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A graphic model of the human hand using CATIA

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Abstract

Anthropometric measurements were made of the hands of 32 subjects. Data from this survey were used in the design of a graphic model of the male human hand. The model was created in the computer-aided design (CAD) package CATIA and reproduced any desired overall hand size. It was made up of 24 solid segments with 23 degrees of freedom at 17 moveable joints. Spans and grasping sizes of the model hand were examined. The representation of the model appeared realistic in several postures, but the model was found to allow some motions which would be impossible for an actual hand. The model could be used to help a designer visualize hand-held products and controls in use.

Relevance to industry

Such a graphical model of the human hand would be a useful addition to a CAD graphics package to be used by industrial designers and ergonomists in the design of hand tools and other hand-held products.

Keywords

Hand; Graphic model; Computer-aided design; Anthropometry

1. Introduction

Computer-aided design (CAD) systems speed up and simplify many parts of the design process but have some drawbacks in the design of products for human use. Without the use of graphic images, it may be difficult for a designer to ensure that the final product can be handled easily and effectively by a human operator. Algorithms and rules of thumb may be used to incorporate the requirements of human anatomy into technical designs, but the great variety of postures, motions and types of products involved limits the utility of this approach. In many cases it is simpler to include a model of the human body in a solid modeling CAD package and to design products around it.

1.1. Background literature

There are a number of whole-body anthropometric modeling programs which can be used in the design of products and workplaces. Several are described and compared by Dooley (1982) and by Leppanen and Mattila (1987). Few whole-body models currently in use include sophisticated articulated hands. This absence may limit the designer's ability to model a grasping action.

Many robotic models with realistic proportions have been developed to simulate the motions (Jacobsen et al., 1984; Mason and Salisbury, 1985; Becker and Thakor, 1988). Typically these are precise models based on the bones and tendons

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of the hand of a single subject and cannot be scaled for other individuals (Buford et al., 1986; Buford and Thompson, 1987; Giurintano and Thompson, 1987).

1.2. Conceptual framework for a CAD hand model

A simplified model of the hand with realistic proportions could be used in computer-aided product design. Alone, it could be used in the design of hand-held products, allowing the designer to visualize how the product could be held. Combined with an existing human body model, it would allow a more realistic display of human notions and actions. For such a model to be useful, five criteria would have to be met:

First, the model should approximate the geometry of a human hand closely enough to be useful for designers, while remaining simple enough to require a minimum of computer memory and processing. Second, the model should limit motions of joints of the hand to realistic postures. Third, the model should be expandable so that modifications or additions may be made. Fourth, the model should be scalable so that different populations and percentile groups can be represented. Fifth, the user should be able to check for intersections between solid sections of the hand and between the hand and a solid object being grasped.

A method of analyzing intersections between various sections of the hand and objects modeled within a grasp would be required to indicate a situation in which tissues of the hand (or soft material in a product) would be deformed. It should be possible either to calculate the depths of such intersections or to limit possible interferences to the allowable level of tissue deformation of each part of a hand. This may be done by the CAD package used as an operating environment.

A solid graphic model based on the proportions of the male human hand was created. Measurements were taken from the literature and from an anthropometric survey. The model had 24 solid segments and 23 degrees of freedom at 17 moving joints. It was developed in the CATIA CAD package. For this study, the model was scaled to the fiftieth percentile measurements of overall hand dimensions found by Garrett in a study of male U.S. Air Force recruits (Garrett, 1970). The model was put in several postures and evaluated (subjectively) for realism. The maximum spanning and grasping sizes of the model were compared to those reported for the population whose overall hand measurements were used (Garrett, 1968).

2. Development of the model

The objective of this project was not to precisely model the bones of the hand or the movements of tissues, but to create a graphic model which could be made to follow configurations, motions, and dimensions of the hand closely enough for use in designing products for a given population. Data describing proportions and allowable motions of the hand were taken from the literature and from an anthropometric survey. The model was created in CATIA Version 3.1 on an IBM 5080 graphics terminal. The survey and the graphic model are more fully described by Davidoff (1990).

