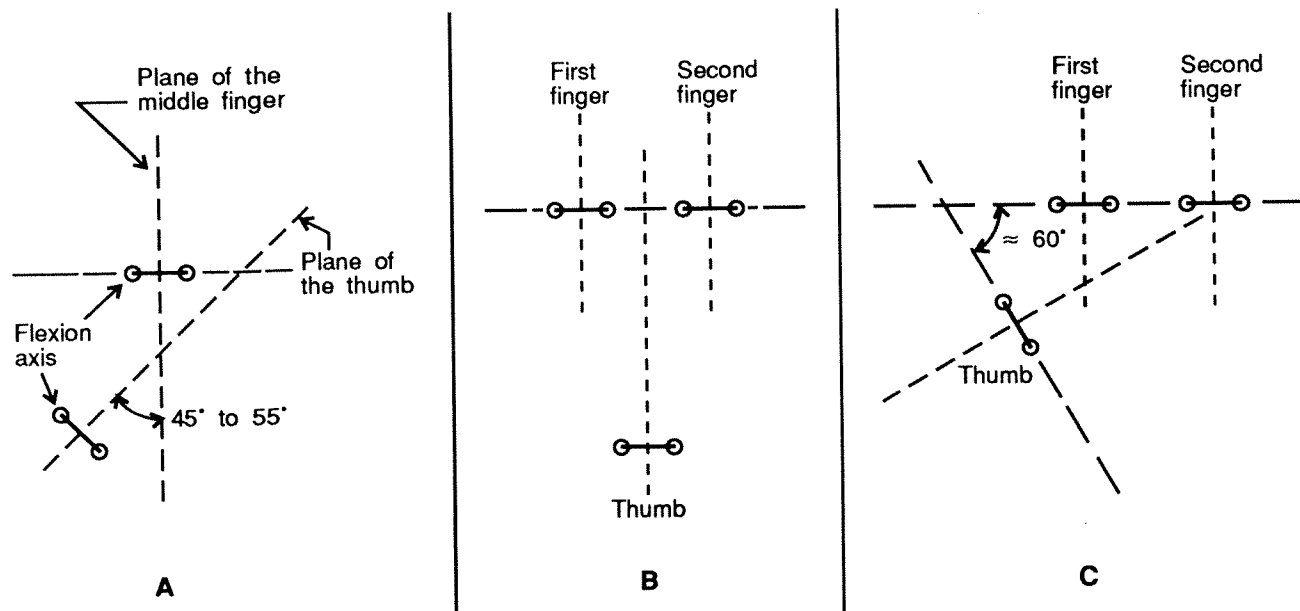**VINET et al.   Design Methodology for Prosthetic Hand**

Figure 1.
Schematic representation of different approaches in the plane of the palm, or palmar view of left hand: A) Study of Lozac'h on the preferred working plane; B) Conventional prostheses, parallel planes of action; C) Study of Davies, et al. on the OBEU hand.

joint and the thumb flexes around an axis inclined at an angle of approximately 60° to the first and second finger axes, which are parallel (**Figure 1c**). The OBEU group has reported improvements in both cosmesis and function.

The design of a multifunctional hand prosthesis around the most essential movements of the thumb obviously requires a different approach from that of conventional prostheses. The geometry of the palm and joints, together with the relative motions of the fingers, needs to be optimized in function of the new plane of flexion of the thumb in order to reach our functional objectives. Other requirements, such as convergent and adaptive finger flexing at the level of two joints, were also considered important. The design of such a hand implies the resolution of complex problems of spatial geometry and visualization, mostly because the angle of each joint axis and finger trajectory is to be precisely defined. Furthermore, the relative phasing of the fingers must also be carefully studied in order to obtain an efficient pattern of prehension. To implement the required kinematics of the four fingers and the thumb, a 4-bar mechanism was specifically designed for each digit. Each 4-bar mechanism is activated by a cable and pulley system, driven by a single electric motor.

