Opposition Space as a Structuring Concept for the Analysis of Skilled Hand Movements*

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INTRODUCTION

The human hand is a highly articulated device which, as an extension of the arm, provides a mechanism for complex interactions with the environment. A large variety of skilled behaviors involving the human hand can be observed ranging from subtle and precise manipulations to smooth and forceful exertions, involving over 20 degrees of freedom (*dofs*) (see Tubiana 1981; Kapandji 1982). How is this large and complex space of possibilities for movement restricted so that the uniquely useful configurations of the system observed in actual practice appear in appropriate circumstances? (see Whiting 1984, and Turvey et al. 1978 for discussions of the synergies approach to the degrees of freedom problem originally described by N. Bernstein.)

We are taking a task analysis approach, which is similar to studies done in other multiarticular systems. In analyzing the task of handwriting, Hollerbach (1981) describes two functional *dofs* (writing direction and letter height), and suggests a controller containing coupled oscilators. In posture control, McCollum et al. 1984, Nashner and McCollum 1985) find specific parameters for a controller relevant to the task of maintaining balance, such as ankle torque, relative amplitude between two muscle synergies, and a timing parameter between hip torque and braking. In speech production, researchers (Abbs et al. 1984; Kelso, this volume; Kelso et al. 1982) find the covarying of the upper and lower lips within the task (production of specific words) an important parameter, rather than the absolute position of the lips. Of the wide range of movements in the repertoire of the hand, we are studying the *grasping* and *picking up* of objects. An example of this type of task is grasping a mug (Arbib et al. 1985). A person, reaching for a visually perceived mug, preshapes the hand into a shape suitable for gripping the handle. This preshaping movement is coordinated with the timing of the reach which carries the hand to the location of the object to be grasped (Jeannerod 1981, 1984; Wing and Fraser 1983). At an appropriate point during the reach, the preshaped hand closes around the handle, and stably grips it for lifting.

In this paper, we describe a functionally effective space of kinematic possibility which is sufficient for manipulation tasks, given the basic link segment structure of the hand and its dynamic properties. Researchers in the robotics domain, in looking at manipulation tasks, have analyzed these requirements for simple two-fingered hands (Fearing 1983; Mason 1982), and dextrous three- or four-fingered hands (Salisbury 1982, Wolter et al. 1985). The task of controlling functionally

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effective activity has two mutually constraining component parts. The first is the sources of constraint which reduce the complexity of the space of kinematic possibility; the second is finding a suitable control system to manage behavior in that space.

We have defined the *virtual finger* (Arbib et al. 1985) as a group of fingers (perhaps even including the palm) which act as a single functional unit in a structure representing the task. The hand in preshaping organizes according to an appropriate arrangement of virtual fingers. In the mug task, three independent functional units operate cooperatively to effect a stable grasp, but the way in which the actual fingers are incorporated into the three virtual fingers – the thumb, the fingers that go through the handle, and the fingers that go beneath the handle – varies with handle size. We suggested a coordinated control program involving the activation of *schemas* (Arbib 1981), which organize and control the virtual fingers using dynamic visual and tactile input.

In this paper, we introduce the concept of *opposition space*. For a given manual task, this is the area within the coordinates of the hand where opposing forces can be exerted between virtual finger surfaces in effecting a stable grasp. At first, we only consider static stable postures of the grasping hand, irrespective of whether or not the arm is moving. (We recognize that this approach can achieve only a first approximation to the repertoire of human hand grasping behaviors, since active manipulation of objects involves at least transitions between postures.) We will show that regions within the broad capability of the hand correspond to specific functional capabilities of particular hand postures. Virtual finger formation is then shown to be channelled by the selection of a region (an opposition space) for a given task. Finally, we map task constraints into virtual finger configurations needed to perform the task, and show that schemas as units of motor control can be defined to control virtual fingers. Since schemas organize and control virtual fingers by taking advantage of the architectural limitations of the hand and additional dynamic properties of the prehensile actuators, only a limited but useful number of postures and kinematic forms will occur.