2.1. Data collection

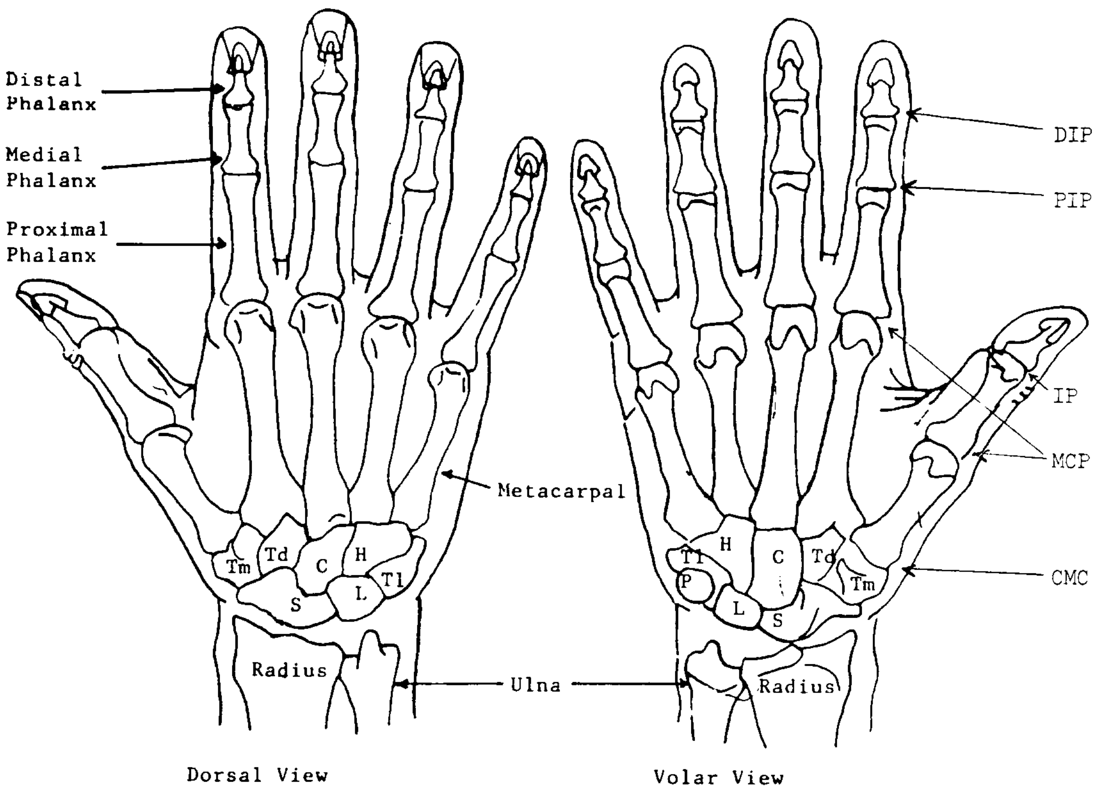
Bones and joints of the hand are identified in Fig. 1. An anthropometric survey was made with 32 subjects (15 men and 17 women). Measurements included dimensions of the palm and of the metacarpal region of the thumb, lengths of the phalanges of the digits, and ranges of passive motion of all metacarpophalangeal and interphalangeal joints in flexion and extension.

All dimensional measurements were calculated as a percentage of overall hand length, breadth and thickness. Data from male populations were used in the development of the hand model created in this study. The model could be rescaled in three dimensions for use with any male population. A separate set of dimensions were found in the survey for a female population, but these were not tested.

Many good estimates have been made of the overall dimensions of the hand for different populations. The model could be easily adjusted in three dimensions based on a proportion of the overall hand size. Certainty of the dimensions of each segment would allow a full hand model to be constructed directly from the segments, but such a model would have to be modified for each individual subject. For this study, the model was scaled to the fiftieth percentile measurements of overall hand dimensions found by Garrett in a study of male U.S. Air Force recruits (Garrett, 1970).