METHODS

General Design Specifications

In addition to the general specifications based on those proposed by Kay and Rakic (7), some specific requirements are defined for the multifunctional hand prosthesis:

1.   the palm and finger segments resemble the human model in both configuration and proportion
2.   the fingers and thumb are powered by a single self-contained electric motor located in the palm
3.   the motor-gearbox unit is self-locking and free of objectionable noise
4.   the maximal opening between the thumb and the second finger tips shall not be smaller than 9 cm and the closing time from open position to tridigital pinch will not exceed 0.8 sec
5.   the total weight of hand and glove will not exceed 500 grams
6.   a pinch force of 45 N has been specified for the tridigital pinch. However, the functional characteristics of our design allow a stable grip with a substantially lower force.

Functional Characteristics

For a natural hand, it is generally accepted that the most useful patterns of prehension are the tridigital (palmar) type followed by the lateral prehension (1). As a consequence, the design of our hand prosthesis is based on these two patterns. However, it is worth mentioning that because of the thumb's plane of flexion (45°), this hand prosthesis will be very well adapted for the cylindrical, spherical, and hook grasping patterns.

The following descriptions represent some of the functional characteristics that have been integrated within our new hand prosthesis (8).

The Thumb

With conventional hand prostheses, the thumb has generally been mobilized about the metacarpophalangeal (MP) joint only. With our proposed pattern of prehension, the thumb is now actively flexed about the carpometacarpal (CMP) and the interphalangeal (IP) joint. A third, but passive, joint has been located in the plane of the palm at the level of the CMP joint. This permits the thumb's plane of flexion to incline for the execution of a lateral prehension. In terms of multi-functionality, using an active CMP instead of the MP joint offers several functional advantages:

- the possibility to obtain and optimize ergonomically both the tridigital and lateral prehension patterns
- to provide a stable tridigital grip which is also well suited for the palmar prehension of cylindrical (or any voluminous) objects.

The Fingers

- the MP joints describe, as in the natural hand, a domed curve in both the transversal and longitudinal planes of the palm
- the four fingers flex about both the MP joints and the proximal IP joints. The distal IP joints are fixed at an angle of 30°
- the flexion rate of the digits will increase from first to fourth. This helps and enhances the phasing of the digits and contributes to decrease the functional ergonomical interference usually associated with the third and fourth fingers during the tridigital grasping of small objects
- the finger segments should be activated through a spring-loaded mechanism to allow independent adaptability for each finger

- all digits should flex passively when pushed backward by an external force
- the finger tips should spread apart during extension.

General Design Methodology

The general methodology used to design the fingers of our hand prosthesis is based on the following sequence:

1. obtain the external geometry (morphology design) of the hand prosthesis using computer-aided design (CAD) techniques to check the kinematic behavior of all the joints
2. for each finger, design a different 4-bar mechanism in order to get the required flexion angles for each desired mode of prehension.

Hardware and Software

This complex geometrical design is a proper subject for the application of the Computer-graphics Aided Three-dimensional Interactive Application program (CATIA), a new 3-D graphical tool (9). This program is installed on the main frame computer at the École and requires an IBM 5080 graphical station.

In brief, CATIA is a powerful interactive program allowing a user to define, visualize, animate, and analyze different entities in 2-D or 3-D space. It can be used to create entities such as points, lines, axes, planes, surfaces, curves, volumes, and solids. With the help of these entities, the user can create, edit, and file complex geometrical models. Many CATIA functions allow the user to visualize the model in different angles, scales, and colors. With this tool, it is possible to make a detailed analysis of each part of the model. Moreover, it is possible to get velocities, instantaneous center of rotation, forces, or couples at each finger joint of the prosthesis when in animation mode. By successive trials, proper hand morphology and grip patterns have been obtained by moving the fingers, modifying the orientation of their planes of action, and adjusting the flexion angles of the active joints. Internal mechanisms must be designed to obtain these desired flexion angles. The 4-bar mechanisms have been designed and optimized with the help of OPTLIB library (10) on the same main frame computer.