CONSTRAINTS IMPOSED BY TASKS

The hand, as it reaches to grasp an object, preshapes into a configuration suitable for the anticipated interaction (Jeannerod 1981). What determines the shape that the hand is taking? To gain some intuition, we observed two tasks that differed in how an object was to be used. Grasping activity was videotaped and subsequently studied in slow motion with stop action.

Description of Two Similar Tasks

Both tasks required that the same object be picked up from a table by a seated participant. The object was a medium-sized cylinder standing on its base. The first task (Fig. 1a–c) was to grasp the cylinder, pick it up, and set it onto a circle on which it could just fit (the "place cylinder" task). The cylinder, providing two opposing surfaces which were pinched between the thumb (virtual finger 1, or VF1) and finger pads (VF2), was lifted (Fig. 1b) and carefully guided onto the circle (Fig. 1c). The grasp, called a precision grasp by Napier (1956), or palmer prehension by Schlesinger (1919), allows the object to be translated or rotated in the fingers and thumb so that fitting the cylinder onto the circle could be more easily and accurately accomplished. Such fine

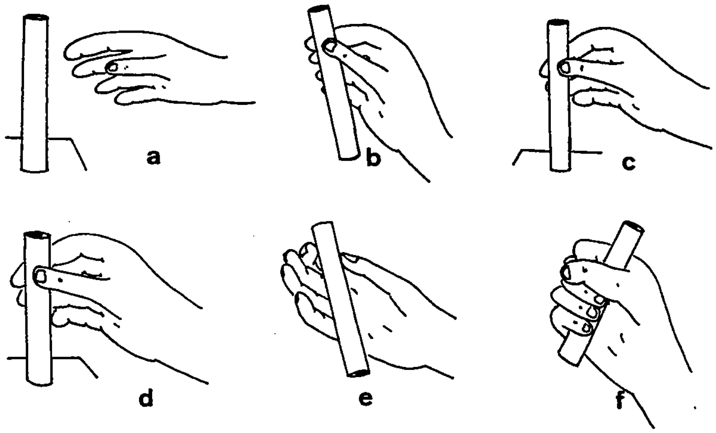

Fig. 1. Two grasping tasks. a. Preshape hand for place cylinder task. b. Grasp and lift cylinder. c. Place cylinder onto circle. d. Grasp and lift cylinder for shake cylinder task. e. Transition of cylinder from initial grasp to a more firm grasp. f. Shake cylinder

control is better effected by the fingers, a low mass system, than by the arm, with its greater structural mass.

The second task (Fig. 1d–f) was to grasp the cylinder, pick it up, and shake it vigorously two or three times along its long axis (the "shake cylinder" task). The cylinder was initially grasped (Fig. 1d) using the same precision grasp between thumb (VF1) and finger pads (VF2) as described above. However, once the object was securely lifted in the hand, a transition in grasping postures occurred (Fig. 1e). Using an axis between thumb and index, the object was allowed to be rotated by gravity into the palm where first the ring and little fingers and then the long and index fingers and thumb wrapped it in a secure grip against the palm (Fig. 1f). This grasp, called a power grasp by Napier (1956) or cylindrical prehension by Schlesinger (1919), provides a strong and stable grasp to counteract the forces that developed during the shaking task. The cylinder body again provided opposing surfaces to grasp, but this time the palm (VF1) and digits (VF2) were used. The thumb, pressing against VF2, secures the object.

Task Constraints

The particular preshape and grip configuration used during the task relate to the functions that are to be performed during the task. A task determines a set of functional requirements that must be satisfied by the postures that the hand assumes. A generic functional requirement of all prehensile lifting tasks is to avoid dropping the object. In the place cylinder task, the goal is to guide the cylinder onto the circle, which adds the functional requirement that the axis of the cylinder be matched with a normal to the circle at its center. A functional requirement of the second task is to not let the object move in the grip, specifically to avoid translations of the object transverse to the hand due to the rapid oscillations.