2.2. Geometry and motions of the model

The model consisted of 24 solid sements, not all of which moved: carpal (wrist) segments underlying each digit except the thumb, metacarpal segments for each digit, proximal, medial and



Carpal Bones
(Bones of the Wrist)

Tm -- Trapezium

Td -- Trapezoid

C -- Capitate

H -- Hamate

Tl -- Triquetral

S -- Scaphoid

L -- Lunate

P -- Pisiform

Joints of the Hand *

DIP -- Distal Interphalangeal

PIP -- Proximal Interphalangeal

IP -- Interphalangeal

MCP -- Metacarpophalangeal

CMC -- Carpometacarpal

* Several intercarpal surfaces may also be considered joints within the hand.

Fig. 1. Skeletal structure of the human hand.

distal phalanges of each digit (except the thumb, with only two phalanges), and the arm. All segments were created as primitives in CATIA or developed with Boolean operations using constructive solid geometry. The final model can be seen in Fig. 2.

The carpal and metacarpal segments were not meant to follow the locations of bones within the palm but were designed to allow the user to identify the locations of geometric interactions. These parts of the hand could be tested independently for interferences with an object being held.

The complete hand model included 17 moving joints with 23 degrees of freedom. These were defined as 23 robotic joints in CATIA. An actual hand has many more degrees of freedom, but 23 rotational axes were found to be sufficient for most hand postures.

