OPTIMISATION OF ANTHROPOMORPHIC ROBOT HAND DESIGN THROUGH HUMAN MANUAL DEXTERITY TESTING

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Abstract – In this work, a new systematic approach towards the classification of the attributes of anthropomorphic hands with respect to their influence on manual dexterity is proposed. This approach involves the application of standard manual dexterity tests, normally applied in medically related fields and in industry, on healthy human subjects who have specific attributes of their hands selectively constrained or blocked for the duration of the tests. The contribution of the constrained attributes towards manual dexterity can then be assessed from the test results. To demonstrate this method, we have investigated the contribution of different degrees-of-freedom of the human hand to its performance rating in the dexterity tests, with the objective of using the results to help us design a new robot hand that maximizes dexterity through optimal use of resources. Further applications of this approach are also discussed.

1. Introduction

The concept of dexterity in robotic grasping and manipulation has remained one that is difficult to define succinctly or to express as a quantifiable parameter. One reason for this is the wide variety in the design features of existing robot hands, as well as of robot hands that do not yet exist but that can be envisaged. This diversity of designs hinders the development of standard and/or universal methods of calculating the dexterity of artificial hands, since in general the dexterity of different hands may depend on different sets of parameters.

If we consider only robot hands that are anthropomorphic, then this problem is mitigated somewhat because the condition now imposes a limitation on the variety of possible design features of the hands, and therefore on the number and type of parameters that could be included in a standard dexterity formula. The derivation of such a formula, however, still remains elusive, because it is difficult to describe analytically, and in an encompassing manner, general properties such as the manipulation capability of an anthropomorphic hand. An alternative approach to this problem could involve the application of standard tests, which have long been available in medically related fields and in industry to obtain comparative measurements of manual dexterity in human subjects, towards the measurement of the dexterity of anthropomorphic robot hands.

In this work, we have followed this line of reasoning further and applied it to a common problem that is often encountered during the design stage of an anthropomorphic robot hand. This problem concerns the decision which almost invariably needs to be taken (for various reasons such as design complexity, budgetary constraints or time limitations), regarding which of the numerous specific attributes of the human hand to omit from the artificial model. A survey of anthropomorphic hands found in the literature reveals that none of these hands possesses all of the attributes of the human hand (see, for example, [1] for a comparative study of various robot hands). Among the attributes that are missing, to varying degrees, from these artificial hands, are specific degrees-of-freedom (e.g. missing digits, or missing joints on the available digits), sensory capabilities (e.g. no touch, force, and/or slip sensing) and actuator capabilities (e.g. coupled joints, or limited force capabilities). The selection of attributes to be omitted is often based on analytical estimates that can potentially lack objectivity, since different results can be obtained depending on the approach taken. In some cases, the selection of attributes may even be based purely on intuitive reasoning.

We suggest a new systematic approach towards the classification of the attributes of anthropomorphic hands with respect to their influence on manual dexterity. This approach involves the application of standard manual dexterity tests on healthy human subjects who have specific attributes of their hands selectively constrained or blocked for the duration of the tests. The contribution of the constrained attributes towards manual dexterity can then be assessed from the test results. To demonstrate this method, we have investigated the contribution of different degrees-of-freedom of the human hand to its performance rating in the dexterity tests, with the objective of using the results to help us design a new robot hand that maximizes dexterity through optimal use of resources.

2. Factors Influencing Manual Dexterity

A. General

Dexterity is a rather vague concept, and has been interpreted in many ways. Bicchi [2] defines dexterity as the capability of changing the position and orientation of a manipulated object from a given reference configuration to a different one. In the context of robot hands, it is generally understood to refer to the manipulation capabilities of end effectors which are human-like in design. Although concepts of a dexterity spectrum have been addressed [3], ranging from a simple pick-and-place end effector to the human hand, few formal or mathematical definitions for all-round dexterity have been defined, and these are primarily oriented towards representing the human hand using the Denavit-Hartenberg convention [4], [5].

Wright and Bourne [6] categorised different types of grasps, distinguishing between force and form closure, and showed the trade-off that exists between power and dexterity. This classification also demonstrated the relationship between the level of dexterity associated with specific types of grasp, and the size of the object.

The combinations of object size and shape, as well as forces applied, lead to a large variation in theoretical dexterous ability. Since there are undoubtedly many other factors that influence dexterity, it becomes very difficult to accurately define or predict the dexterous capabilities of an end effector.

B. Human Dexterity

The human manual system can very easily be broken down into several components, these being the brain, nerves, muscles and bone structure. These are clearly analogous to the components in a robotic hand, which are the controller, signal carriers, actuators and mechanical structure of the robot hand. The mobility of the arm and wrist also influence the effective dexterity of the manual system. Defects in any of these components will have an adverse effect on the overall performance of the robotic hand. Here again there exists an analogous system in 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 affect on dexterity [7].

One of the reasons why the human hand is so dexterous is due to the ability of the brain to serve as a controller as well as a knowledge base. Under normal operating circumstances, information from the eyes and the fingers is processed and, as a result, the material, texture, weight, temperature and strength of the object may be deduced. The best grip position and strength are then selected, based on previous experience, to grasp the object. A practical example of this would be picking up an egg. We recognise the shape, size and colour of the object to be that of an egg, and hence deduce that the object is fragile. From previous experience we also know how much force to exert in order to pick up the egg and what type of grasp is most suited – from the classification of [6], this would be a precision, compact, circular grasp. If the egg is steaming, we deduce that it has been boiled. We are aware that a boiled egg is not as fragile as a raw one, and therefore slightly more pressure can be exerted on the shell. We are also aware of the elevated temperature of the shell. Excessive pressure will increase the contact area and heat transfer, thus increasing the risk of damage to our fingertips.

The input of intelligence from the brain also plays an important role when the hand is not functioning properly. In the case of an injury or illness, mobility may be affected. The person can, through simple, perhaps involuntary, experiments learn to what extent he/she is limited, and modify certain motions to perform a task satisfactorily, despite the restricted mobility.

