TOWARDS THE RATIONALIZATION OF ANTHROPOMORPHIC ROBOT HAND DESIGN: EXTRACTING KNOWLEDGE FROM CONSTRAINED HUMAN MANUAL DEXTERITY TESTING

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Received 18 April 2011
Revised 6 January 2012
Accepted 16 January 2013

In this work we take a new approach to the determination of the quantified contribution of various attributes of the human hand to its dexterity, with the aim of transposing this knowledge into supportive guidelines for the design of anthropomorphic robotic and prosthetic hands. We have carried out a number of standard dexterity tests on normal human subjects with various physical constraints applied to selected attributes of their hands, and have analyzed the results of the tests to extract knowledge on the quantified contribution of each attribute to overall manual dexterity. This knowledge is particularly significant in cases where it is important to optimize the trade-off between dexterity and complexity in the design of artificial hands. The data collection was made over 35 hours of direct experimentation involving 40 volunteers during two separate runs, and the results represent empirically-derived upper limits on the achievable performance of humanoid robot hands having the specified deficiencies. We discuss the implications of our results in the context of a minimal anthropomorphic dexterous hand, which would incorporate the lowest possible number of degrees of freedom and other attributes while still retaining an acceptable level of dexterity. We end the paper with a suggestion on how the general approach presented herein could be extended to provide a platform for the quantification of the dexterity of anthropomorphic artificial hands.

Keywords: Manual dexterity; artificial hand design

1. Introduction

Since the pioneering models of the 1960s,[1,2] 1970s,[3,4] and early to mid 1980s,[5,6,7] the interest in developing a robotic replica of the human hand has continued unabated on a global scale throughout the last 25 years. Major research groups worldwide have recently been demonstrating an increased interest in the area as they continue to invest heavily in the design and development of new or improved anthropomorphic robot hands, and to report significant progress and findings in this regard.[8,9,10,11,12] A key target in all of these robot hand designs is the maximization of the dexterity of the device, and this is normally approached through trying to emulate the human hand as closely as possible.

Despite the general activity in robot hand development, the literature has been somewhat lacking of a corresponding number of recent studies on the development of supportive guidelines for the design of these devices. Whereas most publications on new hands contain a section that describes the philosophy behind the particular design being presented, the design philosophies themselves are often based on the authors' own interpretation and intuition on how best to optimize the dexterity of their devices, and the resultant devices often differ significantly from each other, even though the general design goals are normally very similar.

Attempts to establish generic guidelines for robot hand design have been made occasionally, even during the earlier years. Erskine Crossley and Umholtz in 1977 already recognized that the design of an artificial hand needs to address various features such as its kinematic form, its drive mechanism and scale, the number of and control approach of the actuators, and the feedback sensors, and they then proceeded to derive the design specifications for their device based on their interpretation of how best to optimize these features.[3] It is interesting to note that these authors referred to the kinematic form of the robot hand as being the sole determinant of the dexterity of the device; however they did not define the word "dexterity". The design of the Stanford/JPL hand in the early to mid 1980s was based on a systematic study on mobility, kinematic and force analysis of articulated hands.[13,14] Iberall in 1997 analyzed human prehension using the *opposition space model*, and concluded that grasp synthesis based on this model could result in the development of effective new designs for more powerful and versatile robot hands.[15] The design recommendations given in this latter study were therefore based on the direct observation of the human hand function.

In the first half of the last decade, general high level design aspects for dexterous robot hands have been addressed to a considerable extent by the Robotics research group at the University of Bologna in Italy. In 2002 the need to adopt a concurrent engineering approach to the design of dexterous hands was emphasized, in order to include provision for sensors, wires and skin pads at an early stage, and the authors also advocated the use of an endoskeletal approach (i.e. similar to the human hand) and the use of compliant materials and mechanisms in the hand.[16] In 2003 the mechatronic approach, involving the consideration of information technology and control theory aspects in the early design stage, was emphasized, and the authors also highlighted the importance of reducing complexity.[17] In an internal report in 2004, and in earlier works referenced therein, an *anthropomorphism index* for robot hands was discussed, as a measure of how closely an artificial hand resembles the human hand in its kinematics, contact surfaces and size.[18]

A few other proposals for design methods for robot hands have been made recently. Soto Martell and Gini in 2007 attached passive markers to the human hand and used these in conjunction with vision sensing to establish with precision the complex hand movement during the execution of common tasks, with the aim of analyzing these offline to determine the least complex mechanical / control system design to replicate these motions.[19] Researchers at the German Aerospace Center (DLR) Institute of Robotics and Mechatronics have used anatomical, surgical, and rehabilitation data to extract a number of specific guidelines for the design of the thumb in a robot hand,[20] as well as medical, grasping, and aesthetics tests to propose a function based design approach methodology for robot hands.[21]

A common theme in most of the above cited works is the observation and study of the human hand, as a basis for the design of an anthropomorphic robot hand with as high dexterity as possible. In all cases (with the exception of some of the recent tests reported by the DLR group) it was a normal human hand in a normal mode of operation that was observed. Furthermore, in the absence of an accurate quantifiable measurement of robot hand dexterity, the degree of dexterity was normally inferred in a mainly qualitative way, as the (normally non-quantified) extent to which the designed robot hand would be able to reproduce the functions of the human hand.

In this work we wish to extend, in a novel way, the theme of observing human hand function for the purpose of providing useful data for robot hand design. Our approach is to carry out a systematic series of tests using a statistically significant sample of normal human volunteers, during which specific attributes of the hand are constrained, and to observe the detrimental effects of the constraints on a quantifiable performance index of the hand. The aim of this work is to provide objective quantifiable data pertaining to the contribution of each of the investigated attributes to the overall dexterity of the human hand, in order to provide, or confirm, a number of high level guidelines for the design of anthropomorphic robot hands, particularly with respect to the traditional trade-off between dexterity and complexity/cost.

The attributes of the hand investigated in this work comprise the various degrees of freedom of the fingers, and the sense of touch. Our preliminary results in this area have already been published.[22] The present paper focuses mainly on our new results, however a summary and re-analysis of the early results are also included in the relevant sections in order to provide a complete and comprehensive description and interpretation of the outcome of this research.

2. Manual Dexterity

2.1. *Definition and measurement of dexterity*

Since dexterity is a theme that is central to our present work, we here present a short resume of some important work that has been done on this subject, followed by a description of our approach to the problem.

As indicated in section 1 above, the term *dexterity* has been used in conjunction with robot hand performance from an early stage, albeit before the emergence of an established definition and without quantification. By the mid 1980s, authors were trying to describe the concept more precisely. The different types of grasps were categorised, distinguishing between *force* and *form closure,* and showing the trade-off that exists between power and dexterity.[23,24] This classification also demonstrated the relationship between the level of dexterity associated with specific types of grasp, and with the size of the object.

Towards the end of the 1980s, with the emergence of a large number of different robot hands (of both the anthropomorphic and the non-anthropomorphic type) worldwide, it became important to try to develop a widely applicable quantifiable measure of the performance of these hands, mainly for comparative reasons. From the onset it became clear that this task was going to be a daunting one. The problems lay in the number of dissimilar attributes of the hand that contribute to its dexterity (e.g. kinematic configuration, number and type of sensors, number and type of motors, control system, knowledge base, etc.), and the great variety of existing and potential robot hand designs. Clearly the bottom-up analytical derivation of a reliable "dexterity formula" based solely on the attributes of the hand was not possible, and therefore the dexterity measure needed to be somehow inexorably linked to the task and/or to the actual or theoretical performance of the hand.