Morphology Design

Our first prototype was designed in male adult size. The geometric dimensions of all fingers and of the palm

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are based on selected average values of human hands (11). Points and lines were used on CATIA to generate axes, then solids, to get a first external shape of the hand. The next step was to adjust finger positions and orientation of their flexion planes and angles in order to visualize the obtained prehension patterns. CAD functions of CATIA were used, for example, to:

- translate the fingers (ROBOT) (**Figure 2**)
- change the orientation of the fingers (ROBOT) (**Figure 3**)
- flex the finger joints (ROBOT) (**Figure 4**)
- grasp a sphere (ROBOT; TASK) (**Figure 5**)
- check for interference between fingers or any solid elements (SOLID/ANALYSIS) (**Figure 6**).

The adjustment and positioning of each finger is functionally very important (12) in order to get a more physiological prehension without any interference. The work has been long and tedious, because it has to be done by successive trials. **Figure 7** shows a 3-D representation of the proposed prosthesis for the two preferred prehension patterns.

In the design process to obtain the desired kinematic behavior of our hand prosthesis, the following positions are defined (13) with respect to a reference position for which all joint angles, measured between phalanx axes, are zero:
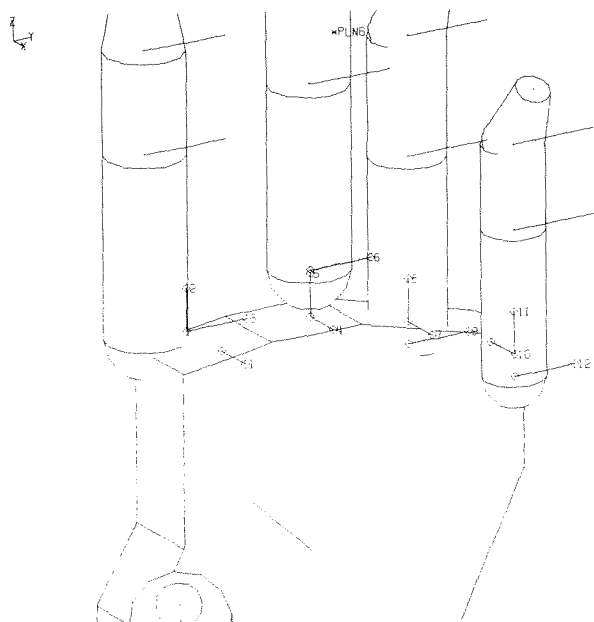

Figure 3.
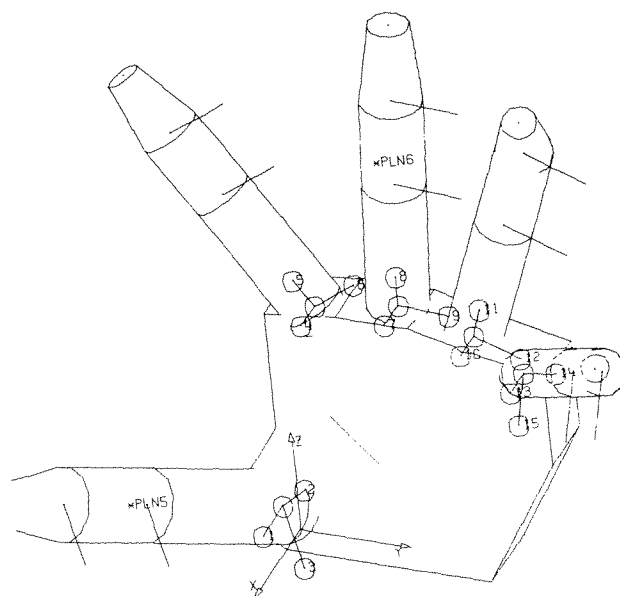View of robot ORIENT (orientation of fingers).

