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A comparison of the grip force distribution in natural hands and in prosthetic hands

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Abstract

Purpose: The aim of this study is to analyse the grip force distribution for different prosthetic hand designs and the human hand fulfilling a functional task.
Method: A cylindrical object is held with a power grasp and the contact forces are measured at 20 defined positions. The distributions of contact forces in standard electric prostheses, in a experimental prosthesis with an adaptive grasp, and in human hands as a reference are analysed and compared. Additionally, the joint torques are calculated and compared.
Results: Contact forces of up to 24.7 N are applied by the middle and distal phalanges of the index finger, middle finger, and thumb of standard prosthetic hands, whereas forces of up to 3.8 N are measured for human hands. The maximum contact forces measured in a prosthetic hand with an adaptive grasp are 4.7 N. The joint torques of human hands and the adaptive prosthesis are comparable.
Conclusions: The analysis of grip force distribution is proposed as an additional parameter to rate the performance of different prosthetic hand designs.

Introduction

Prosthetic hands can partly replace functions of the missing hand, such as grasping and holding an object, and they restore the outer appearance. So far, standard electrically driven prosthetic hands have had a non-adaptive grip. They possess one or two degrees of freedom and the materials are non-compliant. The ability to conform to the shape of an object makes the grip adaptive and is one of the most important features of a natural hand.[1] The human hand has 22° of freedom and the skin and tissue are compliant. Thus, the contact force is spread over a wide contact area and grasping is very effective. Natural hands require little energy for the stable holding of an object. They can be regarded as a benchmark for the design of future artificial hands where energy is restricted. Therefore different research projects created multi-articulated prosthetic hands with adaptive grasping abilities.[2–4] However, comparisons of different prosthetic hand designs are difficult and have been restricted to aspects like the width of grip, maximum whole hand grip force, and hand weight,[4–6] or the time to complete a task in a test procedure.[7] These parameters are insufficient for an objective hand assessment to provide major information on hand performance so as to make different hand designs comparable to each other and to the human hand as a benchmark.[8]

One criterion that may contribute to judging different hand designs is the distribution of contact forces during grasping. A study of literature revealed that only a few data that quantify the distribution of pinch forces required for completing functional tasks. Theoretical considerations regarding the distribution of grasping force can be found in robotics research.[9] An overview of different methods used for measuring grip force in clinical practice is given in.[10] There, the devices used for measuring total grip force are classified into hydraulic, pneumatic, mechanical, and strain gauge devices. To evaluate the biomechanical hand function, adequate sensors are needed. It was recommended that they should be small in size, have a low mass, and a high resolution even for low contact forces. Furthermore, they should not disturb the movements of the hand.[11] One type of sensor that fulfils these criteria is a modified Force Sensor Resistor (FSR^{TM}).[12] Different research groups used this type of sensor successfully in tool grip optimization,[13] applications of telerobotics[14] and virtual reality,[15] and the evaluation of the hand function in

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quadriplegic rehabilitation.[16] Other biomechanical research groups focus on human hands when measuring the applied grip forces for fulfilling functional tasks. Examples are the determination of fingertip loading when using a computer keyboard,[17] the metacarpophalangeal and interphalangeal loads in functional activities,[18] the minimal grip force necessary to prevent slipping,[19] or controlled lifting activities.[20] For comparing grip force distribution, a power type of prehension was chosen. This type of prehension is of high significance to both natural and prosthetic hands in everyday life. Prosthetic hands are not used for fine motor tasks like manipulating small objects, but rather for supporting, holding, and stabilizing actions.[21, 22] However conventional prosthetic hands, including hands with integrated automatic adjustment reach their limit of mechanical skills when grasping a flexible object. For example a liquid-filled paper cup does not give sufficient resistance and it will be squeezed completely.

In this article, the data obtained from force distribution measurements of natural hands are compared with the data obtained for two different types of prosthetic hands with adaptive grasping and non-adaptive grasping, respectively.