Lu *et al.* in 1989 described dexterity in terms of fingertip manipulation of an object without slippage, and defined the *rotational dexterity index* of a hand in terms of the extent to which a standard spherical object can be rotated by the fingertips without slippage.[25] In the same year Wright *et al.* defined a multi-dimensional spectrum of specific manual tasks, ranging from very simple to very complex, thus enabling the dexterity of a robot hand to be derived by positioning it within this spectrum, in terms of the type of tasks that it is capable of carrying out.[26] Sturges and Wright, also in 1989, proposed a general theoretical definition of dexterity that is a function of the number of degrees of freedom, the natural frequency, and the speed of a device.[27] In 1990 Sturges extracted the dexterity of a robot hand from the *index of difficulty* of the most difficult task that it can accomplish,[28] using the quantitative definition by Fitts of the index of difficulty for a basic part relocation process.[29] The *net dexterity* of an end effector with respect to a specific task was then defined to be zero if the end effector could only just carry out that task.

Following this chronologically short spurt of contributions towards the derivation of precise quantified definitions of dexterity, this directed line of research appears to have abated, or at best it became implicitly absorbed into the more general analytical studies of robotic manipulation.[30] In an important review paper, Bicchi in 2000 cemented the definition that dexterity means manipulation capability, and then addressed mainly the qualitative aspects of dexterity and of how various design approaches have sought to optimize this quality.[31] At around the same time, the "minimalist" approach to manipulation, through which dexterity is sought using as simple a mechanical design as possible, was addressed analytically through the proposed exploitation of rolling contacts in a nonholonomic system.[32]

The "orthogonal" nature of anthropomorphism and dexterity was pointed out by Biagiotti *et al.* in 2004, emphasizing that one does not necessarily imply the other,[33] and the definition of dexterity was extended to include grasping and to recognize that further subdivisions or different levels of the concept could be identified.[18] Melchiorri and

Kaneko in 2008 have stated that although the notion of dexterity is settled, the way to achieve it is still being debated, particularly in view of the large number of attributes of the hand and of its control system that contribute to this property.[34]

A recent approach to achieve high grasping capability by a multi-degree-of-freedom artificial hand using only a small number of control inputs, is based on the realization by Santello *et al.* in 1998 that human hand postures can be described in large part by means of a small number of motion synergies of the hand joints.[35] In this regard *principal component analysis* has been applied to the determination of principal hand postures,[36] to the control of a prosthetic hand,[37] and to the choice of contact forces.[38] It is however not yet clear to what extent this approach will be applicable to manipulation capability.

While we fully concur with the recent summary by Melchiorri and Kaneko referred to above, we feel that in addition to the debate on how to *achieve* dexterity, there remains still the twenty-year-old loose end of how to *measure* the dexterity of a hand in a reliable, practical and widely applicable manner that is *task independent* (i.e. in a manner such that the dexterity value would be associated only with the hand, and not with the hand-task combination). Indeed, for the purpose of the objective that we set ourselves in this work, it was necessary to find a way to quantify the changes in dexterity of the human hand when some of its features were suppressed. To address this problem we looked beyond the field of engineering to the medical / rehabilitation field, where manual dexterity has long been defined and quantified in terms of a number of standard tests, carefully developed to assess the function of the human hand and, where present, the degree of impairment. Some of these tests are also used in the manufacturing industry to select personnel for employment in manual production.

2.2. ***Human dexterity***

The human manual system can be broken down into several subsystems, including the brain, the nerves, the muscles/tendons, the bone structure, the cutaneous receptors, and the contribution of the eyes. These are in the most part analogous to the subsystems of a robotic hand, which respectively would be the controller, the signal carriers, the actuation/transmission system, the mechanical structure, and if present the tactile sensors and visual feedback system. In both humans and robots, the mobility of the arm and wrist also influence the effective dexterity of the manual system. Defects in any of the above listed subsystems of a robot hand will have an adverse effect on the overall performance of the device. Here again there exists an analogy with the human being, where disorders such as peripheral neuropathy, cerebral palsy, muscular dystrophy and osteoarthritis affect different parts of the musculo-skeletal and nervous systems but all have a detrimental effect on dexterity.[39]

Two of the main reasons why the human hand is so dexterous, and which are sometimes overlooked to some extent when comparing the performance of artificial hands to that of their natural counterpart, are due to the wealth of information coming from visual feedback from the eyes, and due to the ability of the brain to serve not only as a controller but also as a knowledge base. Thus when we pick up and manipulate a familiar object such as a fragile glass for example, we are able to do this gracefully not only because of the mechanical, kinematic, sensory and actuation properties of our hand, but also because we have invaluable feedback from our eyes, and because we know beforehand that a fragile object of a certain shape has to be handled in a specific manner. This distinction between the contribution to dexterity that is due to the hand itself, and the contribution to dexterity that is due to external sensors and to the properties of the controller, must be made also in the case of robot hands.

Whilst the medical field may not be particularly concerned with the attributes of the human hand that make it so dexterous, a reduction in dexterity is often taken as a measure of severity when a person is suspected to suffer from disorders such as those mentioned above. The established practice is to interview the patient, and then to perform a series of standardized dexterity tests. Although the optimum results for these tests cannot be ascertained for each individual, standard results or norms do exist, depicting the expected results according to age group, gender, and so on.

3. Tests and Methods

3.1. *Selection and description of the dexterity tests*

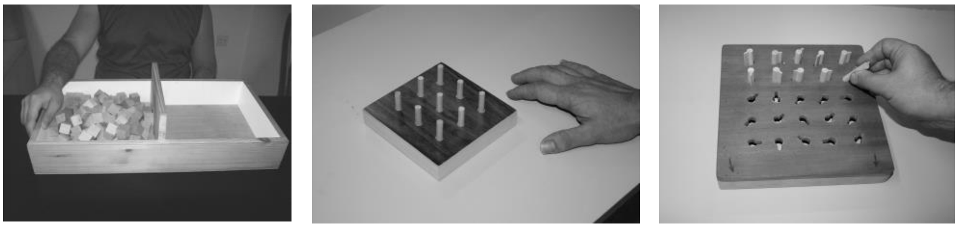
There are numerous standard tests that measure manual dexterity in humans.[40] All of these tests involve grasping of objects, but the degree of manipulation involved varies between the different tests. For the purpose of our work we selected the *box and block test*, the *nine-hole peg test*, and the *grooved pegboard test*. These three tests, and the reasons for their selection, are described briefly below.

The box and block test (BBT) was originally developed to evaluate the gross motor manual dexterity of adults with cerebral palsy. It is composed of a box divided into two equal compartments by a raised partition. Before the start of the test, 150 wooden cubes of side 25 mm are placed randomly in the side of the box that corresponds to the hand under test. The subject picks blocks one at a time from this side of the box and drops them into the other side, as fast as possible for a period of one minute. The number of blocks transferred successfully constitutes the result of the test.[41] This test was selected for our work because it involves predominantly grasping, and would therefore enable us to isolate, to some extent, grasping performance from manipulation performance.

The nine-hole peg test (NHPT) was originally introduced as part of a study on strength and dexterity. It involves grasp and release functions, refined pinches, moderate eye-hand coordination, and moderate in-hand manipulation. Working as fast as possible, the subject picks up nine pins (diameter 6.4 mm, length 38 mm) one at a time from a shallow container and inserts them in the holes of a nine-hole pegboard. As soon as all the pins are inserted in the holes, the subject takes them out one by one and puts them back in their container. The total time elapsed from start to finish constitutes the result of the test.[42] This test was selected for our work because it provided a setting where the grasping and manipulation functions could be tested concurrently.