Figure 2.
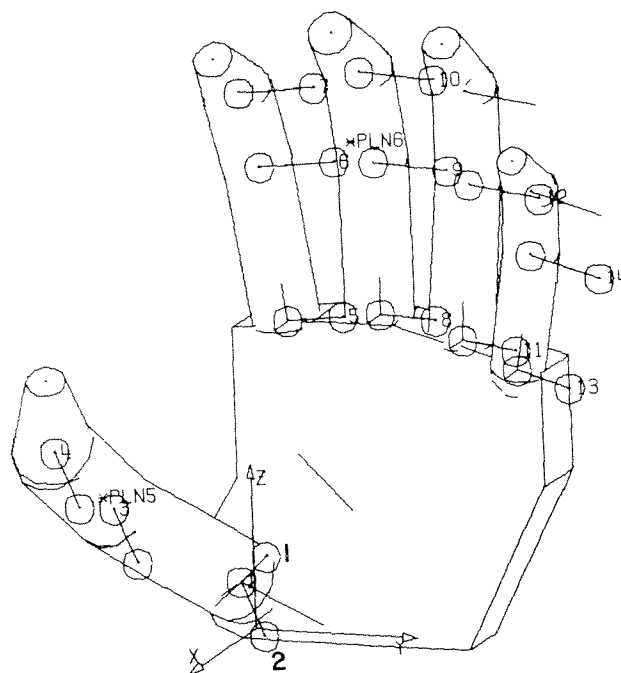View of robot TRANSL (translation of fingers).

Figure 4.
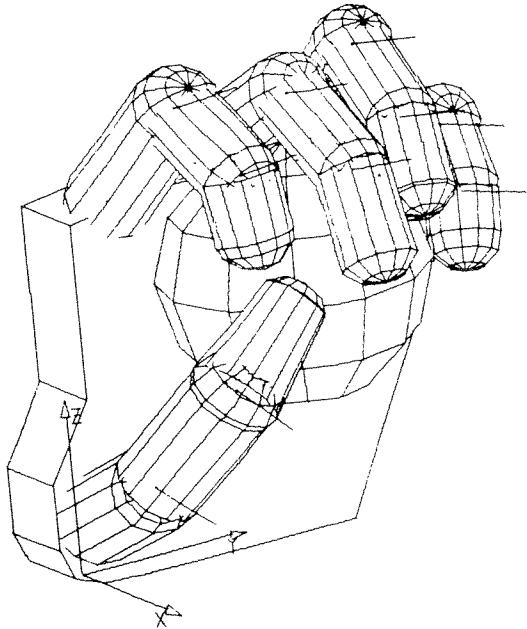View of robot FERME (flexion of the phalanxes).
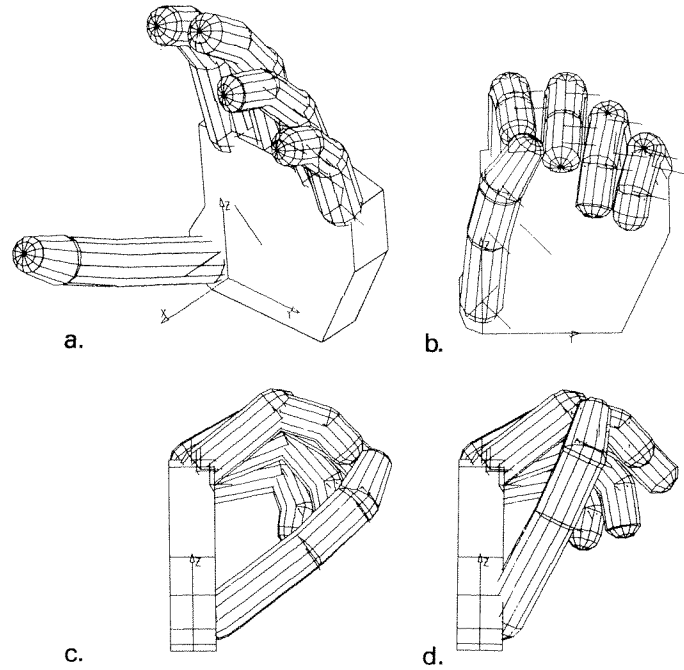
Figure 5.
View of a spherical grasp.