The hand and the manipulated object each have a large variety of physical properties. Out of these sets, the functional requirements point to a subset of physical properties relevant to the task. These subsets (from the hand and from the object), when taken in relation to one another, constitute the *physical constraints* on the activity. For example, to lift an object, the hand must supply a force which cancels the force due to gravity, and the posture taken on by the hand must be appropriate for the application of that force. To avoid dropping an object, properties such as weight, size, surface shape, and friction determine potential surfaces for opposition where these properties are scaled relative to strength, surface friction, and size properties of the hand. Potential surfaces are further constrained by the orientation of the object relative to its environment (i.e., which surfaces are available for grasping).

Thus, the chosen hand shape, which we call *opposition space*, as exhibited in the preshape, is preparatory for a grasp which satisfies the anticipated physical constraints. These physical constraints will be looked at in the next section. We then go on to explore how a controller might be designed, which can map functional requirements onto physical constraints, successfully resolving the issue of conflicting requirements.

OPPOSITION SPACE

Conditions for a Stable Grasp

A rigid object can be both translated along and rotated about any of the three Cartesian coordinate directions to any degree of combination. Thus, specifying the behavior of a rigid object over time is a matter of determining its manner of variation with respect to each of this six *dofs*. (Only a single rigid body will have six *dofs*. An object such as a pair of scissors has an additional *dofs* corresponding to its hinge. Opposition space as developed in this paper concerns only manipulations of single rigid bodies.) If the object is to be manipulated in some manner while in the grasp, then the object must vary along a specified set of *dofs* in a controlled fashion. Variation must remain within specified bounds.

Fearing (1983) defines a grasp to be stable if the object is in equilibrium, if all forces on the object are within an angle relative to the surface normal (as related to the coefficient of friction), and if motion can be prevented by increasing the grasping forces without moving the fingers. The conditions for equilibrium in any static grasp are that all forces and moments sum to zero (Williams and Lissner 1962; McLean and Nelson 1978; Fearing 1983):

$$\sum_i \vec{F}_i = 0$$

$$\sum_i \vec{r}_i \cdot \vec{F}_i = 0$$

Thus, each force tending to make the object translate in some direction must be cancelled by an equal force in the opposite direction. If forces are represented using vector notation, and if we restrict consideration to co–planar forces, each force vector of a certain length and in a certain direction must be cancelled by a co–linear force vector of equal length and opposite direction.

Successful equilibrium for an unmoving hand and object requires a force oppositely directed to gravity equal to the weight of the object. This force might be supplied simply by the hand's forming a support surface normal to gravity, or else by two or more hand surfaces making contact with the object. If the surface of the hand were frictionless, problems would arise from the fact that the human hand is subject to a low amplitude "physiological" tremor of about 10 Hz (Marsden et al. 1969). However, the hand surface has useful frictional qualities, which can be used to prevent objects from moving in a stable grasp. Coulomb's law states that the tangential force of friction is constrained to be no greater than the product of the normal force with the coefficient of static friction, or:

$$F_T < \mu_s F_N$$

This relationship, first conjectured by Leonardo da Vinci, and later described by Amontons (1699), only holds for materials where the deformation between them is plastic in nature (Comaish and Bottoms 1971; Bowden and Tabor 1950). It defines an angle of friction $\Phi_s = \tan^{-1}\mu_s$, such that, if the grasping force is applied to the surface at an angle larger than this angle, the object will slip (Fearing 1983; Mason 1982). If the object does slip, but if the motion can still be prevented by increasing the normal force, the grasp is still stable (Fearing 1983; Hanafusa and Asada 1982). For small microslips in human precision grasping, Johannson and Westling (1984) have shown that this is the case.