The grooved pegboard test (GPT) is a manipulative dexterity test which requires more complex visual-motor coordination than most other pegboards.[43] This pegboard contains 25 holes with randomly positioned slots. Pegs (diameter 9 mm, length 50 mm), which have a key along one side, must be rotated to match the hole before they can be inserted. Working as fast as possible, the subject picks up the pegs one at a time from a shallow container and inserts them in the holes of the pegboard in a specified order. The total time elapsed from start to finish constitutes the result of the test. This test was selected for our work because of its increased focus on precision manipulation.

The apparatus required for the testing were fabricated in house to the standard specifications as prescribed in the literature, and are shown in Fig. 1.



(a) BBT-N (b) NHPT-N (c) GPT-N

Fig. 1. The selected, and fabricated, dexterity test sets

3.2. *Selection of the test subjects*

Observation of the published norms for the BBT,[41] NHPT,[42] and GPT[43] shows that performance in these tests varies with age, with gender, and with whether the hand being tested is the dominant or the non dominant hand. In general, performance deteriorates considerably with age, is slightly better for females than for males, and is considerably better for the dominant hand than for the non dominant hand. Furthermore, for the reasons discussed in section 2.2 above, we expected that the performance in these tests would possibly also depend on the visual and on the mental acuity of the subject, and also that it would be reduced if the subject were suffering from any injury or disability that could affect hand function. In view of these observations, and in order to minimize extraneous variations in our results, all of the test subjects were chosen to satisfy strictly all of the following criteria:

- The subject is male. (The male gender was selected over the female gender due to the greater number of potential volunteers in our Engineering Faculty.)
- The subject is between 20 and 24 years of age.
- The subject is right handed. (Right handedness was selected over left handedness once again due to the greater number of potential subjects. We decided to impose this

restriction, rather than to set up the tests differently for right and left handed individuals, in order to eliminate any possible increase in variance associated with introducing this variation.)
- The subject is a University Engineering student.
- The subject has good eyesight (glasses or contact lenses were allowed).
- The subject has no history of injury or illness that could affect his dexterity.

Thirty subjects were chosen to carry out the tests.

3.3. *Selection of hand attributes to be investigated*

The selection of the hand attributes to be investigated was carried out on the basis of whether each attribute could in fact be effectively constrained in practice, and whether the hand would still retain sufficient basic functionality to carry out the tests. The following attributes were selected.

- The presence of each individual finger (index, middle, ring, and little).
- The presence of the inter-phalangeal joints (for each individual finger and for the thumb, and for all five digits together).
- The capability for abduction / adduction motion (for all four fingers together).
- The sense of touch (for all four fingers and thumb together).

The contribution of each of the above attributes to manual dexterity was investigated by *suppressing* the attribute during the test, and measuring the resulting reduction in test performance. It is pointed out that the full suppression of the thumb was not attempted, since this was considered to result in too drastic a reduction in anthropomorphism and would probably have resulted in an inability of the subject to carry out the tests.

3.4. *Test conditions and procedures*

A set of standard procedures were prepared for the conduction of the tests, to ensure that every individual was examined under the same conditions.

The subjects carried out the tests while seated on a standard height chair at a standard height table. They were asked to remove any jewellery, and any cumbersome clothing such as jackets, that could hinder their movement. They were also discouraged from talking during the actual testing time to prevent lowering of their concentration. During the small interval between one test and another, the volunteers were asked to raise any queries that they may have had. During these intervals restrictions to the hand were being altered. In cases where the subject talked a lot during the actual test, the subject was asked to repeat the test.

In total, each subject was required to perform 27 tests. Twelve tests were performed on the BBT apparatus, thirteen tests on the GPT apparatus, and another two tests on the NHPT pegboard. The tests were carried out in the same order for all the subjects, as described in section 3.5 below. The duration of the entire testing procedure for each subject was of approximately 45 minutes.

To reduce the learning effect in the test results, each subject was given a trial period on each of the three sets of apparatus prior to the commencement of formal testing. For the BBT this consisted of one minute to perform the test without any restriction. The trial period on the GPT and on the NHPT, consisted of inserting all the keys in their respective holes without any physical restrictions on the hand.

3.5. *Test sequence and methods of constraint*

The sequence of tests for each subject is given in Table 1. All constraints were implemented very carefully such that, as much as possible, only the hand attribute(s) under test would be affected. In the case of tests 4 to 11, each finger in turn was immobilized using a wooden splint in conjunction with a fingerless glove and masking tape as illustrated in Fig. 2. The splint was long enough to enable it to be attached securely at both ends, but not long enough to interfere with wrist movement. The glove was used to avoid hair removal when removing the tape. In the case of tests 12 and 13, the four fingers were constrained to the maximum abduction position using plastic inserts in conjunction with the fingerless glove as shown in Fig. 3(a). This time the glove had a cushioning function. In this configuration finger flexion was still allowed as shown in Fig. 3(b). For tests 14 and 15, rubber thimbles were used to suppress the sense of touch while still maintaining friction as shown in Fig. 4. Multiple sets of thimble sizes were provided so that each subject could select the best sizes that fit snugly and did not leave air gaps at the fingertips. For tests 16 to 27, wooden splints were once again used as illustrated in Figs 5(a) and 5(b). In all cases where splints were used, care was taken not to apply masking tape to the fingertip, so that the sense of touch was retained.

In Table 1 the three types of tests are referred to as BBT-N, NHPT-N and GPT-N to distinguish these from the earlier tests reported in the next section.

Fig. 2. Whole finger immobilized

Table 1. Description and sequence of the new tests

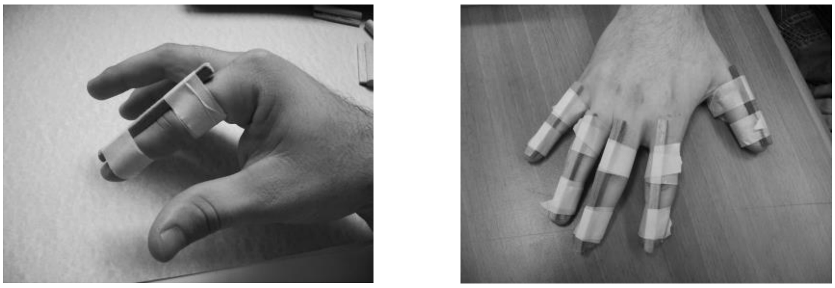
Test No.	Test	Constraints	Constraint Code
1	BBT-N	None	F
2	GPT-N	None	F
3	NHPT-N	None	F
4	BBT-N	Index finger – MCP and IPs	I
5	GPT-N	Index finger – MCP and IPs	I
6	BBT-N	Middle finger – MCP and IPs	M
7	GPT-N	Middle finger – MCP and IPs	M
8	BBT-N	Ring finger – MCP and IPs	R
9	GPT-N	Ring finger – MCP and IPs	R
10	BBT-N	Little finger – MCP and IPs	L
11	GPT-N	Little finger – MCP and IPs	L
12	BBT-N	All four fingers – abduction / adduction	AA
13	GPT-N	All four fingers – abduction / adduction	AA
14	GPT-N	All four fingers and thumb – touch	FT
15	NHPT-N	All four fingers and thumb – touch	FT
16	BBT-N	Thumb – IP	XT
17	GPT-N	Thumb – IP	XT
18	BBT-N	Index finger – IPs	XI
19	GPT-N	Index finger – IPs	XI
20	BBT-N	Middle finger – IPs	XM
21	GPT-N	Middle finger – IPs	XM
22	BBT-N	Ring finger – IPs	XR
23	GPT-N	Ring finger – IPs	XR
24	BBT-N	Little finger – IPs	XL
25	GPT-N	Little finger – IPs	XL
26	BBT-N	All four fingers and thumb - IPs	XA
27	GPT-N	All four fingers and thumb - IPs	XA