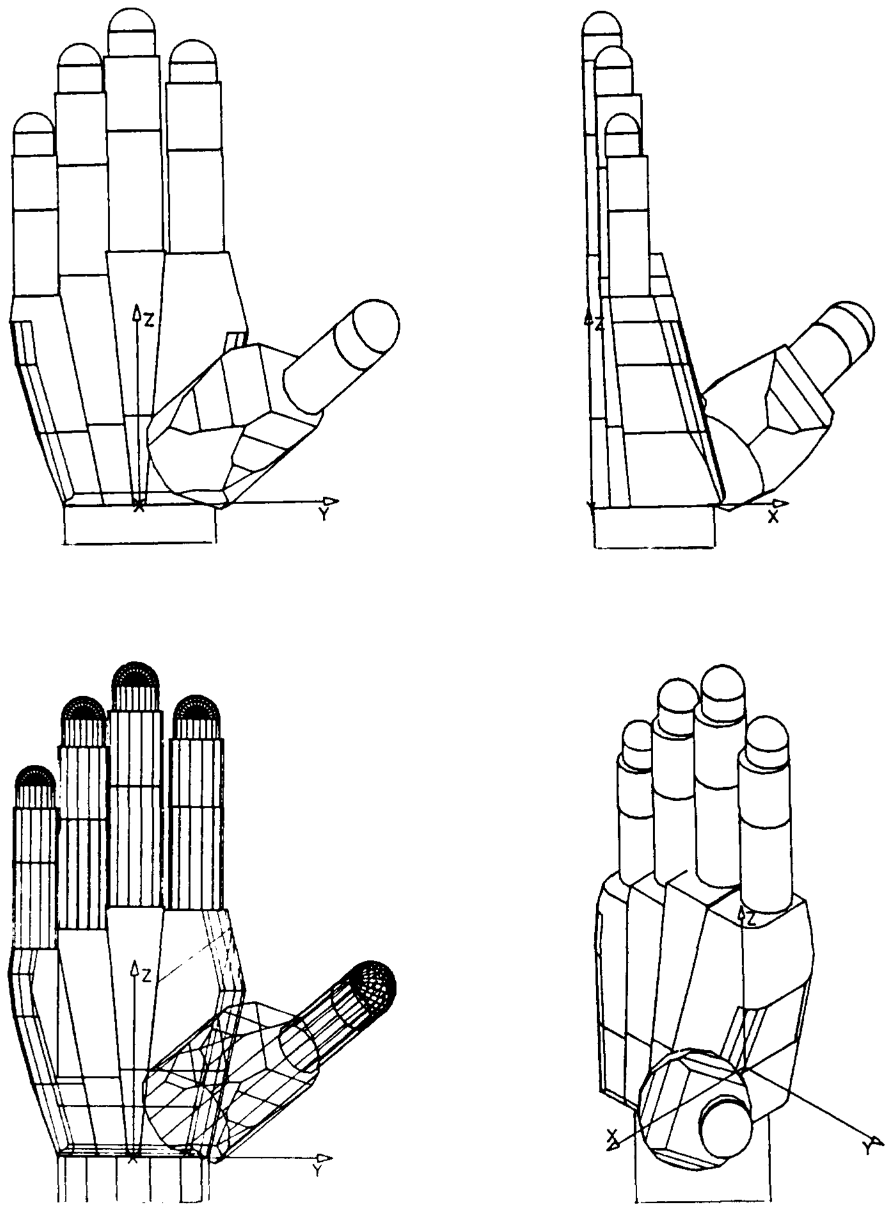


Fig. 2. The hand model in default position.

The thumb was modeled with three axes of rotation at the carpometacarpal joint (CMC), one at the metacarpophalangeal joint (MCP), and one at the interphalangeal joint (IP). The four fingers each had two axes of rotation at the MCP joint, one at the proximal interphalangeal joint (PIP), and one at the distal interphalangeal joint (DIP). The two ulnar fingers (the ring and little fingers) also included an axis of rotation for the CMC joint. (Movement at the CMC joint is not significant for the index and middle fingers.) Details on the joints and ranges of motion are provided in Table 1.

Locations of rotational axes and ranges of motion were found in the literature and from the present survey. While instant centers of actual human joints do move during rotation, the centers of rotation of joints as small as those of the hand generally occur within a very small range and can be modeled in practice by a static center of rotation. The center of rotation for a joint was assumed to be that which would account for the overall change in posture in a 90-degree rotation.

It was desired to constrain motion of a given joint to ergonomically reasonable limits and to have all the segments of a finger distal of a given joint move together about the joint. The ROBOTS module in CATIA allowed this. In CATIA Version 3.1 a robot can have up to 20 degrees of freedom. In practice, errors resulted when more than 12 were used. The model was defined as three CATIA robots. These represented, respectively, the thumb, the index and middle fingers, and the ring and little fingers. Motions of the wrist were not considered in this study.