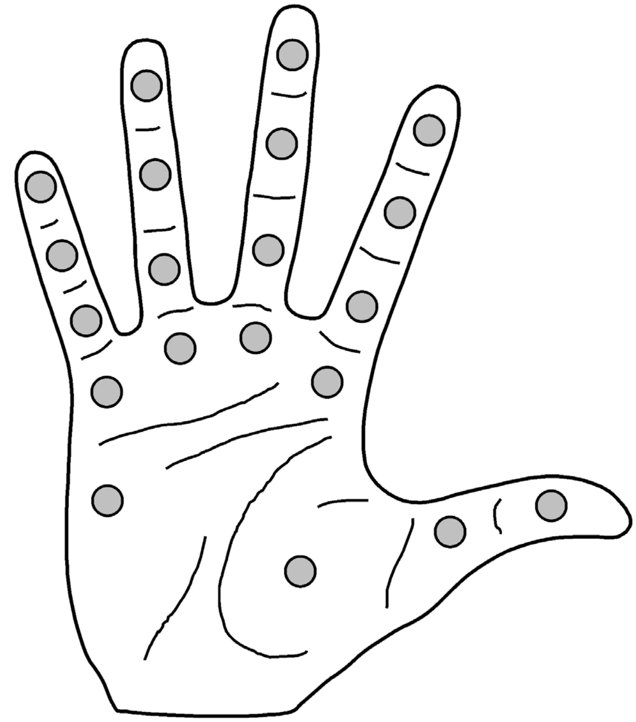

Figure 2 The 20 pre-defined positions of contact force measurement.

Materials and methods

SENSORS

Small conductive polymer sensors (FSR) were modified to work as a force sensor (figure 1). An elastic silicone rubber dome was mounted onto the sensing area to direct all applied forces and a solid plate at the bottom prevented the sensor from bending in order to avoid erroneous measurement.[23]

In order to obtain a force distribution pattern of natural and prosthetic hands, the grip forces were measured at 20 predefined positions (figure 2). All fingers, including the thumb, were equipped with three sensors each. They were attached to the middle of the phalangeal pads. Another four sensors were positioned on the palm at the metacarpophalangeal joints and one sensor at the hypothenar. Using double-sided adhesive tape, they were attached directly to the palmar surface of the fingers and the metacarpal hand, which ensures accurate positions of the sensors relative to the hand during prehension.

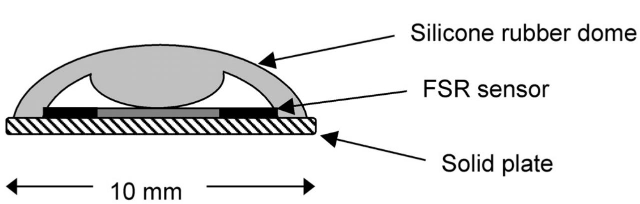

Figure 1 Schematic cross-section of the modified force sensor.

Via an analogue-to-digital converter, the sensors were connected to a personal computer for real-time data acquisition. During measurement, the amount of force was not displayed. Prior to the measurements, each sensor was calibrated for a range between 0 and 30 N using a test rig with a digital lab scale as a reference.[23]

SUBJECTS AND PROSTHESES

Eight upper limb-deficient persons who reported regular use of their conventional electrical prosthetic hand (hand sizes ranged from 7¼ to 8¼) agreed to take part in the experiment (table 1). Three of them used a System-Electro-Hand™ with a maximum grip force of 90 N at the fingertips. The other five subjects used a Sensor-Hand™ from the same manufacturer.[24]

This type of prosthesis has an integrated force control to ensure a minimum contact force of 10 N and to automatically increase the contact force. The maximum grip

Table 1 Upper limb-deficient subjects participating in the experiment

Upper limb-deficient persons	*Sex*	*Age*	*Affected side*	*Type of prosthesis*	*Cause of amputation*
1	Female	34	Right	OB-SEH	Congenital
2	Female	31	Right	OB-SH	Congenital
3	Female	18	Right	OB-SH	Congenital
4	Male	36	Right	OB-SH	Congenital
5	Male	35	Right	OB-SH	Congenital
6	Male	35	Right	OB-SEH	Congenital
7	Male	30	Right	OB-SEH	Congenital
8	Male	13	Right	OB-SH	Congenital

OB-SH = Otto Bock Sensor-Hand™, OB-SHE = Otto Bock System-Electro-Hand™.

force at the fingertips is 100 N. Except for the tactile sensor, the mechanical construction of both hands is similar: The thumb is always in direct opposition to the index and middle fingers of the hand. Thus, a tripod palmar prehension and a cylindrical prehension can be performed. Objects cannot be grasped adaptively, because this hand has only 1° of freedom (DOF) and the materials have a low compliance.