Whilst the medical field may not be particularly concerned with the attributes of the human hand that make it so dexterous, dexterity (or lack thereof) 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 standardised dexterity tests. Although optimum or ideal results for these tests cannot be ascertained for each individual, standard results exist, depicting the expected results according to age group, gender, and so on.

C. Manual and Mental Dexterity

The discussion above highlights the distinction that needs to be made between the contribution to dexterity that comes from the hand itself (e.g. mechanical structure, actuators, and sensors of the hand), and the contribution that comes from the controller of the hand (in the case of the human hand, the controller is the brain).

The control system of a human hand includes the brain, taking input signals from force, tactile, temperature and other natural sensors, as well as visual input. These signals are processed very rapidly and an output is sent to the muscles (actuators) via the nervous system. This closed-loop control system can be replicated artificially to some extent, with sensors now available to measure variables such as pressure, temperature and slip, however, the human brain offers far more capabilities than just a simple servo-controller. Among the most prominent characteristics of the human control system are its fast response time, its flexibility and its adaptability. As indicated above, another very important property of the human brain is its capability to serve as a vast knowledge base.

In the previous example, where the task is to grasp an egg, the brain recognises the object through this knowledge base. In recognising the egg, we immediately know that the shell is fragile, and through experience we know how much pressure should be exerted in order to successfully grasp the egg without breaking the shell.

This example clearly demonstrates the importance of the contribution of visual feedback, image processing and a knowledge base to the overall control system. More importantly, it exposes a strong link between a person's mental abilities and his/her manual dexterity.

This distinction between the contribution to dexterity that is due to the hand itself, and the contribution to dexterity that is due to the controller, must also be made in the case of robot hands. At the same time, the strong link that exists between the capabilities of the controller of the robot hand and the overall manual dexterity of the system must be recognised.

D. Anthropomorphism of Robot Hands

Many modern dexterous end effectors are based on the shape and functions of the human hand, i.e. they are anthropomorphic. This allows the programmer to visualise the motions with greater clarity. The use of a glove input device to control the hand further simplifies matters, since this enables automatic tracking of the motions of the operator's hand, as opposed to the requirement for manual programming of the sequence of movements to be carried out.

In [1], Biagiotti *et al* carried out a comprehensive study on various anthropomorphic hands currently available or under research, detailing the physical, mechanical, sensory and kinematic properties of these end effectors. In an attempt to quantify anthropomorphism, the authors defined an 'anthropomorphism index', consisting of a weighted sum of ten aspects associated with anthropomorphism, with each aspect related to either the kinematics, the nature of the contact surfaces or the size/proportion of the robot hand in comparison to the human hand. For a given hand, each of these aspects would be assigned a score between zero and one, in accordance with its similarity to the corresponding feature in the human hand. Based on this measure, the human hand serves as the reference and has the maximum index of ten.

E. Specific Attributes of the Hand

The human hand, independently of the contribution from the brain, nerves, eyes, arm and wrist, has a number of specific attributes that directly influence its dexterity, and that may be replicated, to varying degrees, in a robot hand. These include the number of degrees-of-freedom; the range of motion of each of these degrees-of-freedom; the speed capability of each of the degrees-of-freedom; the maximum force as well as the force resolution that can be applied by the fingers and thumb; the presence, ranges and resolutions of force, touch, slip and temperature sensing mechanisms on the hand; and the limits of ambient conditions (e.g. force, temperature) that can be withstood without damage to the hand.

Here we consider only one of these attributes, that of the number of degrees of freedom. The human hand has 21 degrees-of-freedom: 4 for each finger, and 5 for the thumb. Therefore, in order to replicate the human hand correctly, an anthropomorphic end effector would need to have all 21 degrees-of-freedom. In practice, such a high number of joints and mechanisms would make the end effector bulky. Although miniature components do exist, their use would dramatically increase the complexity and cost of the end effector. For practical reasons, it is therefore desirable to minimise the number of degrees-of-freedom to be incorporated in the robot hand. In order to optimise the performance capability of the hand and its dexterity, it then becomes vital to select correctly which of the 21 degrees-of-freedom to leave out when designing the artificial hand.

3. Dexterity Tests

Dexterity tests are used commonly in industry, in areas such as screening and employee selection. In areas that involve the operator carrying out manual tasks, especially those of a repetitive nature, the selection process for employees would involve specific dexterity tests, which may be designed to investigate different aspects of dexterity – speed, precision, coordination etc. These tests may range from simple reflex actions, where a response to stimulus is tested, to more complex manipulative tasks involving assembly and/or positioning of objects.

As mentioned previously, the medical field also has an interest in testing for dexterity. These tests can be designed to pin-point problems or deficiencies within the human manual system and also to help diagnose and monitor conditions relating to different parts of the system.

In this research, tests were carried out to investigate the individual degrees-of-freedom of the hand, with regard to their contribution to the overall manual dexterity. This would then assist in identifying which degrees-of-freedom are more, or less, critical when performing a particular range of tasks. Transposing this information from the human field to the robotic field, a robotic end effector could then be designed more effectively, with redundant or unnecessary degrees-of-freedom being omitted. Here, the strong connection between mental ability and manual dexterity was exploited, and a series of standard medical tests were chosen. The results of these standard tests are normally used to gauge mental ability according to manual dexterity [7]. In our case however, we attempted to do the reverse, i.e. to gauge manual dexterity from the results, assuming the subject has normal mental abilities. Brief descriptions of the more popular dexterity tests are given below. Most involve some measure of time or speed, and tasks vary according to what aspect of dexterity is being investigated (gross motor, fine motor etc.).

Minnesota Rate of Manipulation Test (MRMT):

The MRMT (Fig. 1a) consists of a rectangular base with evenly positioned holes. Large checker-like disks painted black on one side and red on the other are provided. The board is placed in front of the person and five tests are performed: placing, turning, displacing, one-hand turning and placing, and two-hand turning and placing. This test is used to measure hand-eye coordination and gross motor skills.

Grooved Pegboard Test:

The Grooved Pegboard Test (Fig. 1b) is a manipulative dexterity test consisting of a board with slotted holes, having random orientation. Pegs with a key along one side are rotated to match the slot before they can be inserted. This test requires more complex visual-motor coordination than most pegboard tests, and is also influenced by the subject's fine motor skills.