Surface Properties of the Hand and Friction Force

The surfaces of the palm and the pads of the digits have three properties which contribute greatly to the stability of grasps (Glicenstein and Dardour 1981). First, these surfaces are padded (Quilliam 1978), giving them a good measure of elastic compliance. This compliance tends to increase the amount of friction between the hand surface and the surfaces of objects grasped, and automatically supplies a force sufficient to counteract small amplitude perturbations of the object (Hanafusa and Asada 1982; Moore 1972; Fearing 1983). Second, these surfaces of the hand contain small ridges; and third, the pad surfaces are self-lubricating through small pores located along the tops of these epidermal ridges. The lubricant is greasy, having good adhesive qualities at low shear velocities, enhanced by the hills and valleys of the ridged surface which extends the total shearing surface area (Moore 1972, 1975). At high shear velocities, friction is reduced, thus minimizing wear and tear of the hand surface. Altogether, the surfaces of the palm, thumb, and fingers have frictional qualities quite conducive to stable grasping of objects.

Comaish and Bottoms (1971) analyzed the coefficient of friction between skin and various materials in order to determine whether it obeys Coulomb's law. They found that the frictional force is not proportional to the load, and that, for some materials, the static coefficient of friction increased with the area. While their data showed a proportional response for loads over 100 g for *in vitro* skin, the data for *in vivo* skin was definitely nonlinear. Skin has been shown to be viscoelastic (Wilkes et al. 1973), meaning that it is capable of both deformation and flow in response to an applied load. Thus, living skin does not obey Coulomb's law.

Westling and Johannson (1984, Johannson and Westling 1984) looked at the effects of varying the surface material of objects as subjects picked them up. They found that subjects maintained the applied force (the grip force) slightly above the slip force, the force below which the object would drop out of the hand. In experimental conditions where subjects could not actually see the surface, they noted that subjects varied their grip force, not to the surface, but to the friction conditions. They looked at the influence of frictional conditions from previous objects against the skin. If the previous trial required the subject to grasp a texture such as silk, with a low coefficient of friction, the subject would grasp a texture with a higher coefficient of friction (such as sandpaper) harder than normal. In one experiment, subjects washed their hands after about 15 trials of lifting the same object, and the results indicated that the grip force adapted not to the surface, but to the friction conditions (more grip force was used right after washing).

Force Balance Between Parts of the Hand

Equilibrium requires that the force applied to the object by the hand to create friction be cancelled by an equal and opposite force. The opposite force can be supplied by additional hand surfaces impinging on surfaces of the object generally parallel to (for curved surfaces, parallel planes tangent to) the initial object surface. Parallelism can be within a tolerance, such as the angle of friction (Fearing 1983; Mason 1982), allowed by the frictional properties of the hand–object contact surface. For example, when grasping a cup with sloping sides, the component of force pressing the cup upwards is counteracted not only by gravity, but by friction as well. Generally parallel oppositely facing object surfaces are referred to as *opposable surfaces. Opposition* occurs when equal and oppositely directed, co–linear force vectors (within a tolerance) act (along the *opposition axis*) to freeze an object's translational degree of freedom relative to the hand. Additional *dofs* may be controlled by friction at opposable surfaces.

Moment Balance

Whenever an opposition axis fails to pass through a vertical line through the center of mass of an object, a moment (or torque) around that axis will be created. In addition, to the extent that the vertical line through the center of mass is at some perpendicular distance from a plane normal to an opposition axis and bisecting it, there will be a torque tending to twist that axis of opposition.

Moments around an opposition axis can be cancelled in either of two ways short of repositioning opposition axes. Requisite cancelling torques can be provided by friction between hand and object surfaces. Thus, by squeezing an object harder, a larger contact force (normal to the surface) is created, increasing the amount of friction. However, since the effective lever arms are typically short for the friction force, such lever arm length being constrained by finger surface breadth, this source of torque quickly requires large amounts of normal force generated in proportion to the required torque. Since this can be very tiring, the second way of cancelling undesired torques is more desirable. Either the fingers or the palm positioned along the surface of the object may provide force not in opposition to force exerted by other parts of the hand, but in opposition to moments. The amount of force required will decrease with an increase in the distance from the opposition axis constituting the axis of the moment.