Representing a new generation of artificial hands with an adaptive grasp, a prototype of the hydraulically driven prosthetic hand was chosen (hand size 8¼).[3] It is multi-articulated (up to 15 DOF) and allows to perform five different prehension types, such as lateral grasp, cylindrical grasp, spherical grasp, tripod palmar prehension, and hook grasp. In combination with elastic materials, the fingers can conform to the shape of an object, but the maximum force at the tip of the fingers is limited to 16 N. All prosthetic hands involved in the experiment were controlled via two myoelectric surface electrodes. As a reference, the right hands of 10 male and 3 female healthy subjects aged between 24 and 50 years with hand sizes from 7 to 9 were included in the experiment. The volunteers were recruited from the institute staff. The study was performed in accordance with the guidelines of the Ethical Committee of the Orthopaedic University Hospital Heidelberg. Consent was obtained from all participants.

TEST PROCEDURE

Data acquisition started 5 s before the object was grasped, the hands were not in contact with the object. A glass bottle of 57 mm in diameter and 522 grams in weight had to be held for 20 s in a cylindrical power grip. The subjects were instructed to hold the object stably without redundant force. Subsequently, the object had to be released onto the table and data acquisition was stopped. The subjects sat on a chair and had to assume the measurement position standardized by the American Society of Hand Therapists[25] with adducted shoulder and an elbow flexed to 90°, the forearm in a neutral position, and the wrist in an extension between 0 and 30°. Each measurement was repeated 10 times and the whole test procedure took 20 min. To find out the hand size, the circumference of the palm was determined using a measuring tape. For a calculation of the joint torques, the joint angles were gauged with a protractor. The length of each finger phalanx was measured as well (figure 3).

CALCULATION OF JOINT TORQUES

Using the Jacobian matrix, joint torques were computed from the normal contact forces F, phalanx lengths L, and joint angles φ assuming contact points in the middle of the phalanges $l = L/2$ (figure 3). In line with the results from,[26] it was also assumed that the fingers exerted normal contact forces on the phalanxes in power grasping. A more detailed description of the calculation of joint torques and the sum of torques can be found in.[27]

Results

CONTACT POSITIONS

Contact was defined with a force higher than > 0.1 N registered by the sensor. It can thus be concluded that in the majority of the measurements less than 20 positions were in contact with the object (table 2).

In human hands an average of 17.2 sensors are in contact with the object (standard deviation (SD) 2.9), thus reaching the widest contact area. They are followed by the adaptive prosthesis with an average of 16.2 contact points (SD 0.8) and the non-adaptive hands with 9.1 (SD 1.4). There is no contact between the object and the non-adaptive prostheses in the metacarpal region, whereas a significant contact can be noticed at the meta-