Figure 7.
CATIA three-dimensional representation of the positions defined for the design of the prosthesis: a) A hand opened in functional position; b,c) Frontal and side views of the tridigital prehension pattern; d) Side view of the lateral prehension pattern.
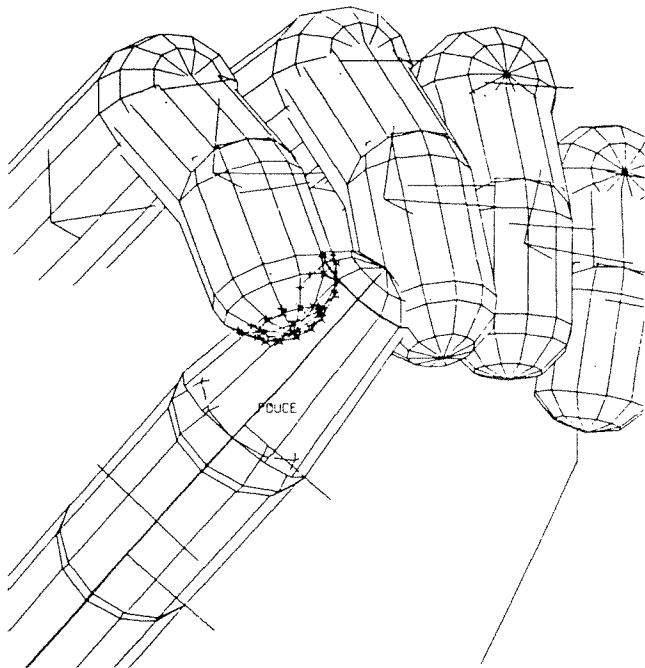
- functional position: also called the resting position, it corresponds to an approach position (open hand, **Figure 7a**)
- tridigital prehension: prehension pattern in which the thumb pad simultaneously opposes the index tip and the lateral side of the medius (**Figure 7b-c**)
- lateral prehension: prehension pattern in which the thumb pad opposes the lateral side of the index finger (**Figure 7d**)
- closure position; all fingers except the thumb are fully flexed.

CATIA was used to define all the flexion angles with respect to the reference position. **Table 1** shows the values of these angles (14) for the prehension patterns considered in **Figure 7.**

An important constraint was to get positive angle variation in every joint during the closing process. It is noted that identical flexion angles were obtained for the tridigital and lateral prehension patterns, the only exception being the CMP joint angles (27° and 28.5°). Since the difference was negligible, an intermediate value was considered to have them identical. This find-

Figure 6.
Interference checking between the index and the thumb.

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Table 1.
Flexion angles of phalanxes for defined positions using CATIA.

Finger	Joint Identification	Flexion angles in degrees*				
		HO	TP	LP	TC	LC
Thumb	CMP	8	27	28.5	8	8
	MP (fixed)	10	10	10	10	10
	IP	10	33	33	10	10
Index	MP	10	53	53	77	77
(forefinger)	IP1	20	49	49	80	80
	IP2 (fixed)	30	30	30	30	30
Second finger	MP	15	61	61	80	80
	IP1	20	48	48	80	80
	IP2 (fixed)	30	30	30	30	30
Ring finger	MP	20	60	60	80	80
	IP1	20	65	65	80	80
	IP2 (fixed)	30	30	30	30	30
Little finger	MP	20	66	66	82	82
	IP1	20	67	67	82	82
	IP2 (fixed)	30	30	30	30	30
Thumb	Inclination	25 or 59	25	59	25	59

* The flexion angle of a phalanx is measured between finger segments at the joint. All flexion angles are zero at the reference position, excluding the fixed joints. The zero reference position of the CMP joint is orthogonal to the plane of the palm. HO = hand open, resting position; TP = tridigital prehension; LP = lateral prehension; TC = closure position, tridigital; LC = closure position, lateral.

ing greatly simplifies the design of internal mechanisms for each finger. The only difference between these two prehension modes is the angle of inclination of the thumb (25° or 59°). This angle is measured between the plane of the thumb and a plane perpendicular to the plane of the palm, having the 45° line of the thumb as axis (**Table 1**).