Purdue Pegboard Test:

The Purdue Pegboard Test (Fig. 1c) consists of a test board having two columns of holes. At the top of the board there are four cups containing metal pins, washers and collars. There are various tests, including placing the pins in the holes using the right hand, left hand and both hands, assembly of sets of pin–washer–collar–washer groups and inserting them into the holes on the board. This test measures fine motor dexterity and differences between the dominant and nondominant hands.

O'Connor Finger Dexterity Test:

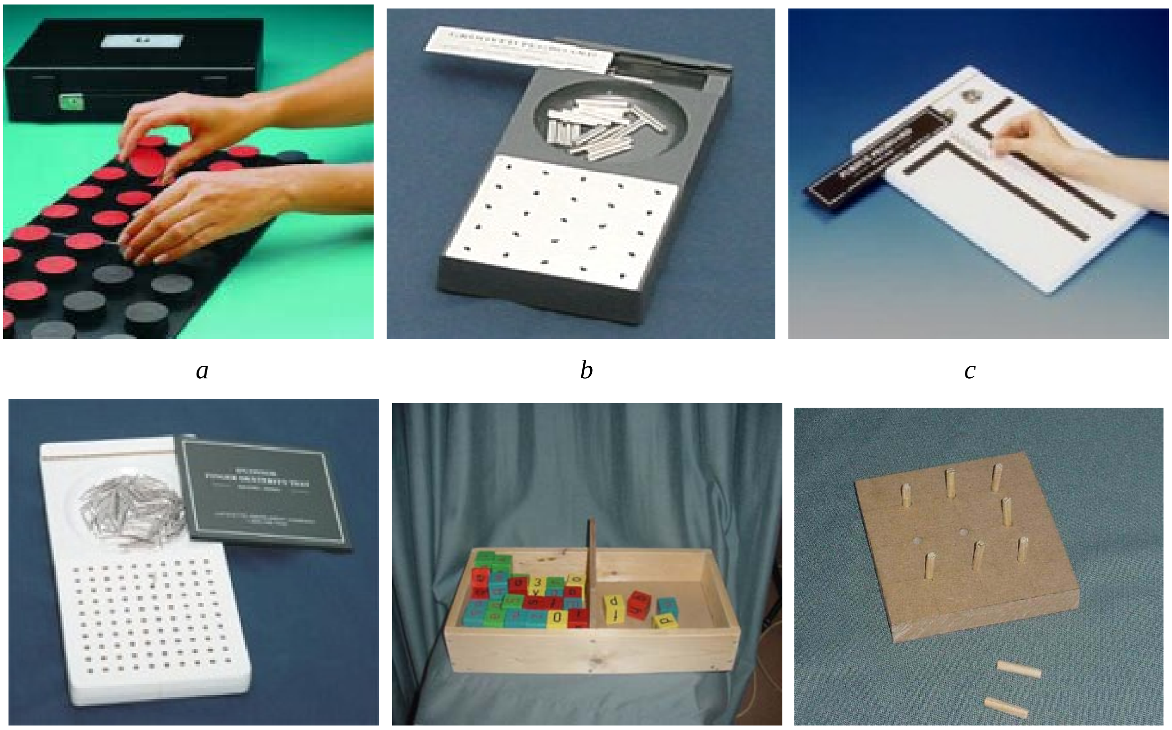
The O'Connor finger dexterity test (Fig. 1d) requires hand placement of three pins per hole in a number of holes on a board. This test has been used successfully as a predictor for rapid manipulation of small objects, as in assembly line work. It has also been found useful in predicting success for instrument work, such as the assembling of armatures, miniature parts of clocks and watches, rapid hand and eye work, filling vials and small lathe work.

O'Connor Tweezers Dexterity Test:

The Tweezers Dexterity Test is similar to the O'Connor finger dexterity test, and requires the use of tweezers in placing a single pin in each 1.5mm diameter hole. A high score indicates manual aptitude for work involving the use of precision small tools, such as hair replacement procedures.

Box and Block test:

The Box and Block test (Fig.1e) was originally developed to evaluate the gross motor manual dexterity of adults with cerebral palsy. The test consists of a partitioned box having two equal sides with wooden blocks placed randomly in one side of the box. Using one hand, the human subject is required to grasp one block at a time and transport it over the partition into the opposite side, transporting as many blocks as possible within a specified time limit.



a *b* *c*

d *e* *f*

Figure 1
Reproduced from [8]

Nine-Hole Peg Test:

The nine-hole peg test (Fig. 1f) consists of a square base having nine equidistant holes, and nine pegs that are kept separate from the base. The person is required to place the nine pegs into the holes in any order, and then remove them whilst being timed. This test measures finger dexterity and fine motor dexterity skills.

Although many more standardised dexterity tests do exist, the ones that have been outlined above are relatively straightforward to perform, without needing complex manipulative or coordinative tasks. This property is important because a broad investigation of manual dexterity is needed before more detailed analysis can be carried out.

The Box and Block Test, and two versions of the Nine-hole peg test were chosen for our experiments. The first peg test had slender pegs, 8mm in diameter, and the second had 18mm diameter pegs. The time limit for the box and block test was set at thirty seconds. The selected tests do not involve complex reasoning or movement patterns, therefore minimising the effect of differences in mental acuity that may exist between the human subjects. Moreover, the apparatus needed to perform the selected tests can be bought off the shelf or easily manufactured.

4. Experimental Procedure

The aim of the experiments was to investigate the effects that certain imposed restrictions to mobility may have on the overall dexterity of the human hand. This was done by carrying out a series of dexterity tests that were repeated several times by a group of volunteers, each time altering the restrictions on the subjects' hands. The effects of these alterations on the test results were later analysed.