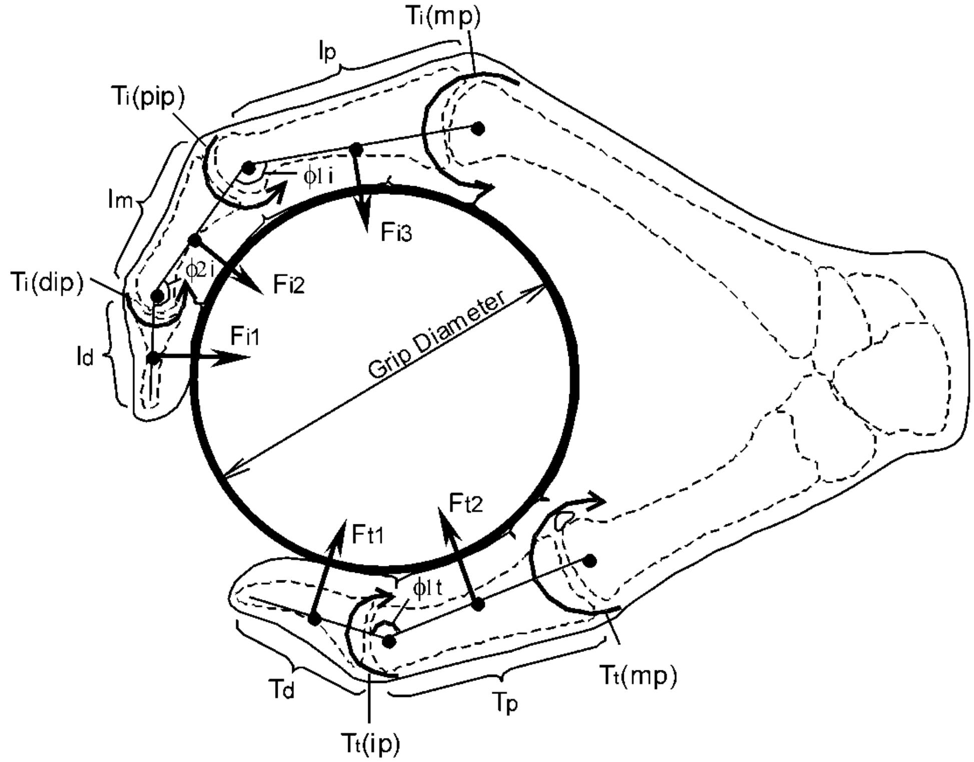

Figure 3 Orientation of contact forces (F_{index}) measured by sensors. Torques (T_{index}(joint)) produced at finger joints: ip – interphalangeal joint; mp – metacarpophalangeal joint; pip – proximal interphalangeal joint; dip – distal interphalangeal joint. Index of phalangeal lengths (T_{index}) and (I_{Index}) between finger joints: p – proximal, m – middle, d – distal. Joint angles φindex .

Table 2 Average number of contact positions [and standard deviations] during grasping for different hand sizes

Palm circumference [mm]	*Hand size* [inch]	*Human hand*	*Non-adaptive prostheses*	*Adaptive prosthesis*
180 – 195	$7-7\frac{3}{4}$	16.3 (5.5)	9.3 (0.6)	–
200 – 225	$8-8\frac{3}{4}$	17.3 (1.5)	9.0 (1.7)	16.2 (0.8)
230 – 245	$9-9\frac{1}{2}$	17.5 (3.1)	–	–
All sizes		17.2 (2.9)	9.1 (1.4)	16.2 (0.8)

carpophalangeal joint of the adaptive prosthesis (figure 4).

In order to investigate the dependence between hand size and contact area, the hands were subdivided into three different hand sizes and the number of contact positions was determined. Contact positions tend to increase in larger sized human hands.

CONTACT FORCE

The lowest contact forces during grasping are found in human hands. The average contact force for all 20 positions is 0.8 N (table 3). The maximum contact force measured is 3.8 N at the proximal phalanx of the index. Additionally, the highest average forces are encountered at the distal phalanx of the middle and ring fingers, and the thumb (figure 4). The sum of forces of the fingertips and of all positions also is lowest with 6.3 N and 16.7 N, respectively. Higher average and maximum contact forces are found in the prosthesis with an adaptive grasp, the force distribution pattern resembling the human hand (figure 4). The highest grip forces for the same prehension task are found in the two different types of non-adaptive prostheses. Average contact forces of up to 6.5 times of those found in natural hands are measured at the thumb and the distal phalanges of