(a) Plastic inserts

(b) Finger flexion

Fig. 3. Constrained adduction

Fig. 4. Suppressed touch



(a) One finger (b) All fingers and thumb

Fig. 5. Interphalangeal joints immobilized

3.6. *Earlier tests*

The nature and sequence of our earlier tests, carried out two years prior to the above described tests, are shown in Table 2. In these tests three sets of apparatus were used, a box and block test apparatus, a nine-hole peg test with smaller pegs (8 mm diameter) and holes, and a nine-hole peg test with larger pegs (18 mm diameter) and holes. The sizes of the apparatus were non standard, and the time set for the box and block test was of 30 seconds instead of the standard 60 seconds. However, since the focus of this work is to extract the *relativity* of performance scores under constrained and free configurations, these tests still gave useful results, and it was also possible to reanalyse these early results and compare / include them with our new results. The three tests are designated respectively BBT-E, NHPT-ES, and NHPT-EL. A sample size of 10 subjects participated in these tests, with selection criteria similar to the above except that both males and females were included. Finger joint constraints were implemented using splints as above, except that bandages rather than masking tape were used (Fig. 6). These tests are described in more detail in our previous work.[22]

Table 2. Description and sequence of the earlier tests

Test No.	Test	Constraints	Constraint Code
i	BBT-E	None	F
ii	NHPT-ES	None	F
iii	NHPT-EL	None	F
iv	BBT-E	Wrist – pitch and yaw	W
v	NHPT-ES	Wrist – pitch and yaw	W
vi	NHPT-EL	Wrist – pitch and yaw	W
vii	BBT-E	Index finger – MCP and IPs	I
viii	NHPT-ES	Index finger – MCP and IPs	I
ix	NHPT-EL	Index finger – MCP and IPs	I
x	BBT-E	Middle finger – MCP and IPs	M
xi	NHPT-ES	Middle finger – MCP and IPs	M
xii	NHPT-EL	Middle finger – MCP and IPs	M
xiii	BBT-E	Ring finger – MCP and IPs	R
xiv	NHPT-ES	Ring finger – MCP and IPs	R
xv	NHPT-EL	Ring finger – MCP and IPs	R
xvi	BBT-E	Little finger – MCP and IPs	L
xvii	NHPT-ES	Little finger – MCP and IPs	L
xviii	NHPT-EL	Little finger – MCP and IPs	L
xix	BBT-E	Index and middle fingers – MCP and IPs	MI
xx	NHPT-ES	Index and middle fingers – MCP and IPs	MI
xxi	NHPT-EL	Index and middle fingers – MCP and IPs	MI
xxii	BBT-E	Index and ring fingers – MCP and IPs	RI
xxiii	NHPT-ES	Index and ring fingers – MCP and IPs	RI
xxiv	NHPT-EL	Index and ring fingers – MCP and IPs	RI
xxv	BBT-E	Index and little fingers – MCP and IPs	LI
xxvi	NHPT-ES	Index and little fingers – MCP and IPs	LI
xxvii	NHPT-EL	Index and little fingers – MCP and IPs	LI
xxviii	BBT-E	Middle and ring fingers – MCP and IPs	RM
xxix	NHPT-ES	Middle and ring fingers – MCP and IPs	RM
xxx	NHPT-EL	Middle and ring fingers – MCP and IPs	RM
xxxi	BBT-E	Middle and little fingers – MCP and IPs	LM
xxxii	NHPT-ES	Middle and little fingers – MCP and IPs	LM
xxxiii	NHPT-EL	Middle and little fingers – MCP and IPs	LM
xxxiv	BBT-E	Ring and little fingers – MCP and IPs	LR
xxxv	NHPT-ES	Ring and little fingers – MCP and IPs	LR
xxxvi	NHPT-EL	Ring and little fingers – MCP and IPs	LR

Fig. 6. Pairs of fingers immobilized

Although less reliable due to the smaller sample size, and due to the wider diversity of human subjects, these earlier tests are significant in that they include runs with different combinations of two fingers constrained, and also that the results of the early tests where single fingers were constrained can be compared, as an independent data set, to the new results.

4. Results and Analysis

Our results and analysis are presented in Tables 3 through 8, and in Fig. 7.

In Table 3, the title segment gives the apparatus used (in this case, BBT-N) and the sample size n (in this case, n=30), the applied constraints (e.g. interphalangeal joints of the ring finger immobilized), the shorthand code assigned to the constraint (in this example, XR), and the test reference number. The following segment of three rows gives the statistical results (in number of blocks) of these tests, where M is the sample mean, SD is the standard deviation of the sample, and SE is the standard deviation of the sample mean or the *standard error*. It is noted that SD is a measure of the degree of dispersion of the data, whereas SE is an indication of the expected accuracy of the test score with respect to the population mean. In particular the dispersions depicted by SD (and SE) are due in part to the different aptitude levels (dexterities) of the test subjects, and in part to the normal statistical dispersions that would occur even if all the subjects had exactly the same aptitude level.

The next segment of three rows in Table 3 gives the mean, for each constrained test, of the differences between the unconstrained and constrained test scores of each subject (depicted M_d) in number of blocks, and the standard deviations and standard errors for these differences (depicted SD_d and SE_d respectively). M_d is defined only for the constrained tests and is given by Eq. (1). It is noted that the effect of different aptitude levels is suppressed in these differential scores (due to the subtraction) and thus SD_d and SE_d are respectively less than SD and SE as expected.

$$\mathrm{M_d(constrained\ test)} = \frac{\sum_{i=1}^{\mathrm{n}}[(\text{free score})_i - (\text{constrained score})_i]}{\mathrm{n}} \qquad (1)$$

The last segment of three rows in Table 3 gives the test scores expressed as a measure of dexterity, in units of percentage of the mean unconstrained test score. The dexterity score *D* is given by Eq. (2). For the unconstrained test, SD_D and SE_D are derived directly from SD and SE of this test, while for the constrained tests, SD_D and SE_D are derived from SD_d and SE_d. Eq. (2) returns a linear scale for dexterity with respect to the test scores, i.e. for example a constrained test that results in a mean number of blocks transferred that is three quarters of the mean for the unconstrained test, would attribute a dexterity level of 75% to the constrained hand configuration. (Alternatively, the constraint is considered to result in a 25% loss in dexterity of the hand.)

$$D\text{ (constrained hand)} = \frac{[\mathrm{M(free\ test)} - \mathrm{M_d(constrained\ test)}]}{\mathrm{M(free\ test)}} \times 100\% \tag{2}$$

The results in Tables 4 through 8 are analysed and presented in a similar manner, except that where the test scores are in seconds, M_d and *D* are calculated using Eq. (3) and Eq. (4). Eq. (4) returns a linear scale for dexterity with respect to the reciprocal of the test time, i.e. for example a constrained test that results in a mean time that is one and one third (i.e. 4/3) of the mean time for the unconstrained test, would attribute a dexterity level of 75% to the constrained hand configuration.

$$\mathrm{M_d(constrained\ test)} = \frac{\sum_{i=1}^{n}[(\text{constrained time})_i - (\text{free time})_i]}{\mathrm{n}} \tag{3}$$

$$D\text{ (constrained hand)} = \frac{\mathrm{M(free\ test)}}{[\mathrm{M(free\ test)} + \mathrm{M_d(constrained\ test)}]} \times 100\% \tag{4}$$

A summary of the test results is presented graphically in Fig. 7.