Although the human hand has a large number of degrees-of-freedom, the tests that were carried out investigated the thumb, each of the four fingers, and the wrist as whole units, and not broken down into their individual joints. Thus, for example, experiments were carried out with each finger either fully restrained, or completely free. Restraints were imposed by using splints or braces, preventing the person from utilising the full dexterity of the hand. Figure 2, for example, shows the nine-

Figure 2

hole peg test being carried out with the middle and ring fingers restrained. Treatment and comparison of the results would then show the effects of eliminating certain sets of degrees-of-freedom on manual dexterity.

The tests required the participation of a group of persons, and selection criteria were set for the human subjects as follows:

- Gender: male and female, roughly equal proportions.

  This was in order to obtain a sample closely resembling the actual population

- No history of serious injury to hand, wrist or upper extremity of forearm resulting in impaired movement of the hand.

- Not suffering from any disease or chronic disabling condition (no orthopaedic or neurological dysfunction, no congenital abnormality).

- Functional visual acuity.

  These three criteria helped to eliminate external influences and sources of error by preventing any condition other than the imposed restrictions from inhibiting the subject.

- Ability to follow the test instructions, thereby signifying an average intelligence.

  An average intelligence was needed in order to minimise any hesitation of the subject during the experiment.

- Right-handedness.

  Apparatus and subject positioning may have had different effects on right- and left-handed people, hence the tests were set up in favour of right-handed people as they are predominant in the actual population.

A minimum of at least two fingers and the thumb were kept unrestrained in all the experiments, in order to maintain a minimum degree of anthropomorphism in the grasp. Here, it was assumed that the thumb is always necessary for grasping and manipulating tasks. In the case of the wrist, immobilisation was achieved by using a hard brace to restrain the pitch and yaw motions. Roll of the wrist could not be restrained since this is actually a function of the forearm and not the wrist joint itself.

The test subjects were first instructed to perform the Box and Block Test without any hand restraints, and were given a trial period of 2 minutes. Since each experiment would be repeated many times, the practise period was intended to reduce the effect of gradual improvement in performance each time the test was repeated.

The actual test with the unrestrained hand was carried out next, and this had a time limit of 30 seconds in which to transport as many blocks as possible. The test was then repeated with the first restriction, this being the immobilisation of the wrist pitch and yaw motions. The restriction was accomplished by using a hard wrist brace. Following this, the wrist brace was removed and the test was carried out with the index finger immobilised using a wooden splint. The splint was then removed and the procedure was repeated again for the middle, ring and little fingers respectively restrained, with only one finger restrained in any one test.

Figure 3

The next group of tests involved immobilising two fingers at once, and were carried out six times, as each combination of two out of the four fingers (*index and middle; index and ring; index and little; middle and ring; middle and little; ring and little*) was tested.

This procedure of practising, performing the test unrestrained, and subsequently performing the test with the whole series of restraints was then used for both variants of the Nine-Hole Peg Test (Fig.3). In these tests, the time taken to place and remove the nine pegs was recorded instead of the number of blocks transported.

In all the tests, when an object was being held, it was required to be in a stable grasp. If the object was dropped, the test was halted and restarted. These precautions were taken in order to minimise any effect of progressive learning as the test was taking place, and to minimise inconsistencies in the results.

5. Test Results

Each of the three dexterity tests was attempted 12 times, once for every combination of restricted degrees-of-freedom and once unrestrained. The results are shown in Tables 1, 2 and 3.

For each of the three tests, readings were plotted as superimposed series, with each series representing a person. Separate graphs were plotted for the box and block test (Fig. 4), the nine-hole peg test with small pegs (Fig. 5), and the nine-hole peg test with large pegs (Fig. 6). In these graphs the ordinate shows the elapsed time or number of blocks transported, as applicable, whereas the categories on the abscissa show which degree-of-freedom was immobilised. These categories were sorted in order of increasing average elapsed time (or decreasing number of blocks) such that the best mean result was on the left hand side and the worst on the right. (This sorting was also applied in the Tables 1, 2, and 3).

6. Analysis of Results

The superimposed plots shown in section 5 were not in a form that could be interpreted clearly, so further processing of the results was carried out. The readings were normalised in order to accentuate any trends that may have been present. Normalising involved shifting each series vertically, such that the mean times for all ten people became coincident. The coincident point was chosen arbitrarily as the mean of all ten means. New graphs were then plotted for the normalised readings of box and block test (Fig. 7), the nine-hole peg test with small pegs (Fig. 8), and the nine-hole peg test with large pegs (Fig. 9).

Although these normalised results indicated possible trends, the number of volunteers taking part in the tests was small and may not have yielded an entirely accurate set of results, when compared to the dexterous capabilities of humans in general. For this reason, statistical analysis was carried out on the primary set of readings in order to obtain a more accurate picture.

The approach chosen was to obtain a confidence interval for the population mean from the available small sample. This standard statistical analysis can be found in many texts such as [9].

Person	Restrained degrees-of-freedom											
	little	ring + little	none	wrist	middle + little	ring	middle	middle + ring	index	index + little	index + ring	index + middle
1	19	18	20	17	15	18	16	14	17	17	16	13
2	22	20	21	18	18	18	21	21	20	18	16	19
3	24	22	21	19	23	19	19	19	18	20	16	13
4	22	19	23	22	18	20	17	19	19	16	16	17
5	33	29	29	30	30	28	32	31	29	32	29	24
6	25	24	21	21	21	21	21	20	20	21	21	21
7	28	28	22	25	25	25	23	25	24	22	24	22
8	32	31	25	30	32	31	30	30	28	31	31	30
9	29	27	28	27	24	25	22	22	24	22	23	21
10	27	27	27	25	24	22	24	23	23	23	22	23
mean	26.1	24.5	23.7	23.4	23.0	22.7	22.5	22.4	22.2	22.2	21.4	20.3

Table 1: Number of blocks transferred in 30 seconds during the box and block test