The origin of the model axis system was on the dorsal wrist, opposite the medial wrist crease and along the line of the third metacarpal. In its home position, the palm of the hand faced slightly upward from the line of the positive X axis, with the thumb on the side of the positive Y axis. The thumb had its own set of axes, offset from that of the hand as described by Cooney et al. (1981).

The dorsum (back) of the third digit lined up along the Z axis of the model. In the default posture, the palm was flat (except for the metacarpal of the thumb). The arcs of the hand affected only the dorsal edges of the second, fourth and fifth digits (the index, ring and little finger) when the carpometacarpal joints of the last two digits were not moved. As with the default positions of the interphalangeal joints, these were found to allow easier use in design

Table 1

Joints and ranges of motion of hand model (degrees)

Human/ CATIA joint	CATIA axis number	Type of motion	Minimum angle	Maximum angle
CMC(I)	1	Adduction (−Abduction)	−15.90	38.80
	2	Flexion (−Extension)	−27.50	17.10
	3	Pronation (−Supination)	0.00	90.00
MCP(I)	4	Flexion (−Extension)	−9.67	54.00
IP(I)	5	Flexion (−Extension)	−21.67	73.67
MCP(II)	6	Radial Dev. (−Ulnar Dev.)	−23.30	32.70
	7	Flexion (−Extension)	−35.00	85.20
PIP(II)	8	Flexion (−Extension)	−0.67	94.80
DIP(II)	9	Flexion (−Extension)	−1.67	77.47
MCP(III)	10	Radial Dev. (−Ulnar Dev.)	−11.20	31.50
	11	Flexion (−Extension)	−36.33	86.67
PIP(III)	12	Flexion (−Extension)	−0.67	88.80
DIP(III)	13	Flexion (−Extension)	−0.33	80.20
CMC(IV)	14	Volar (−Dorsal)	−5.00	10.00
MCP(IV)	15	Radial Dev. (−Ulnar Dev.)	−7.20	27.20
	16	Flexion (−Extension)	−35.67	86.00
PIP(IV)	17	Flexion (−Extension)	−0.67	93.20
DIP(IV)	18	Flexion (−Extension)	−0.33	79.13
CMC(V)	19	Volar (−Dorsal)	−10.00	20.00
MCP(V)	20	Radial Dev. (−Ulnar Dev.)	−5.40	47.00
	21	Flexion (−Extension)	−34.00	83.67
PIP(V)	22	Flexion (−Extension)	−0.67	90.47
DIP(V)	23	Flexion (−Extension)	−1.00	78.13