Moments tending to twist the axis of opposition likewise can be cancelled either by increasing friction between the object and hand surfaces or by increasing the number of fingers contacting the

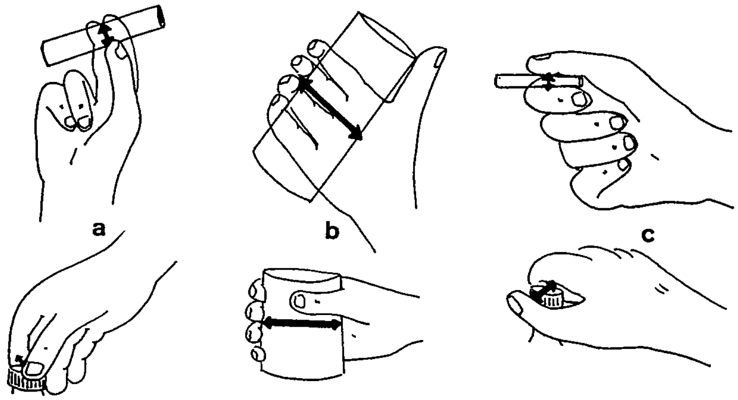

Fig. 2. Basic oppositions of the human hand. a. Pad opposition. b. Palm opposition. c. Side opposition

object. A long cylindrical object, such as a pen, could be held horizontally (wrist pronated and dorsiflexed) in a precision grasp between the thumb pad and index finger; however, if the chosen opposition axis is not near the object's center of mass, a twisting moment arises. With the help of additional fingers and a new opposition axis, this moment can be cancelled without increasing the amount of active force and without knowing the exact location of the center of mass. (This issue extends into the grasping of circular objects, such as jar lids, where again twisting moments are cancelled by using more than two fingers.)

OPPOSITION

Current terminology in the hand literature (Napier 1956; Schlesinger 1919; Landsmeer 1962; Long et al. 1970; Lyons 1985) lacks the flexibility for describing how the hand preshapes in order to bring to bear functionally effective forces for grasping an object within a task context. Grasps tend to be composites of power and precision requirements (Napier 1956). A more useful approach is to focus on the types of opposition available in the hand.

The first, *pad opposition*, is opposition between the pads of one or more fingers and the thumb pad (see Fig. 2a), along an axis roughly parallel to the palm. Opposition at the digit pads offers greater flexibility in finely controlled manipulations of an object at the expense of stability and maximum force. An object held by the digit pads can be translated in a direction roughly normal to the palm by finger and thumb flexion and extension. The object can be translated in a direction laterally across the palm by sliding and climbing along the object with the fingers and thumb. There is also a slight translation possible in the distal–proximal direction. The object can be rotated in two directions by rolling it between oppositely translating finger and thumb surfaces. Finally, the object can be rotated about the axis of opposition between thumb and finger by modulating the torque created by friction. If the opposition axis runs through the center of mass of the object, an additional torque has to be supplied manually. If the opposition axis is off from the center of mass, then gravity can be enlisted to effect the rotation. Pad opposition is strongest and most stable in the direction parallel to the axis of opposition. Forces ensuring equilibrium on the other *dofs* may be supplied by friction for both translations and rotations or by support for rotations (e.g., opposition to gravity–induced torques). Typically the weakest *dof* most subject to destabilization is rotation around the axis of opposition. In sum, flexibility regarding the manipulation of an object along its *dofs* can be had in pad opposition at the expense of a lack of stability along those same *dofs*.