Table 3. Results for the BBT-N test

Apparatus: BBT-N, n = 30												
	Free	**No addn.**	**Interphalangeal joints immobilized**						**Whole finger immobilized**			
			Little	**Ring**	**Middle**	**Index**	**Thumb**	**All**	**Little**	**Ring**	**Middle**	**Index**
C. Code	**F**	**AA**	**XL**	**XR**	**XM**	**XI**	**XT**	**XA**	**L**	**R**	**M**	**I**
Test#	**1**	**12**	**24**	**22**	**20**	**18**	**16**	**26**	**10**	**8**	**6**	**4**
M (blocks)	79.8	73.4	80.4	76.3	73.2	75.3	75.3	68.3	78.6	73.5	69.5	68.7
SD	6.3	5.9	5.4	5.4	5.4	5.1	6.7	4.7	6.5	6.2	4.9	4.4
SE	1.2	1.1	1.0	1.0	1.0	0.9	1.2	0.9	1.2	1.1	0.9	0.8
M_d (blocks)		6.4	-0.6	3.5	6.6	4.5	4.5	11.5	1.2	6.3	10.3	11.1
SD_d		3.5	3.1	4.8	3.9	4.6	4.2	4.6	3.9	3.9	4.5	4.9
SE_d		0.6	0.6	0.9	0.7	0.8	0.8	0.8	0.7	0.7	0.8	0.9
Dexterity Score (%)	**100.0**	**92.0**	**100.8**	**95.7**	**91.8**	**94.4**	**94.4**	**85.6**	**98.5**	**92.1**	**87.1**	**86.1**
SD_D	7.9	4.4	3.9	6.1	4.9	5.8	5.3	5.8	4.9	4.9	5.6	6.2
SE_D	1.4	0.8	0.7	1.1	0.9	1.1	1.0	1.1	0.9	0.9	1.0	1.1

Table 4. Results for the GPT-N test

Apparatus: GPT-N, n = 30													
	Free	No touch	No addn.	Interphalangeal joints immobilized						Whole finger immobilized			
				Little	Ring	Middle	Index	Thumb	All	Little	Ring	Middle	Index
C. Code	**F**	**FT**	**AA**	**XL**	**XR**	**XM**	**XI**	**XT**	**XA**	**L**	**R**	**M**	**I**
Test#	**2**	**14**	**13**	**25**	**23**	**21**	**19**	**17**	**27**	**11**	**9**	**7**	**5**
M (s)	40.2	59.5	61.4	40.6	43.8	50.4	45.8	44.6	66.9	42.1	47.8	59.2	49.1
SD	4.4	5.6	8.0	3.4	4.5	5.6	4.9	4.3	9.7	3.8	5.8	7.5	5.1
SE	0.8	1.0	1.5	0.6	0.8	1.0	0.9	0.8	1.8	0.7	1.1	1.4	0.9
M_d (s)		19.4	21.3	0.4	3.6	10.2	5.7	4.4	26.7	2.0	7.6	19.1	9.0
SD_d		5.3	7.4	2.9	3.8	3.8	3.3	3.4	7.7	2.6	4.7	6.1	4.4
SE_d		1.0	1.3	0.5	0.7	0.7	0.6	0.6	1.4	0.5	0.9	1.1	0.8
Dexterity Score (%)	**100.0**	**67.5**	**65.3**	**99.0**	**91.7**	**79.7**	**87.6**	**90.1**	**60.1**	**95.3**	**84.0**	**67.8**	**81.8**
SD_D	11.0	13.1	18.4	7.3	9.5	9.4	8.3	8.6	19.1	6.4	11.7	15.1	10.9
SE_D	2.0	2.4	3.4	1.3	1.7	1.7	1.5	1.6	3.5	1.2	2.1	2.8	2.0

Table 5. Results for the NHPT-N test

Apparatus: NHPT-N, n = 30		
	Free	No touch
C. Code	**F**	**FT**
Test#	**3**	**15**
M (s)	17.6	28.9
SD	1.5	4.3
SE	0.3	0.8
M_d (s)		11.3
SD_d		3.4
SE_d		0.6
Dexterity Score (%)	**100.0**	**60.9**
SD_D	8.7	19.6
SE_D	1.6	3.6

Table 6. Results for the BBT-E test

Apparatus: BBT-E, n = 10												
	Free	Whole finger immobilized				Pairs of fingers immobilized						Restr. wrist
		Little	Ring	Middle	Index	Little + ring	Little + middle	Little + index	Ring + middle	Ring + index	Middle + index	
C. Code	**F**	**L**	**R**	**M**	**I**	**LR**	**LM**	**LI**	**RM**	**RI**	**MI**	**W**
Test#	**i**	**xvi**	**xiii**	**x**	**vii**	**xxxiv**	**xxxi**	**xxv**	**xxviii**	**xxii**	**xix**	**iv**
M (blocks)	23.7	26.1	22.7	22.5	22.2	24.5	23.0	22.2	22.4	21.4	20.3	23.4
SD	3.3	4.5	4.4	5.1	4.1	4.6	5.3	5.4	5.2	5.5	5.1	4.7
SE	1.0	1.4	1.4	1.6	1.3	1.4	1.7	1.7	1.6	1.8	1.6	1.5
M_d (blocks)		-2.4	1.0	1.2	1.5	-0.8	0.7	1.5	1.3	2.3	3.4	0.3
SD_d		2.8	3.3	3.7	2.5	3.3	4.0	4.0	3.8	4.1	4.1	2.6
SE_d		0.9	1.0	1.2	0.8	1.0	1.3	1.3	1.2	1.3	1.3	0.8
Dexterity Score (%)	**100.0**	**110.1**	**95.8**	**94.9**	**93.7**	**103.4**	**97.0**	**93.7**	**94.5**	**90.3**	**85.7**	**98.7**
SD_D	13.9	12.0	13.8	15.5	10.8	13.9	16.8	16.8	16.0	17.3	17.4	11.1
SE_D	4.4	3.8	4.4	4.9	3.4	4.4	5.3	5.3	5.1	5.5	5.5	3.5

Table 7. Results for the NHPT-EL test

Apparatus: NHPT-EL, n = 10												
	Free	Whole finger immobilized				Pairs of fingers immobilized						Restr. wrist
		Little	Ring	Middle	Index	Little + ring	Little + middle	Little + index	Ring + middle	Ring + index	Middle + index	
C. Code	**F**	**L**	**R**	**M**	**I**	**LR**	**LM**	**LI**	**RM**	**RI**	**MI**	**W**
Test#	**iii**	**xviii**	**xv**	**xii**	**ix**	**xxxvi**	**xxxiii**	**xxvii**	**xxx**	**xxiv**	**xxi**	**vi**
M (s)	16.2	14.7	16.3	18.3	16.5	16.7	18.0	17.4	20.0	20.7	19.4	16.5
SD	3.0	2.6	2.4	3.9	2.9	3.8	4.0	3.6	3.5	3.6	3.3	2.6
SE	1.0	0.8	0.8	1.2	0.9	1.2	1.3	1.2	1.1	1.2	1.0	0.8
M_d (s)		-1.5	0.1	2.1	0.3	0.5	1.8	1.2	3.8	4.5	3.2	0.2
SD_d		1.6	2.1	2.5	1.8	2.5	2.1	1.9	2.2	1.4	1.8	1.4
SE_d		0.5	0.7	0.8	0.6	0.8	0.7	0.6	0.7	0.4	0.6	0.4
Dexterity Score (%)	**100.0**	**110.4**	**99.4**	**88.5**	**98.5**	**97.3**	**90.0**	**93.2**	**81.2**	**78.4**	**83.5**	**98.5**
SD_D	18.6	9.9	12.9	15.4	10.9	15.6	13.2	11.7	13.4	8.4	10.9	8.6
SE_D	5.9	3.1	4.1	4.9	3.4	4.9	4.2	3.7	4.2	2.7	3.5	2.7