Person	Restrained degrees-of-freedom											
	little	ring + little	none	ring	wrist	index	index + little	middle + little	middle	middle + ring	index + middle	index + ring
1	22.3	22.6	27.9	24.3	28.7	26.6	27.4	31.5	30.7	31.3	29.9	34.6
2	20.0	18.1	21.8	22.2	21.4	25.2	25.0	26.3	25.9	30.7	30.6	29.5
3	18.5	16.9	18.1	16.3	18.9	17.5	17.0	19.9	23.1	27.7	21.0	26.6
4	21.2	23.7	19.4	21.4	23.5	23.2	27.1	19.7	27.8	26.9	30.5	24.2
5	17.2	15.3	16.2	15.8	18.5	18.3	20.0	21.6	23.8	26.5	26.5	26.5
6	18.5	21.9	22.1	22.7	20.0	22.1	22.9	23.0	23.7	29.2	28.0	34.6
7	17.9	17.4	20.3	18.7	18.0	19.7	19.2	19.3	18.8	22.4	24.1	24.3
8	15.3	14.4	14.5	16.5	14.6	16.0	17.5	17.2	17.8	18.1	18.2	19.2
9	16.8	22.2	16.9	18.6	20.6	22.0	18.3	20.9	21.2	16.9	27.2	32.3
10	16.0	20.2	18.2	19.5	20.2	20.3	19.1	19.5	19.8	22.5	23.2	28.8
mean	18.4	19.3	19.5	19.6	20.5	21.1	21.3	21.9	23.3	25.2	25.9	28.1

Table 2: Time (seconds) for nine-hole peg test with small pegs

Person	Restrained degrees-of-freedom											
	little	none	ring	wrist	index	ring + little	index + little	middle + little	middle	index + middle	middle + ring	index + ring
1	18.0	20.8	19.3	21.8	20.8	18.9	23.1	24.0	25.6	22.4	25.0	26.6
2	16.9	17.8	19.7	19.2	19.2	24.7	21.3	22.0	19.3	23.7	24.4	24.2
3	13.9	15.8	15.4	15.7	14.8	15.1	15.7	16.1	16.2	17.4	18.6	20.6
4	18.0	17.9	18.5	16.2	20.8	17.8	22.2	23.7	22.7	24.2	21.5	21.8
5	12.1	14.2	13.6	15.2	14.7	13.6	14.5	15.1	16.7	17.7	17.2	18.1
6	15.9	20.3	16.4	18.1	17.2	19.7	18.0	19.0	18.5	21.7	21.9	23.6
7	13.1	15.9	14.3	15.3	14.3	14.2	16.1	15.7	16.0	17.7	16.5	18.8
8	10.6	11.2	12.7	12.6	12.8	11.3	12.2	11.9	12.8	14.7	14.4	13.7
9	15.7	14.6	16.5	15.0	15.0	15.7	16.2	16.7	20.8	18.2	18.5	20.5
10	12.5	13.7	16.7	15.5	15.0	15.7	14.6	16.0	14.6	16.6	21.7	18.9
mean	14.7	16.2	16.3	16.5	16.5	16.7	17.4	18.0	18.3	19.4	20.0	20.7