The second basic type of opposition, *palm opposition* between the digits and the palm, is one in which flexibility is sacrificed in favor of stability. Essentially the object is fixed in hand coordinates (see Fig. 2b), along an axis roughly normal to the palm of the hand. Greater stability is achieved in this opposition by a combination of three factors (Thomine 1981). First, the larger surface area of palm provides increased friction force. Second, the more proximal segments of the digits are able to exert greater forces (Hazelton et al. 1975; Chao et al. 1976). Finally, the structural extent of the palm (and fingers) is used to passively cancel torques around the axes lying in the surface. Thus, a large measure of stability is provided, but flexibility must be derived strictly from motions of the wrist or more proximal joints. The thumb in palm opposition, while not part of the opposition itself, adds to its stability in two ways: moving it into a position facing the fingers (i.e., what is called thumb opposition) helps the fingers in opposition to the palm, while, at the same time, increases the surface area of the palm in contact with the object.

A third type of opposition, *side opposition*, between the thumb pad and the side of the index finger, or between the sides of the fingers, is a compromise between flexibility and stability (see Fig. 2c). Its opposition axis occurs primarily along a transverse axis. The thumb, due to the orientation of its articular surfaces, has its pad oriented to the sides of the other digits, giving side opposition using the thumb the extra frictional component. Side opposition between fingers is stronger if the object is held proximally in the fingers (with less control), and weaker more distally (with more available *dofs*). This distal opposition is similar to pad opposition, without the friction available at the pads. When an object is held in side opposition, the object is aligned in the pronation–supination rotational axis of the wrist. By using pronation–supination instead of flexion–extension or adduction–abduction at the wrist, the strongest possible force available at the fingers can be maintained (Hazelton et al. 1975; Chao et al. 1976), with the whole muscular system of the arm able to be used as well. This is especially useful when the thumb is opposing the side of the index finger, due to its strength and frictional qualities.

The shape the hand takes on during the grasp reflects the use of one or more of these oppositions. As was seen in Fig. 1, the place cylinder task used pad opposition. The shake cylinder task started with pad opposition, but changed to palm opposition, with an intermediate step of opposition to the torque arising while switching. If we look at the mug grasp (Fig. 3a), we see that both palm opposition and side opposition are used. The backs of the fingers are also opposing the torque created by the mug not being supported above or around its center of mass. Other examples of composite oppositions are seen in Fig. 3. In Fig. 3b, a pen cap is taken off the pen using two oppositions: the fingers oppose the palm to hold the body of the pen, and the thumb opposes the side of the index finger to hold the cap. In Fig. 3c, the grasp which Napier (1956) calls a power grip is seen as the combination of two oppositions: palm opposition and side opposition. Grasping different size screwdrivers (Fig. 3d–f) demonstrates how oppositions are affected by object properties: for a large screwdriver (Fig. 3d), palm opposition is seen; for a medium screwdriver (Fig. 3e), side opposition is added; for a small screwdriver (Fig. 3f), pad opposition is seen

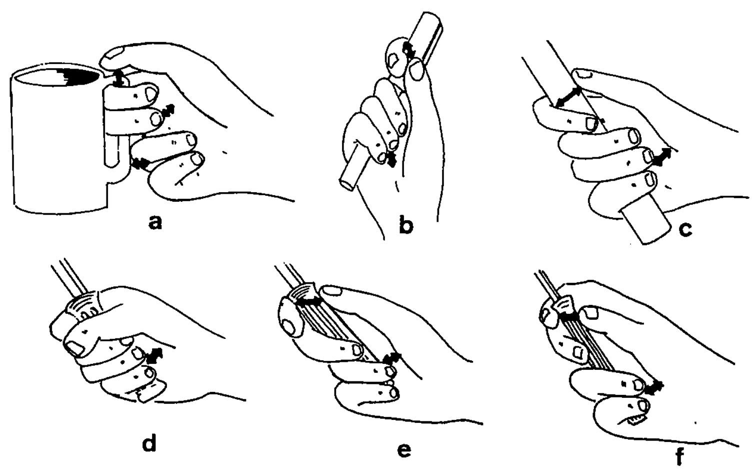

Fig. 3. Composite use of oppositions in grasps. a. Grasping mug. b. Taking cap off pen. c. Holding hammer. d. Grasping large screwdriver. e. Grasping medium screwdriver. f. Grasping small screwdriver

between the thumb and the index and long fingers, while the other two fingers still oppose the palm. Due to the asymmetries of the hand, such mixing of oppositions is commonplace and simple (Tubiana 1981). Composite use of oppositions are the key to understanding features of prehensile hand shapes and opposition space.