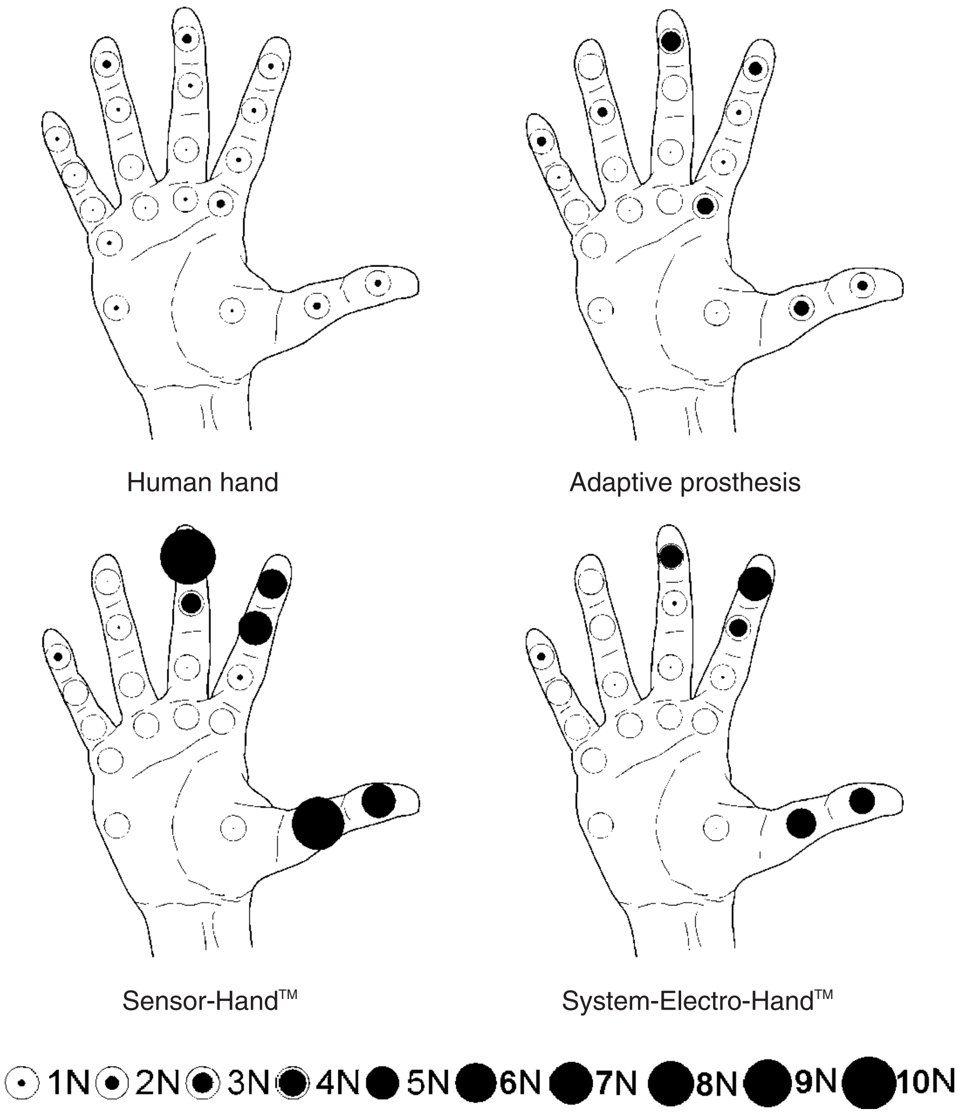

Figure 4 Contact forces of the natural hand, the adaptive prosthesis, and the two types of non-adaptive prostheses.

Table 3 Force characteristics of different hand types [and standard deviation]

	Average force [N]	*Maximum force* [N]	*Sum of forces* [N]	*Force at fingertips* [N]
Human hand	0.8 (0.7)	3.8	16.7	6.3
Adaptive prosthesis	1.3 (0.4)	4.7	21.3	9.9
System-electro-hand™	2.6 (2.7)	13.8	28.5	17.3
Sensor-hand™	3.9 (4.6)	24.7	47.4	24.9

the index and middle fingers, whereas no contact forces are registered at the metacarpal region. The force distribution pattern differs clearly from those of the other hands.

JOINT TORQUES

In this configuration of grasping the highest joint torques are measured at the metacarpophalangeal joints (table 4). Of all hands, the lowest joint torques are exerted by the human hand. The fingers of the non-adaptive prosthesis exert higher joint torques than the fingers of the adaptive prosthesis. The torques of fixed joints are calculated, but they are not comparable to moving joints.