Table 3: Time (seconds) for nine-hole peg test with large pegs

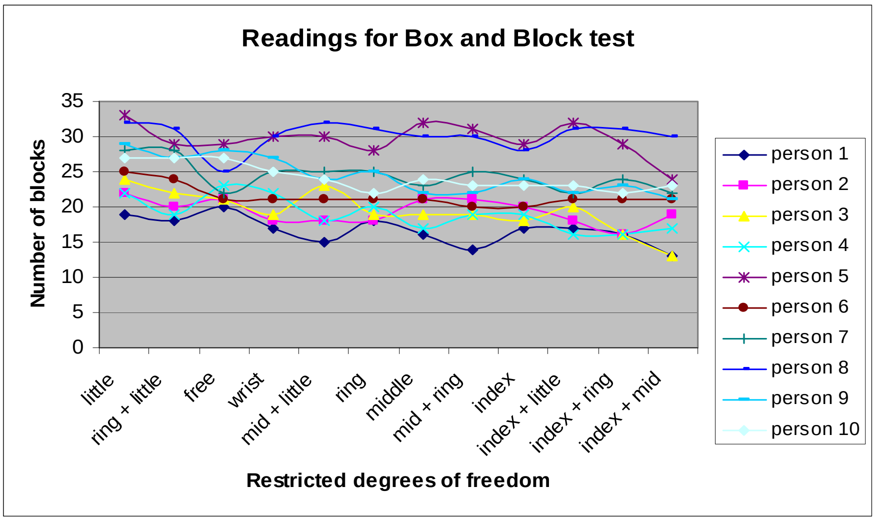


Figure 4

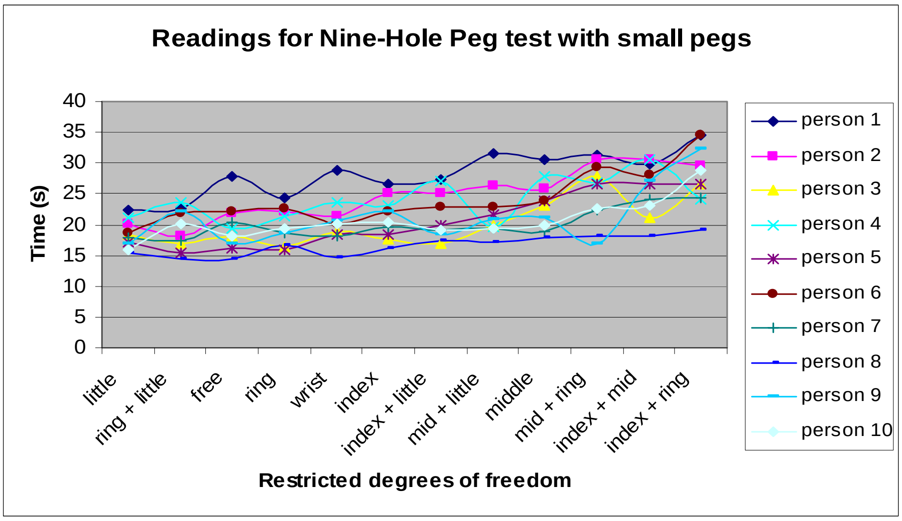


Figure 5

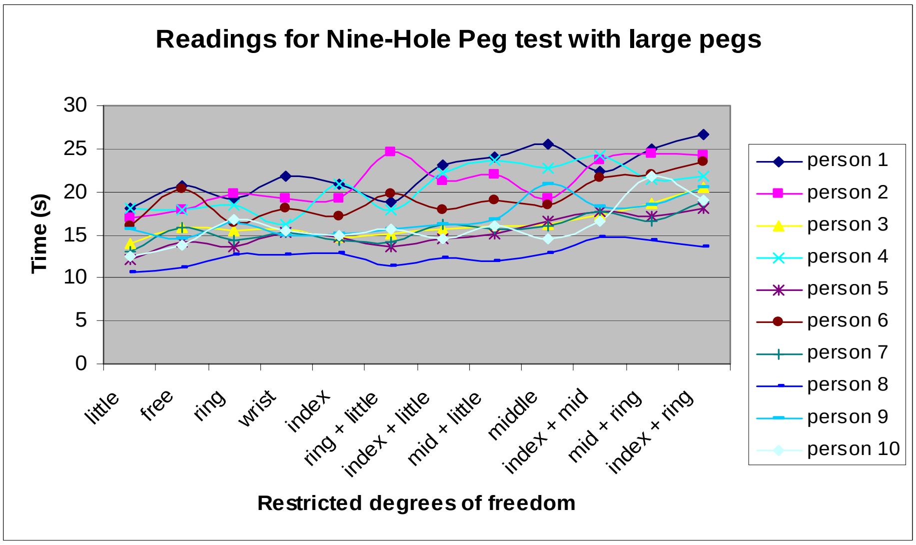


Figure 6

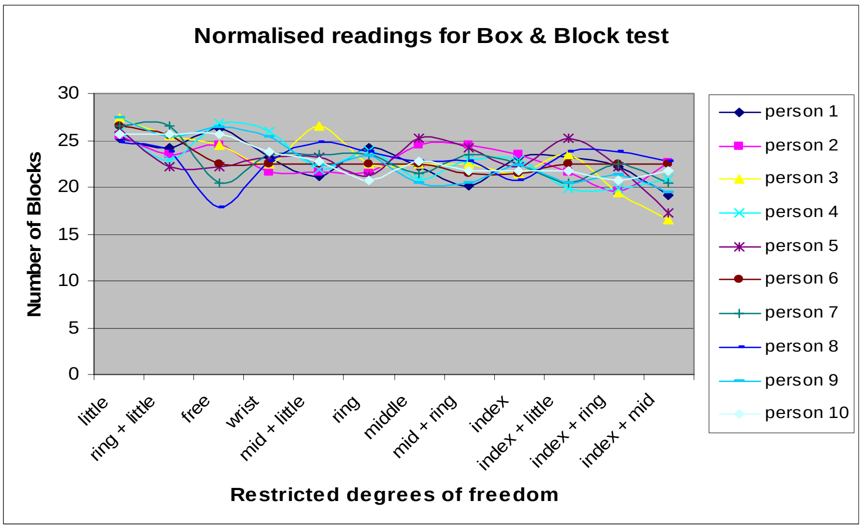


Figure 7

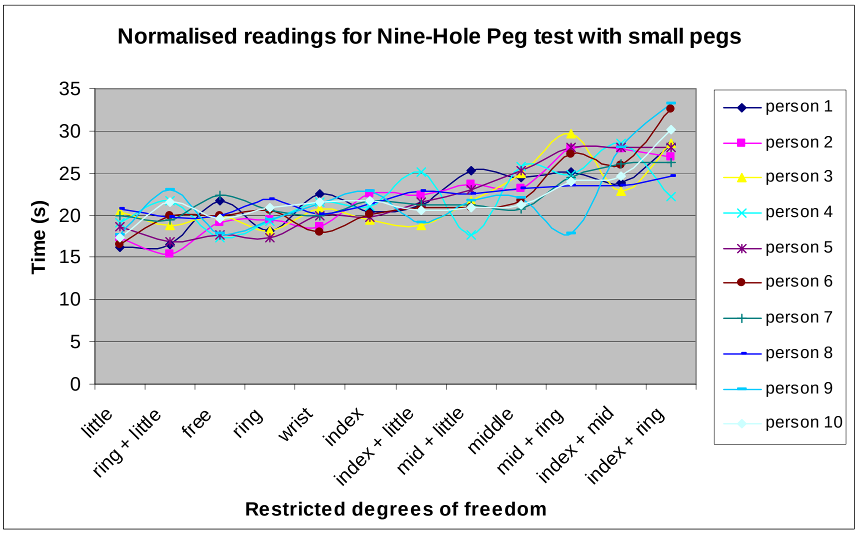


Figure 8

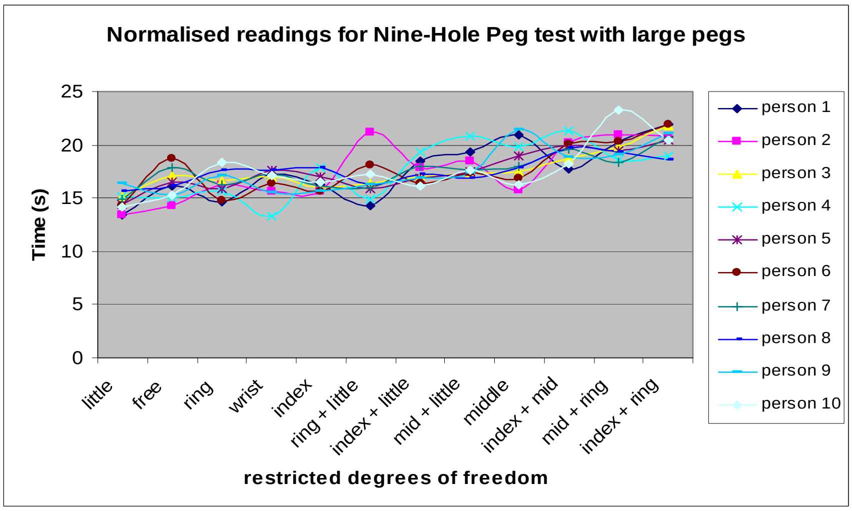


Figure 9

We set

$$\bar{x} = \frac{1}{n}\sum x_i$$

$$S^2 = \frac{1}{n-1}\sum (x_i - \bar{x})^2$$

where

x_i is an individual reading;
n is the sample size; and
$\bar{x}$ is the sample mean

Then, if the population is normally distributed with mean μ,

$$t = \frac{\bar{x} - \mu}{S/\sqrt{n}}$$

is a random variable having the *t*-distribution with parameter $\nu = n - 1$.