Table 8. Results for the NHPT-ES test

Apparatus: NHPT-ES, n = 10												
	Free	Whole finger immobilized				Pairs of fingers immobilized						Restr. wrist
		Little	Ring	Middle	Index	Little + ring	Little + middle	Little + index	Ring + middle	Ring + index	Middle + index	
C. Code	**F**	**L**	**R**	**M**	**I**	**LR**	**LM**	**LI**	**RM**	**RI**	**MI**	**W**
Test#	**ii**	**xvii**	**xiv**	**xi**	**viii**	**xxxv**	**xxxii**	**xxvi**	**xxix**	**xxiii**	**xx**	**v**
M (s)	19.5	18.4	19.6	23.3	21.1	19.3	21.9	21.3	25.2	28.1	25.9	20.5
SD	3.8	2.3	2.9	4.1	3.4	3.3	4.2	4.0	5.0	4.9	4.2	3.7
SE	1.2	0.7	0.9	1.3	1.1	1.0	1.3	1.2	1.6	1.6	1.3	1.2
M_d (s)		-1.2	0.0	3.7	1.5	-0.3	2.3	1.8	5.7	8.5	6.4	0.9
SD_d		2.3	1.9	2.9	2.1	3.4	2.0	2.7	3.5	3.7	3.4	2.2
SE_d		0.7	0.6	0.9	0.7	1.1	0.6	0.9	1.1	1.2	1.1	0.7
Dexterity Score (%)	**100.0**	**106.4**	**99.8**	**84.1**	**92.7**	**101.4**	**89.3**	**91.6**	**77.5**	**69.6**	**75.5**	**95.6**
SD_D	19.4	11.9	9.6	14.9	10.9	17.3	10.4	13.9	17.9	19.0	17.5	11.1
SE_D	6.1	3.8	3.0	4.7	3.5	5.5	3.3	4.4	5.6	6.0	5.5	3.5

5. Interpretation of Results

As seen in Fig. 7, changes in dexterity with hand constraints are considerably more pronounced in the case of the NHPT and GPT tests than they are for the BBT tests. We attribute this effect to the greater extent of manipulation required for these former test types, or more specifically, to the greater proportion of the test time spent on actions requiring manual dexterity. We note that the BBT cycle can be broken into four actions: the grasp, the transfer, and the release of the block, and the return of the hand. Of these, only the time associated with the first action is in general expected to be a function of hand dexterity. Thus we expect that a reduction in dexterity would not have a dramatic effect on the test score. In the case of the NHPT and the GPT the cycles can be broken down into six actions: the grasp, the transfer, the manipulation, the insertion, and the release of the peg, and the return of the hand. (In the case of the GPT, the manipulation consists of both a rotation and an alignment, while in the case of the NHPT there is a separate cycle involved in relocating the pegs from the board back to the container.) Of these, the time segments associated with the grasping, the manipulation, and the insertion of the peg, are expected to be functions of dexterity.

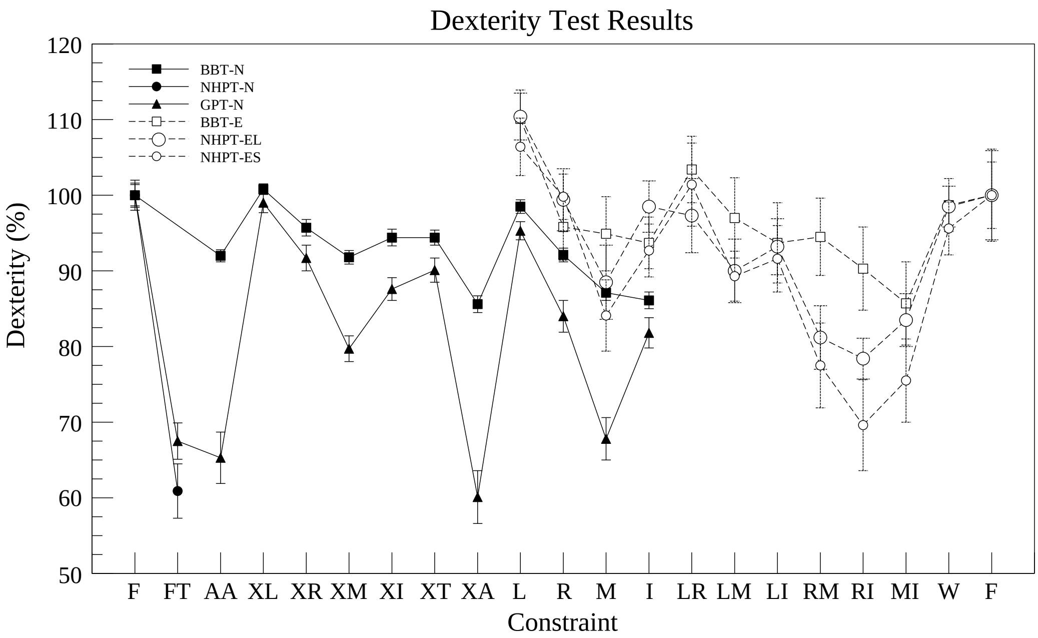


Fig. 7. Summary of the results, showing the effects on dexterity of the various hand constraints, as obtained in the different tests that were conducted. The error bars in this figure are given by ± SE_D. Data points pertaining to the same set of experiments are joined together for clarity. For those points joined together with a solid line (new tests), n = 30, while for those points joined together with a dashed line (old tests), n = 10.

We note from Fig. 7 that the most dramatic reductions in dexterity were obtained when one of the following attributes of the hand was suppressed:

- the sense of touch (32% reduction in the GPT);
- all of the finger abduction / adduction joints (35% reduction in the GPT);
- all of the interphalangeal joints (40% reduction in the GPT);
- the middle finger (32% reduction in the GPT);
- the ring and index finger combination (30% reduction in the NHPT-ES test).

We attribute the large contribution to dexterity of the middle finger, to the fact that when this is constrained, the remaining two major fingers (index and ring) are non-adjacent ones. This would indicate that the collaborative effect of non-adjacent fingers is less effective than that of adjacent fingers, or that a large spacing between the fingers is detrimental to dexterity. This is corroborated by the observation that when the ring and index fingers are constrained simultaneously, resulting in the absolute absence of any adjacent finger pairs, there is also a large reduction in dexterity. The large reduction in dexterity when all of the fingers are constrained at the maximum abduction position, as well as the observation that out of all the interphalangeal joints (when constrained individually) those of the middle finger resulted in the greatest reduction in dexterity, further corroborate this inference.

Our results indicate that the little finger has practically no effect on the performance in these tests – in some of our earlier tests the dexterity was observed to *increase* when this finger was constrained, however this was not seen in the new tests, where greater care was taken to avoid the learning effect. We also noted that the suppression of the interphalangeal joint of the thumb did not result in a very large reduction in test performance as long as the interphalangeal joints of the other digits were available. A final note relates to the suppression of the wrist pitch and yaw movements, which had only a minor effect on the GPT-E, NHPT-ES and NHPT-EL results, indicating that in these tests the human subjects were able to compensate for the restraint using the joints of the arm.

6. Discussion

6.1. *Limitations of the implemented tests*

The tests were subject to a number of minor limitations, both at the conceptual and at the implementation level.

Firstly, it is noted that where the fingers are constrained in their entirety (constraints L, R, M, I, LR, LM, LI, RM, RI, and MI), the protruding splinted finger(s) may potentially interfere with the grasping process, particularly when picking up single items from a pile. In this sense the hand, in addition to being deprived of the contribution of the constrained finger(s), may actually be *obstructed* by them. Observation of the subjects during the tests, and an inquiry made to the subjects on this issue, however confirmed that this was rarely a problem, and the constrained fingers were generally well out of the way during the tests.