work than actual resting postures, in which the hand would be slightly cupped.

Default positions and constraints on motion were set for each joint. All phalanges except those of the thumb pointed straight along the Z axis in the default position. The first two joints of the thumb pointed in the positive Z direction of the thumb's axis system. It was found to be easier for a user to calculate movements from these defaults than from actual resting positions. The distal phalanx of the thumb was inclined ulnarly 5 degrees, in a realistic posture. This exception was made so that the thumb could easily be placed in opposition to the third digit.

3. Validation of the model

The robot joints were controlled interactively through angle rotation commands and cartesian commands (in which CATIA causes a point on a robot to reach a given point in space). Programmed motions are also possible in the CATIA ROBOT module. The model was placed in sev-

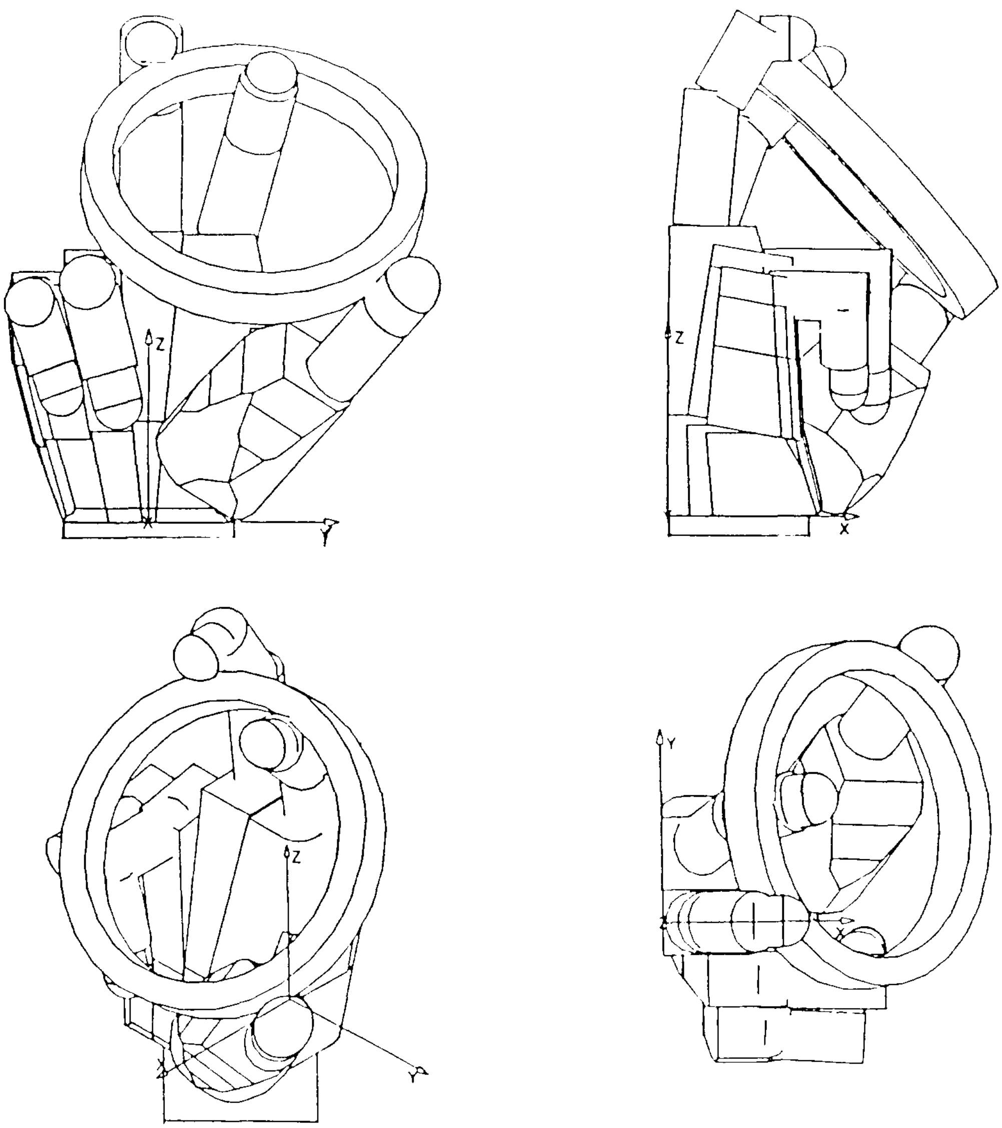


Fig. 3. The hand model holding a ring.

eral postures for evaluation, alone and gripping several solid objects. Some of these can be seen in Figs. 2, 3, and 4 with specific angles listed in Table 2. The model appeared to properly simulate the human hand in these postures. This was necessarily a subjective decision.

Intersections between solid segments were analyzed to determine whether the model could portray a hand with realistic deformation of tissues caused by such grips. Table 3 lists the results of these analyses for the case shown in Fig. 4, in which the hand is portrayed holding a ball with a radius of 35 mm. The four carpal segments, which obviously did not touch the ball, were not examined here. All of the interactions appear reasonable for this hand grip (Gourret et al., 1989).

The maximum grip sizes for the thumb and each finger were found as well as the maximum spans from the thumb to the fifth digit and from the index finger to each other finger (not includ-