Using standard tables for the *t*-distribution it can be shown that, from measurements taken on a given sample, there is 90% certainty that the population mean is within the limits

$$\bar{x} - 1.833\frac{S}{\sqrt{n}} \leq \mu \leq \bar{x} + 1.833\frac{S}{\sqrt{n}}$$

For each combination of joint restraints in each test, the upper and lower limits for the population means (equivalent to 90% confidence error bars) can therefore be obtained.

Graphs of the resultant confidence intervals, for the box and block test (Fig. 10), the nine-hole peg test with small pegs (Fig. 11), and the nine-hole peg test with large pegs (Fig. 12) were then plotted.

6. Interpretation of results

From the results of the box and block test (Fig. 10) a number of factors are apparent. The first is that most of the graph is rather flat, i.e. there does not appear to be a lot of difference between the different combinations of finger restraints with regard to dexterity as measured by this test. In fact, through visual observation during the test itself, it was apparent that the box and block test was greatly dependent on gross motor ability and the speed of the upper arm and shoulder. Whilst dexterity was important in order to grasp the blocks, a greater portion of time was spent transporting rather than grasping. The restraints would therefore have affected only a small percentage of the time involved in the test, specifically the periods during which the blocks were being grasped. The points that are towards the far left and the far right of the graph do however indicate a difference in dexterity, as measured by this test, which could be significant.

The second observation that is made from Fig. 10, in fact, is that all four combinations that involved the restraint of the index finger appear on the far right of the graph. This would indicate that the restraint of the index finger has the most detrimental effect on the performance in this test, and therefore that the index finger, from among the four fingers, has the greatest contribution to dexterity as measured in this test. This would in turn indicate that the index finger may have the greatest contribution towards gross manual dexterity, i.e. in tasks that mainly involve grasping, transportation and releasing of objects of this size. This result contrasts somewhat with earlier results obtained in our laboratory, where we concluded that out of the index, middle, and ring fingers, it was the index finger that contributed the least force during grasping and holding of an object [10]. We reconcile these results by suggesting that whereas the index finger may exert less force while holding an object (perhaps due to the inclination of the plane of the flexion motion of the finger with respect to that of the opposed thumb), it may still be the most important finger during the actual grasping process, perhaps due to its contribution in locating the object to be grasped.