Secondly, we take note of the work by Lin *et al.*[44] wherein it is reported that out of the 32 potential finger and thumb flexion combinations of the human hand, four are often not achievable by many humans under normal circumstances. One of these involves the sole flexion of the little finger and is not applicable to our work. The other three states that are reported to “not be achievable by everyone” are equivalent to grasp postures resulting from our R, RM and RI constraints. We have noted however in our tests that whereas these states may sometimes not be normally achievable, they do become achievable when aided to be so by the splints, albeit with some minor impediment to the motion of the non-constrained fingers. These impediments during our R, RM and RI tests may have affected the results of these specific tests to some extent. In particular, whenever the ring finger was constrained the subjects were observed to often prefer to also abstain from using the little finger, thus reverting to an "achievable" state. Thus the R and the LR constraints were often effectively equivalent to each other, and the RM and RI constraints often effectively became "LRM" and "LRI" constraints, resulting in the use of the thumb together with only one major finger (the index or the middle).

The third issue relates to the learning effect, which in spite of our efforts to minimize may still have been present to some extent. We do not expect however that this effect played a major role in this experiment, since the motions required by the tests are very straightforward and the subjects were given practice sessions before the use of each apparatus. This was particularly emphasized in our new tests. We also note that there could have been a "tiredness effect" that would work opposite to the learning effect.

Fourthly, we note that for the tests with whole single fingers constrained, the absolute dexterity penalties recorded in our earlier tests tended to be somewhat less severe than for the new tests. This may have been due to the various differences between the test runs, and/or to the learning effect mentioned previously, and serves to emphasize the need to use a standard testing procedure. The relative contributions to dexterity of the different fingers as obtained in the earlier tests, were very similar to the ones obtained in the new tests.

As a fifth point, we note a number of side effects associated with the adopted methods of constraint that may have had some bearing on the results obtained. Thus for example when constraining the IP joints of the fingers using the adopted method (Fig. 5(b), tests 18-27), the hand may not be able to align all of the fingertips properly during precision grasps, and fine manipulation may occur at a location proximal to the fingertip on the affected finger(s). Furthermore, for tests 12 and 13, the abduction/adduction degrees of freedom of the fingers may not have been constrained at their optimal angles (i.e. at the angular positions that would have minimized the negative repercussions of the constraint). Thus it should be borne in mind that the numerical penalties associated with these constraints, may under optimized conditions be possibly somewhat less severe than those indicated in Fig. 7.

As a sixth point, we note that during the tests with the FT constraint the sense of touch was suppressed but could not be eliminated completely by the rubber thimbles. The fact that these tests still registered a large reduction in dexterity further emphasizes the important contribution of the sense of touch to grasping and manipulation.

Finally, we note that the NHPT-N apparatus was only applied to two tests, and also that the tests with pairs of fingers immobilized were not repeated during our recent run. We decided that each human subject could not be expected to submit to testing for a period of longer than about 45 minutes, and this placed a limit on the number of tests that could be carried out.

As a general note, we point out that the set of constraints that were applied to the human hand during these tests aimed to address a number of major hand features that are expected to have a significant effect on the dexterity, but do not constitute an exhaustive investigation of *all* of the features of the hand that may contribute to its dexterity. This was due to limitations on the specific hand features that can be practically and effectively constrained, and to limitations on the duration of testing as described above. Thus for example, constraints of individual finger abduction motions, and of subtle hand features such as palmar arching, were not applied during the tests. Furthermore, we note that the selected tests, while widely considered in the medical field to give reliable measurements of manual dexterity, certainly do not cater for all of the grasping and manipulation actions and postures that a healthy and unconstrained hand can realize. This latter point is addressed further in section 6.2 and in section 7.

6.2. *Towards a minimal anthropomorphic dexterous hand*

The main contribution of this work is to provide quantitative data on the specific contributions of the various features of an anthropomorphic hand (in this case of the human hand, i.e. the ultimate in anthropomorphism) to manual dexterity, with the aim of providing support for the decision-making process during the design of robot hands, particularly in the presence of limitations on complexity and cost. Given that it is good design practice to achieve satisfactory performance with minimum complexity, and given that cost is almost always an issue to some extent, particularly more so where the commercialization of an end product is envisaged, this means that the implications of our results have widespread applicability, particularly so as the age of ubiquitous humanoid robots looms closer, and as the quest continues for a hand prosthesis that achieves satisfactory dexterity with as small a number of controllable inputs (and of control outputs) as possible. It is therefore worthwhile to discuss our empirical results in the context of a list of “minimum specifications” for a dexterous robot hand.

Our data indicate that a dexterous artificial hand must have at least two “adjacent” major fingers, each with the equivalent of the human metacarpophalangeal (MCP) joints and interphalangeal (IP) joints. The question of whether the equivalent of *both* the human proximal and distal IP joints (i.e. the PIP and DIP joints) are necessary was not addressed in our experiments, since it is not possible to constrain the human PIP and DIP joints separately due to their coupled nature. This coupling in the human fingers in fact suggests that, possibly, one IP joint per finger may be enough in the minimal robot equivalent. Our data also indicate that the exclusion of the little finger would have a negligible effect on dexterity, even if this is done in combination with the exclusion of the ring finger. By excluding the ring finger we may expect a dexterity penalty, as defined and measured in this work, of about 16%.

Our data also confirm that the presence of the finger abduction / adduction function is important for dexterity, and indicate that its absence could result in a dexterity penalty of about 35%. In an artificial hand with only two fingers (apart from the thumb) this function would be reduced to the presence of a single abduction / adduction joint for the hand.

Intuition strongly suggests that the presence of a multi-degree-of-freedom opposable thumb is necessary for dexterity. In our experiments the investigation of the thumb was limited to the constraint of the IP joint, and rather counter-intuitively the results suggested that the equivalent of this joint could perhaps be excluded from an artificial hand without undue penalty in dexterity. This was later found to be incorrect as described further down in this section. In the human thumb the trapezoid-metacarpal (TM) joint and the MCP joint are each normally modelled as two-degree-of-freedom joints. Possibly some DOF reduction in one or both of these joints could be achieved without undue penalty in dexterity. At DLR, based on quite extensive anatomical, surgical and functional studies of the normal and subnormal human digit, the authors have opted for a 2-DOF TM joint, and 1-DOF for each of the MCP and IP joints, for their new hand design.[20,45]

Finally, our data confirm that a dexterous artificial hand should have a good sense of touch, and that the absence of this attribute could reduce dexterity by about 40%.

Thus, based on the above empirical data and subsequent reasoning, a minimal anthropomorphic artificial dexterous hand would have the following kinematic and sensory attributes:

(i) Two fingers (equivalent to the human index and middle fingers) and a thumb, with total sizes and phalange lengths (where applicable) similar to those of the human;
(ii) Two independent flexion joints (equivalent to the human MCP and PIP joints) on each of the two fingers, with ranges of motion and force capabilities similar to those of the human (the coupled DIP joints may also be required);
(iii) One abduction / adduction joint between the two fingers, with a range of motion similar to that between the human index and middle fingers (about 30^{o} based on the data by Lin *et al.*[44]);
(iv) Four degrees-of-freedom for the thumb, equivalent to the rotation and abduction/adduction of the TM joint, the flexion of the MCP joint, and the flexion of the IP joint, with ranges of motion and force capabilities similar to those of the human (based on the DLR studies); and
(v) An effective sense of touch.