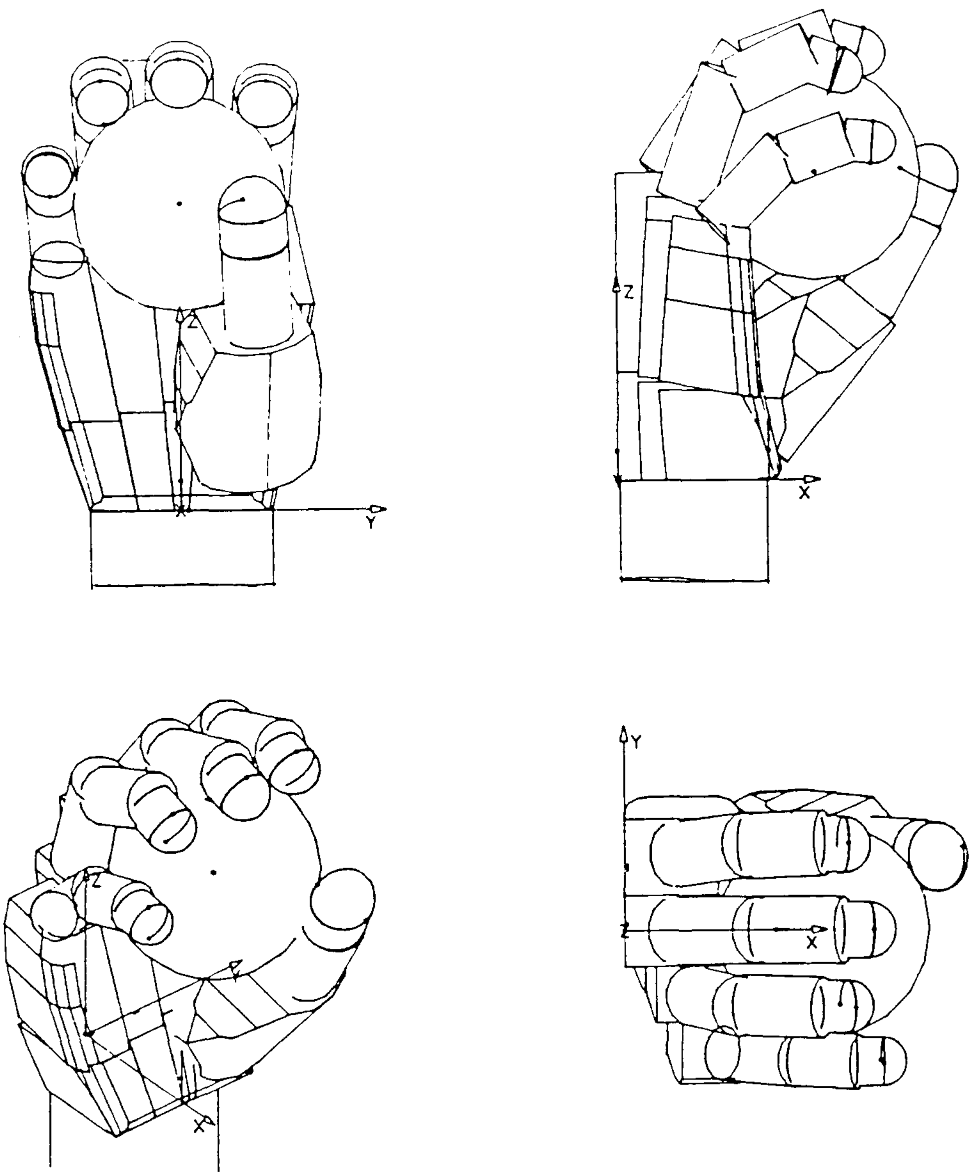


Fig. 4. The hand model holding a ball.

Table 2

Joint angles in modeled postures

Human/ CATIA joint	CATIA axis number	Angles for each posture (degrees)			
		Pinch	With ring	With ball	With rod
CMC(I)	1	10.0	0.0	35.0	−15.0
	2	20.0	10.0	15.0	20.0
	3	20.0	20.0	80.0	50.0
MCP(I)	4	40.0	0.0	10.0	28.0
IP(I)	5	40.0	0.0	5.0	0.0
MCP(II)	6	0.0	−15.0	−5.0	0.0
	7	64.0	19.0	35.0	85.0
PIP(II)	8	25.0	23.0	35.0	45.0
DIP(II)	9	25.0	20.0	35.0	48.0
MCP(III)	10	0.0	0.0	0.0	0.0
PIP(III)	11	0.0	5.0	30.0	85.0
PIP(III)	12	0.0	25.0	35.0	75.0
DIP(III)	13	0.0	80.0	45.0	17.0
CMC(IV)	14	0.0	10.0	5.0	10.0
MCP(IV)	15	27.2	15.0	5.0	10.0
	16	0.0	80.0	15.0	85.0
PIP(IV)	17	0.0	90.0	45.0	80.0
DIP(IV)	18	0.0	0.0	45.0	8.0
CMC(V)	19	0.0	10.0	10.0	20.0
	20	47.1	20.0	5.0	20.0
MCP(V)	21	0.0	80.0	35.0	82.0
PIP(V)	22	0.0	90.0	25.0	90.0
DIP(V)	23	0.0	0.0	25.0	0.0

ing the thumb). These were compared to measurements reported by Garrett (1968), which were taken from the same population as the overall anthropometric to which the hand model was scaled.

Maximum spans and grasping sizes found with the model and reported by Garrett (1968) can be found in Table 4. Wider reaches were generally found with the model. This may be because the model does not check for interactive constraints upon motion. The overall spanning distances are very close, and the differences increase as the measured spans become smaller, between parts of the hand which would be more likely to constrain each other's movement. In an actual hand, for example, the second digit cannot be moved to its most radial position while the third digit is in its most ulnar position.