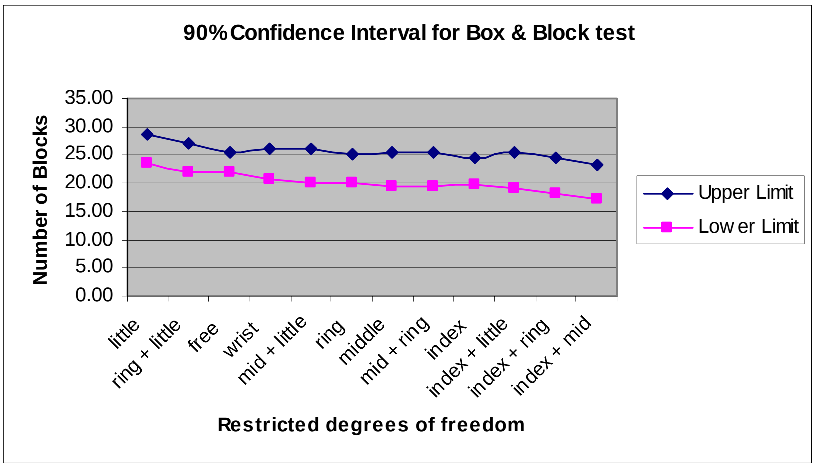


Figure 10

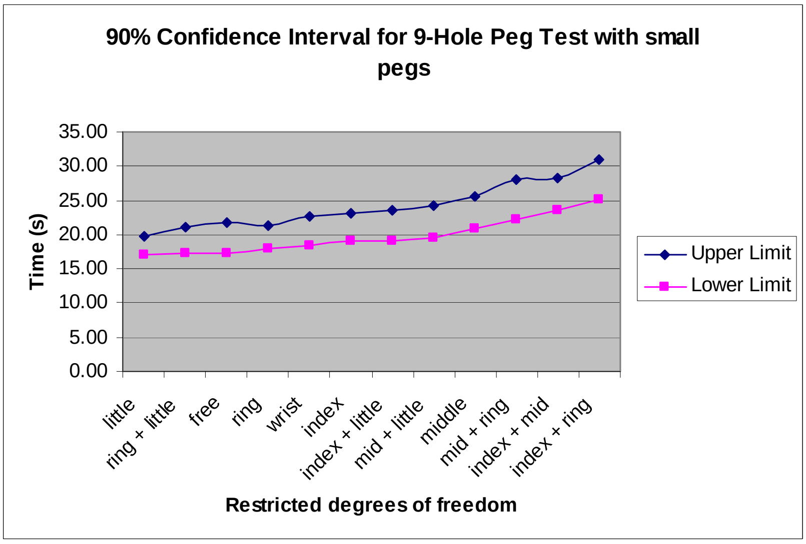


Figure 11

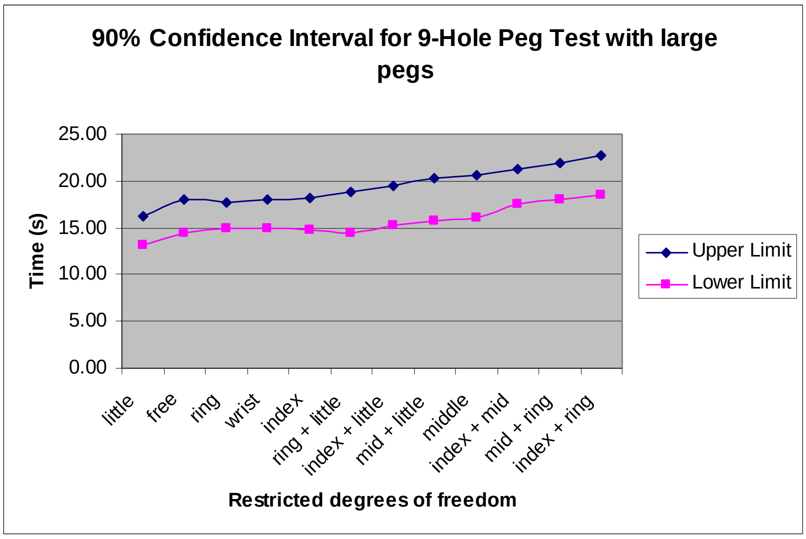


Figure 12

A third, and surprising, observation from Fig. 10 is that there are two combinations that involve the little finger that lie to the left of the *no restraint*, or *free* result. This would indicate that the restraint of the little finger may have been *advantageous* to the performance in this test. In fact, in *all* of the tests (see also Figs. 11 and 12), the performance was best when the little finger was restrained. Although this was unexpected, it agreed with several remarks made by the subjects during the tests themselves. They claimed that when the restrained finger was one that is rarely used for that type of task, they were able to concentrate more effort on grasping and manipulating with the remaining unrestrained fingers, hence improving their performance. It was also noticed that even when the middle and ring fingers were restrained, few volunteers used their little finger. Instead they preferred to use just the thumb and one opposing finger.

In the results for the nine-hole peg tests, Figs. 11 and 12 both indicate that the measured dexterity is most adversely affected, as expected, when a combination of two of the three major fingers (index, middle and ring) are immobilised. The deterioration in performance is more marked in the test that used the small pegs than it is in the test that used the large pegs. These observations indicate that for fine motor dexterity it is important to have at least two of the major fingers free in order to carry out the required manipulation. They also indicate that this effect increases when the object being handled becomes smaller, and therefore when the demands for fine manipulation increase. In both Figs. 11 and 12 the performance was worst when the index and ring fingers were restrained, indicating that the greatest problems with fine manipulation were encountered when the subjects used only the thumb and middle finger. One possible explanation for this is that this configuration afforded significant obstructions, by the restrained/unused fingers, on both sides of the middle finger during grasping.

In both of the nine-hole peg tests, performance was significantly worse when the middle finger was restrained alone, than it was when either the index or ring finger was restrained alone. This result was expected, since it is more difficult to manipulate an object when the two major fingers being used are not adjacent fingers. We also note that when the middle finger is restrained in the extended configuration (as it was in this part of the test), there is a marked reduction in the mobility of the index and ring finger, due to the natural constraints of the hand.

In all three of the tests, restraint of both the ring and little fingers simultaneously had an insignificant effect on performance when compared to the free hand. Indeed, in the box and block test as well as in the nine-hole peg test with small pegs, performance was marginally increased.

In all three tests, the performance when the wrist pitch was restrained was only slightly worse than the performance with the free hand. This indicates that the human subjects were able to compensate for the restraint using the joints of the arm. Another important observation from all three tests was that when the dominant fingers were restrained, the subjects performing the tests commented that they needed to exert more force in order to hold the object securely. This agrees with Wright, Demmel and Nagurka [11] in their description of the trade-off that exists between dexterity and strength.

7. Applications

The results obtained in this work, as well as the general approach that has been suggested here, have a number of potentially useful applications to the design of robotic manipulation systems. For example, the above results indicate that construction of a robot hand comprising only of the thumb, index and middle fingers, may not result in a significant reduction in dexterity, at least in so far as activities similar to the ones in the above tests are involved. In such a hand:

i. The index finger, identified as the most important finger, is retained;
ii. The little finger, identified as a possible hindrance to dexterity, is absent;
iii. The ring finger, identified as being inconsequential when restrained in conjunction with the little finger, is also absent;
iv. Two of the three major fingers are present, and these two fingers form an adjacent pair;
v. These two fingers are the ones that are capable of applying the most force, which is a significant compensating factor if a situation of reduced dexterity arises.

An indication of the dexterity of such a robot hand could be obtained by subjecting it to the above tests, and comparing the results obtained to those achievable by the human hand. In order to remove the effects of the brain and eyes on the dexterity assessment (i.e. in order to ensure that what is being measured is only the contribution to dexterity that comes from the hand itself), such an experiment would need to be carried out in teleoperation mode, using a whole-hand input device worn by a human subject to control the robot hand. In such a situation, the dexterity scores obtained by the human subjects using their own natural hand with the ring and little fingers restrained may provide an upper limit, or benchmark, for the dexterity level that would be achievable by the robot hand.

The observation made by the human subjects during our experiments, in that unused degrees-of-freedom may provide a hindrance to performance, may be applied to the design of more effective teleoperation systems involving anthropomorphic hands and glove input devices. Our results indicate that if the operator's hand were restrained, by means of the glove, such that only motions that were possible with the anthropomorphic robot hand could be performed, then the system may be easier to control. Indeed this concept could be applied to all teleoperation applications where the human operator is controlling a slave device through analogous motions of his/her body. It may also be applicable to situations where the human operator is instead controlling an entity in a virtual reality environment.

7. Conclusion and Future Work

In this work, we have demonstrated a new approach to evaluate the contribution of various attributes of the human hand to its performance in standard dexterity tests. The results of the tests can be used to evaluate the benefit of including each of these attributes in a robot hand. Our future work in this area will focus on extending the human tests to include the restraining of the individual finger and thumb joints, and also by attempting to block other attributes of the hand such as the sense of touch. Another future task will involve an attempt to decouple the contributions of mental and manual dexterity to hand performance, by carrying out tests using one or more anthropomorphic robot hands with varying features controlled by a glove input device. In these latter tests, the degree to which the human brain is able to compensate for deficiencies in the robot hand will give an indication of the contribution of mental dexterity to test performance.

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