This nine degree-of-freedom hand configuration would be expected to potentially attain a dexterity level, as assigned in this paper, of about 84%. Of course, to achieve this potential the full system would have to incorporate the equivalent, performance-wise, of the human control, actuation/transmission, and vision feedback processing systems, themselves major challenges as is of course also the incorporation of the “effective sense of touch”. Other general properties of the human hand that aid dexterous manipulation, such as surface compliance and skin texture, would also need to be effectively reproduced. The hand would also need to be mounted on an arm and wrist with sufficient degrees of freedom. It is noted in particular that, just as the human subjects may have done during the dexterity tests, the robot may need to utilize the degrees of freedom of its arm and wrist to help compensate for the missing degrees of freedom in the hand.

In order to seek a degree of independent experimental validation for this minimal hand configuration, we have tested the approach in a rudimentary but highly indicative manner through a task assumed to require substantial dexterity. The task selected was to wire a standard UK square pin plug, using a number of tools shown in Fig. 8(a). The task involved the use of a pen knife, pliers, two types of screwdriver (for three types of screws), and a wire stripper, and involved also the twisting, manipulation and fine insertion motions of the thin wires. One of us (MAS) first carried out the task with unconstrained hands, taking about nine minutes to do the job. The plug was then unwired and the components returned to the state shown in Fig. 8(a). The ring and little fingers on both hands of the (same) human subject were then firmly constrained using bandages as shown in Fig. 8(b). In order to eliminate interference with the motions of the free fingers for the complex task at hand, the fingers were constrained in the fully flexed rather than in the fully extended positions, and care was taken to apply the bandages in a manner that left free the section of the palm associated with the unconstrained fingers. The IP joints of the thumb were also initially restrained using splints as shown in the figure.

As soon as the task was restarted it became clear that the constraint of the thumb IP joints was a prohibitive one, and it was nearly impossible to handle the pen knife (to initiate the splitting of the outer wire casing) and the screwdriver (to disassemble the plug cover). These joints were therefore released and the test started again.

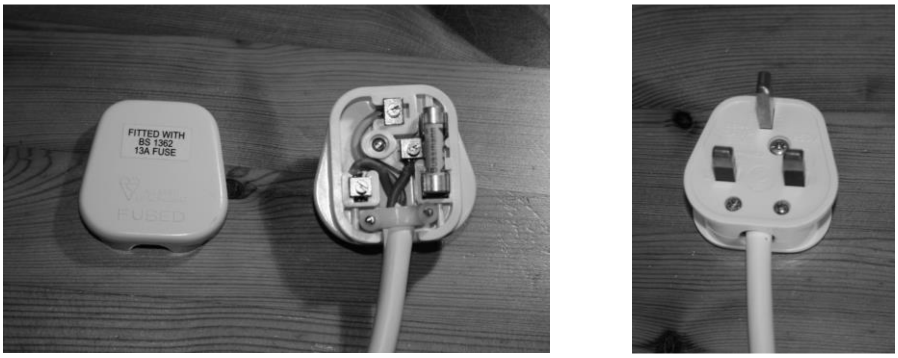
Although the human subject made some very minor changes to the normal handling of the tools (e.g. in opening the pliers), the task could now be carried out without any problems, in about the same amount of time as with the free hands. The installed wires are shown in Fig. 9(a), and the finished task in Fig. 9(b). This result provides evidence that is consistent with the sufficiency of the above proposed minimal anthropomorphic dexterous hand configuration for the achievement of a dexterity level that is close to that of the unconstrained human hand.

With respect to the constraining of the IP joint of the thumb, we have explored the reason for the discrepancy between the expected low dexterity penalty based on Fig. 7, and the actual much higher penalty experienced in the above task. We have observed that with this constraint it is possible to compensate using the other fingers, and to carry out certain manipulation tasks successfully *as long as it is not required to apply large forces / torques*. This is the case with the manipulation (e.g. rotation) of the keyed pegs in the GPT. However, if substantial torque is required, such as in the practical use of the screwdriver, it is no longer possible to compensate for a constrained thumb IP joint. This is an important observation because of the manner in which it links dexterity and strength. Here we are not talking about the trade-off between power and dexterity as

(a) Wiring task apparatus

(b) constraints for the wiring task. The thumb IP splints were later removed.

Fig. 8. Wiring task apparatus and constraints



(a) The installed wires

(b) The completed task

Fig. 9. Task carried out without use of the ring and little fingers

identified by Cutkosky and Wright,[23] but rather about a requirement for increased dexterity in order to enable the use of increased power during manipulation.

As a final general point to the discussion given in this section, we note that the potential adequacy of an anthropomorphic artificial hand that is missing one or both of its minor fingers has already been recognized intuitively to some degree by many researchers over the years. Thus for example, a number of early hands,[3,4] as well as of more recently built hands[46,47] have omitted the equivalent of the human ring and little fingers, whereas other anthropomorphic robot hands have been based on designs that omit the little finger.[7,48] In general however anthropomorphic robot hands with only three digits (i) have not been based on rigorous experimentation or analysis that demonstrated *a priori* that they are capable of executing tasks requiring dexterous manipulation; and/or (ii) have been considered as intermediate prototypes that would ultimately, or in principle, be “upgraded” to full five-digit hands. In the present work one of our intents is to demonstrate, through the systematic set of experiments as well as the validation task reported in this section, that a three-digit anthropomorphic hand may be sufficient in itself as an ultimate design goal even for applications that require the execution of complex manipulation tasks.

7. Conclusion

In this work we have taken a new approach towards the determination of the quantified contribution of various attributes of the human hand to its dexterity, with the aim of transposing this knowledge into supportive guidelines for the design of anthropomorphic robotic and prosthetic hands. These results are particularly significant in cases where it is important to optimize the trade-off between dexterity and complexity. The results represent empirically-derived upper limits on the achievable performance of humanoid robot hands having the specified deficiencies. Based on these results, the robot hand developer can predict in a quantifiable manner the impact of specific design decisions on the grasping and manipulation performance of the end product.

We have applied our results to derive empirically a configuration for a minimal anthropomorphic dexterous hand, which would incorporate the lowest possible number of degrees of freedom and other attributes while still retaining an acceptable level of dexterity. Based on the results presented in this work, such a hand would have nine specified degrees of freedom and an effective tactile sensing system, however the exact configuration of this minimal hand could be further refined through further investigation of the attributes of the thumb, and of the contribution to dexterity of the DIP joints of the human index and middle fingers.

Furthermore, we note that the development and use of a better targeted dexterity test which is able to test for a larger set of grasping and manipulation actions, including high torque application during manipulation, would give a wider representation of the quantified contributions to dexterity of the various hand attributes, and may also impact the selected configuration for a minimal hand.

The search for an effective minimal configuration for use in anthropomorphic dexterous hands is one that has immense commercial implications. In the not too distant future it is likely that a variety of humanoid robots for various common applications will appear on the market, and we anticipate that it would be sufficient for the basic models to be fitted with two such minimal hands. In the area of prosthetics, we feel that there is a sizeable segment of the market that would be more interested in the functionality of a hand prosthesis, and in the ease of attainment of this functionality, than in its strict aesthetic form. The minimal anthropomorphic dexterous hand would therefore also have an important potential application in this area.

With regard to the general problem of dexterity quantification, the dexterity of an artificial anthropomorphic hand system can in principle be measured by applying it to the same tests used to assess humans. Through an empirical approach of this nature, the dexterity of the hand structure would be extracted from its average test score while in teleoperation mode, therefore measuring the contribution to dexterity that is primarily due only to the hand itself. The dexterity of the full manual system, that would include the contributions also of the controller and of extraneous sensors such as cameras, would be extracted from the average score obtained in autonomous mode.

Acknowledgements

This work was partially supported by the University of Malta Research Fund Committee (grant number 73-528).

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