Some changes and additions could be made to improve the utility of the model. A model of the female human hand should be created and made available. It may be possible to include motion constraints which are dependent upon hand posture, such as the interactive constraints described above, rather than allowing each joint the same range of motion at all times. Other possible changes include improvements in the accuracy of the model and programs to scale and change the posture of the model. It may be desirable to find

Table 3

Distances or depths of intersection between phalanges and metacarpals of the hand model and the ball held in the hand (mm)

Segment	Digit	Distance (+) or depth of intersection (−) (mm)
Distal phalanx	1	−2.65
	2	0.09
	3	0.58
	4	−0.69
	5	3.30
Medial phalanx	2	−0.91
	3	−1.56
	4	−0.41
	5	−0.09
Proximal phalanx	1	−2.06
	2	2.65
	3	−1.74
	4	0.13
	5	0.55
Metacarpal	1	0.62
	2	0.73
	3	−0.90
	4	−3.44
	5	7.03

Table 4

Maximum spans and grasps in millimeters from the hand model and garrett (1968)

Measurement	Hand model	Garrett (1968)	
		Mean	*SD*
Maximum span			
1st to 5th	214.39	215.14	15.49
2nd to 5th	171.93	161.29	15.00
2nd to 4th	137.92	123.44	16.26
2nd to 3rd	125.48	92.11	15.75
Grasp reach from thumb			
5th digit	169.91	153.67	13.72
4th digit	157.19	154.18	15.24
3rd digit	150.46	145.80	14.73
2nd digit	128.84	124.21	13.97

new values for some of the parameters used in the model, particularly for the lengths of the phalanges and the locations of rotational axes, which were obtained indirectly.

In the examples shown here, each joint was controlled separately when the posture of the model was changed. The model was developed for the fiftieth percentile of a specific population and would have to be modified in the operating environment for a different target group. It should be possible to develop computer programs to do these tasks automatically.

It is possible to represent hand postures and grips with this graphic model of the human hand. It could be a useful addition to a graphics package to be used in the design of hand tools and other hand-held products. It would allow a user to more easily visualize the way in which a product would be used. With some modifications, it could allow a user to easily determine whether a product could be grasped by members of a given population. The model could simplify the consideration of ergonomic design requirements early in the design process.

The model appears to meet the criteria described in the Introduction. While the model examined here depends in part upon data obtained from a small database (15 male subjects out of a survey population of 32), it appears likely that a similar model could be developed for use with various populations, either through scaling in three dimensions or through compiling a database of all necessary dimensions for each population or percentile group required. A computer program could be made to create the hand model from such a set of parameters.

4. Conclusion and implications

A model of the human hand was created using information found in the literature and in an anthropometric survey. The hand model was made up of 24 solids, 17 of which could be moved, with a total of 23 degrees of freedom. Each joint was limited to a realistic range of motion.

Dimensions of parts of the hand were expressed as a proportion of overall measurements of the hand in three dimensions. This was done so that the resulting hand model could be scaled to any set of overall measurements, to simulate hands from different percentiles or populations. Only one version of the model was created, for a fiftieth percentile right hand from a specific population of male subjects. A new model would have to be created, or each segment of the model would have to be rescaled separately, for a female model. This could also be done if a user wished to redefine the model as a more precise representation of a specific individual's hand. The model could be easily reversed to represent a left hand.

The spans and maximum grasping sizes of the model were compared to those of a sample population reported by Garrett (1968) and found to be similar, with variances probably due to the model's inability to consider interactive constraints between tissues of the hand. Analyses of intersections and distances between solids were used to ensure that the model could be used in the product design process (with the CATIA system as an operating environment).

The model was not a perfect representation of a human hand. It appeared to approximate the geometry of the human hand closely enough for use in product design. The model and operating environment appeared to fulfill the requirements listed in the Introduction (especially realistic motions and postures and a check for segment interactions), although the utility in its current state is marginal. The current model could be useful primarily in the visualization of hand postures. It would allow a designer to plan a product about the represented human hand.

Some changes and additions could be made to improve the utility of the model. These include improvements in the accuracy of the model, consideration of additional populations, consideration of motion constraints which are dependent upon hand posture and programs to scale and change the posture of the model.

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