4-bar Mechanism Design

Many types of articulated finger mechanisms to activate hand prostheses have been reported in the literature (1). After reviewing those mechanisms and considering our general design specifications, a 4-bar mechanism concept has been retained for each finger and thumb. **Figure 8** shows a typical 4-bar linkage that can meet the flexion angles of each joint as defined in **Table 1**. The fixed link R_4 has a known pivot Q which is the MP joint. The pivot M will be located on the palm, but its position is initially unknown. The length of the first phalanx (link R_1) is known and point B is the IP joint with an eccentricity "e" of 2 mm in order to obtain a

proper force at the finger tip. The eccentricity reduces the stretching of the glove at the external side of the IP joint and the necessary driver couple. The length of link R_1 is then deducted from the length of the first phalanx and from eccentricity "e". The positions of A and M are unknown, but they have to respect the external geometry of the finger and the palm. The reference position is chosen from which to calculate all the other positions. Each position "p" is defined as follows:

p = 0 in the functional position

p = 1 in the tridigital or lateral prehension

p = 2 in the closure position.

For each position, all angles θ_{1p} are known and calculated from the length of the first phalanx, the eccentricity "e", and the flexion angle TP1 from **Table 1**. The variations of θ_2 are known from **Table 1** but θ_{20} is unknown. However, all angles θ_{3p} are unknown. The values of R_2, R_3 R_4 and θ_4 are also unknown but constant.

The basic vectorial equation deduced from **Figure 8** is:

$$R_1 e^{i\theta_{1p}} + R_2 e^{i\theta_{2p}} + R_3 e^{i\theta_{3p}} - R_4 e^{i\theta_4} = 0$$
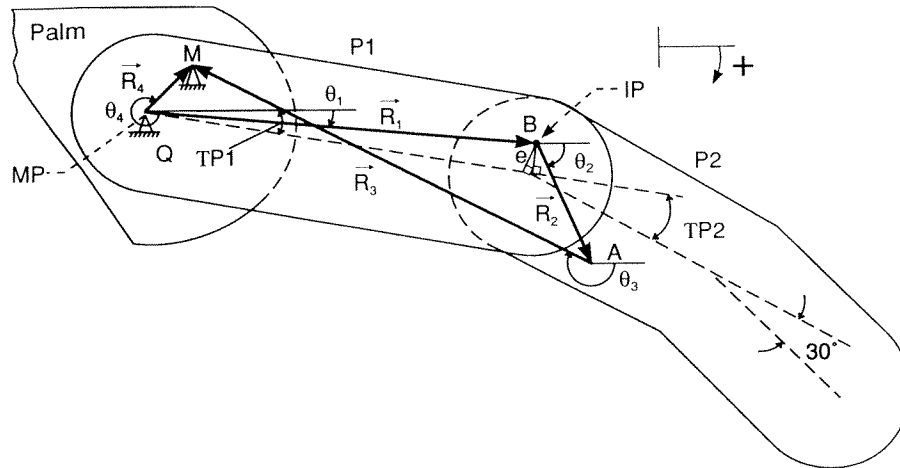
Figure 8.

A typical 4-bar linkage for a finger where TP1 and TP2 are the flexion angles respectively at the MP and IP joints, and

R_1 = driven link (first phalanx)

R_2 = coupler link (second phalanx)

R_3 = driver link

R_4 = fixed link (palm)

Q = metacarpophalangeal (MP) joint

M = axis of rotation of the driver link on the palm

A = axis of rotation of the driver link on the second phalanx

B = interphalangeal (IP) joint

e = IP joint's eccentricity (distance from B to central axis of P_1)

θ_i = angle measured from a horizontal line to the R_i vector in a clockwise direction.

for any position "p" of the finger as defined in **Table 1.** This complex equation is then translated into two real equations as:

$$R_1 \cos \theta_{1p} + R_2 \cos \theta_{2p} + R_3 \cos \theta_{3p} - R_4 \cos \theta_4 = 0;$$

$$R_1 \sin \theta_{1p} + R_2 \sin \theta_{2p} + R_3 \cos \theta_{3p} - R_4 \sin \theta_4 = 0.$$

The three positions defined previously generate six equations, for eight unknown design variables (R_2, R_3, R_4, θ_{20}, θ_{30}, θ_{31}, θ_{32}, and θ_4). An infinity of solutions can exist for every finger, thus creating a need for optimization.

Geometric constraints applied on points M and A, as well as mechanical constraints to avoid dead centers and locking positions, have all been expressed as functions of design variables of the mechanism. The torque needed at point M to equilibrate a given force at the finger tip is the chosen objective function to minimize. Hence, it was possible to define and design a set of five mechanisms using a constrained optimization program in OPTLIB library (10).