Discussion

Shortly after the first electrically driven prostheses had been developed, general standards were defined.[5] These standards include technical aspects like the closure rate, noise level, maximum weight, and minimum opening range. A prehension force of 67 to 76 N was proposed, which can be reduced to 31 N after training. Moreover, functional aspects were specified. The externally driven hands should have a palmar type of prehension at least, operating should be easy, and the fingertips should be resilient. All criteria mentioned are fulfilled by standard prosthetic hands, except for the resiliency of the fingertips and the easiness of operation. Standard prosthetic hands can be used for both lifting heavy objects and supporting actions of daily life. At present, the prototype of the adaptive prosthesis does not reach the recommended prehension force. Hence, it is only usable for the manipulation of fragile objects, office work, and everyday supporting actions.

Other criteria proposed comprise the acceptance of the device by the patient and the ability to perform relevant standardized activities that are rateable in an assessment procedure.[6] However, these characteristics do not take into account that grasping in standard prosthetic hands differs from multi-articulated hands. Due to the non-yielding materials and the single degree of freedom, the contact area with an object is smaller and the force required to hold an object is higher. In certain situations, low contact forces spread over a large contact area are needed, e.g. for holding a paper cup. Hence, to make grasping of different hand designs comparable, other characteristics, e.g. the contact force distribution, are required.

Grip forces during sub-maximal static grasping of cylindrical objects were compared with the results from other research groups (table 5). However, comparability was limited by different methods used in the experimental set-ups. Some research groups also used conductive polymer sensors (FSR), but they attached the sensors to a glove without defining an accurate position of the sensors in relation to the fingers.[14, 16]

Other research groups used an object, the weight of which was almost twice as high as that applied in our experiment,[20] or the object weight was not given.[14, 18]

Differences in the average grasp forces may also result from the object diameter and varying coefficients of friction between the objects and the hands. The coefficient of friction of the sensors used in this study is higher than that of natural palmar skin. In addition, the contact surface and the type of grasping influence the grip

Table 5 Average forces at the fingertips during sub-maximal static grasping

Finger	*This study* d = 57 mm m = 522 g	*de Castro 00* d = 50 mm, m = 400 – 600 g	*Radwin 92* d = 45 and 65 mm m = 1000 g
Thumb	1.3 N	2.8 – 4.5 N	nn
Index	1.0 N	1.8 – 3 N	5.7 N
Middle	0.9 N	1.8 – 3 N	3.8 N
Ring	0.8 N	nn	2.9 N
Small	0.4 N	nn	2.6 N

d = grip diameter, m = weight of object.

Table 4 Torques of the metacarpophalangeal joints (MP), proximal interphalangeal joints (PIP), distal interphalangeal joints (DIP), interphalangeal joints of the thumb (IP) in natural hands (NH), non-adaptive hands (NAH), and adaptive hands (AH). Fixed joints are presented in brackets

Finger	*Joint*	*Natural hands* [Nm]	*Non-adaptive hand* [Nm]	*Adaptive hand* [Nm]
Thumb	MP	0.08	(0.54)	0.15
	IP	0.02	(0.08)	0.03
Index	MP	0.09	(0.54)	0.15
	PIP	0.05	(0.29)	0.1
	DIP	0.01	(0.07)	0.04
Middle	MP	0.11	(0.52)	0.15
	PIP	0.07	(0.39)	0.15
	DIP	0.02	(0.11)	0.05
Ring	MP	0.08	(0.04)	0.11
	PIP	0.06	(0.01)	(0.03)
	DIP	0.02	(0.0)	(0.0)
Small	MP	0.04	(0.04)	0.08
	PIP	0.02	(0.04)	(0.06)
	DIP	0.01	(0.02)	(0.02)

forces. The same cylindrical object may be grasped solely with the finger tips (small contact area) or surrounded by the fingers with contact to the palm (large contact area).

Conclusions

Grip force distribution is easy to measure. It is suggested to be used as an additional parameter in the assessment of functional prosthetic hand dynamics. Moreover, a comparison with the human hand as benchmark is possible. The adaptive prosthetic hand exerts low contact forces during grasping, which are spread over a wide contact area, and also the pattern of force distribution resembles the human hand. Due to their construction, non-adaptive prostheses exert high grip forces that are concentrated on a small contact area (the thumb and the distal segments of the index and middle fingers). We consider these results to be helpful for the design and optimization of prosthetic hands.

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