These mechanisms are activated by a cable pulling the driver link R_3. The drum diameters and the pulling point positions were adjusted to coordinate finger flexion from one position to another. This design enables the finger to flex when pushed by an external force as mentioned in the objectives. A return torsion spring at point B (IP joint) keeps the cable under tension the rest of the time. Moreover, the drums are spring-loaded to give adaptability to each finger when grasping an object.

RESULTS

First, a laboratory hand prosthesis was built. After modifications, a few clinical versions were produced (**Figure 9**). In the first phase of the clinical evaluation, three units were fitted to patients already wearing an Otto-Bock myoelectric hand prosthesis. This approach enables us to proceed with a comparative functional evaluation of the prehension performances between the
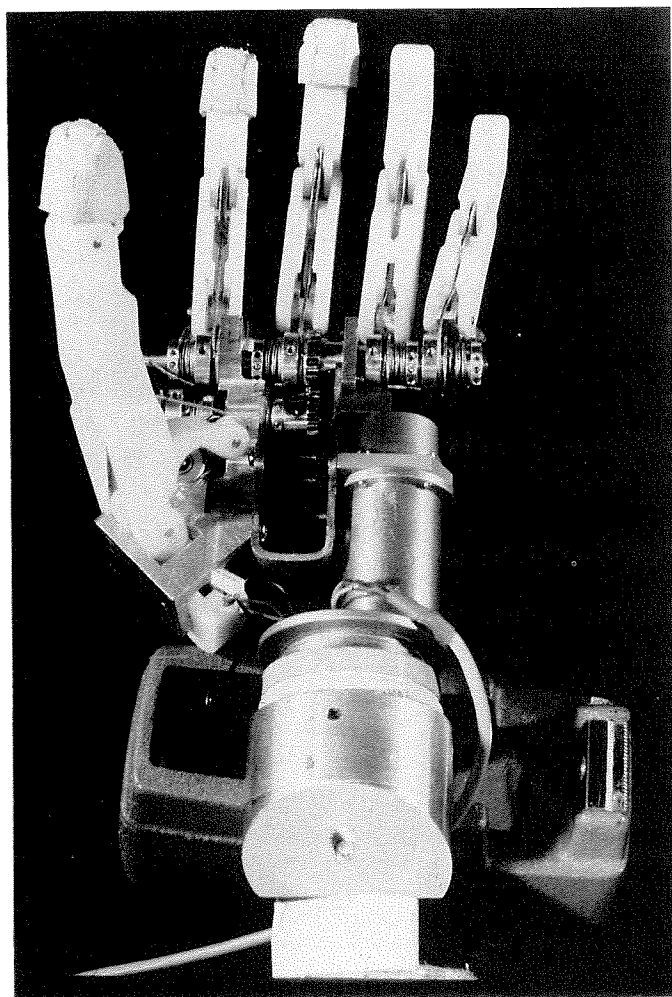
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Figure 9.
Our hand prosthesis prototype.

two hands. Although the results concern a limited number of patients, their preliminary results have already permitted us to identify the following functional advantages over the "pincer type" Otto-Bock prosthesis:

- it greatly minimizes the recourse to arm and body compensatory movements during both the approach and utilization phases of prehension
- it allows a better orientation of the objects held for use
- it provides a stable grip with a lower prehension force
- it improves the working visibility and the cosmesis.

CONCLUSION

A multifunctional hand prosthesis designed around the most essential opposition movements of the thumb

has been presented. We have attempted in this paper to explain our design approach and the ergonomic principles which have guided our decisions. We are aware that any engineering solution of a hand substitute will be necessarily based on many compromises. A preliminary assessment has already permitted us to identify some important functional gains. However, a broader clinical evaluation is the only way to ensure that acceptable compromises and solutions have been chosen.

CAD techniques used to design the external geometry of the multifunctional hand prosthesis have been a powerful tool. Graphical representation and animation of different elements of the model have allowed the designer to get a better understanding of our problem and save time in the design process.

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