PARTITIONING OF THE HAND INTO FUNCTIONAL UNITS

A Mechanism for Control: Schemas

Preshaping anticipates the physical constraints that will arise during the prehensile task. Task constraints, which necessarily include object dimensions, determine opposable surfaces which specify *where* the grip can take place. But the issue in preshaping the hand is *how* the grip can take place. Opposition space defines the "how" in terms of the kinematic and dynamic values available at various grasping postures. The system needs to map task constraints (the functional requirements in the task) to opposition space (the functions available at a given hand posture). A controller for preshaping the hand can then send the fingers travelling to an appropriate opposition space.

How may a suitable control system use these constraints to manage functionally effective behavior? Schema theory (Arbib 1981) postulates the existence of coordinated control programs involving both parallel and sequential activation of perceptual and motor structures, or schemas. A schema monitors information relevant to an activity it controls in order to tune its behavior. The overall behavior of the system is the combined behavior of all of its component schemas; thus, control is distributed across interacting parallel units. Schemas might be activated which try to drive action systems into dissimilar activities, in which case the schemas compete for control of the movement.

Preshape Schema as It Relates to Opposition Space

Opposition space is described by its kinematic and dynamic characteristics. For example, a strong force can be applied by palm opposition involving the use of the anterior surfaces of all fingers (as VF2) and the palm (as VF1). Since the object is defined in terms of opposable surfaces, the problem solved by the controlling schemas is to match virtual fingers to opposable surfaces in such a way as to satisfy task constraints. Two opposable surfaces represent a relationship between two virtual fingers (e.g., their size, their distance from each other, etc.). The larger the virtual finger, the more force is passively available from the friction to overcome the torques, as described above.

The *preshape schema* will map task constraints into virtual finger configurations needed to perform the task. In readying the hand for grasping, the *preshape schema* must place the hand into a shape which meets two criteria: (a) the hand shape is large enough to allow a task–specific part of the object to be centered and contained in the opposition space created; and (b) a smooth movement along the opposition axis or axes will then secure the object in a firm grasp.

Task Parameters for Prehensible Movements

To satisfy the task constraints, we suggest that perceptual schemas extract from the visual information relevant values for prehensile parameters about the object within the context of a task. These include:

1. *Relevant object properties.* The appropriate opposable surfaces and opposition axes are task–specific; for example, where and how a pen is picked up for writing is different from where and how it would be picked up for throwing. The relative distance between virtual fingers must be larger than the width of the object along the opposition axis or axes. The size of the virtual finger (e.g., whether two or three real fingers can be mapped into VF2 in the grasp mug task) depends on the size of the opposable surface area as well as its radius of curvature. The relative location of opposition axes on complex objects such as the mug helps define the necessary opposition space with appropriate oppositions, allowing for an error tolerance which can be corrected for during the smooth enclosing movement.

2. *Functional degrees of freedom.* The *preshape schema* will create an opposition space which makes the task relevant *dofs* available, while the others are frozen out (e.g., in the mug task, the functional *dof* needed is rotation, which can be done using wrist rotation, while freezing out all finger *dofs*). The amount of control (i.e., movement resolution) over a *dof*, relative to the anticipated forces within the task context helps define appropriate oppositions as well as how the functional *dofs* are best mapped into actual *dofs* (e.g., finer control of the translational *dofs* is needed in the place cylinder task, more so than in the shake cylinder task). The range of the functional *dofs* also effects the mapping (e.g., the wrist allows an object to rotate further than do the finger pads).

3. *Anticipated forces and torques.* The created opposition space must cancel (or perhaps use) anticipated forces and torques (gravity–induced from the weight of the object, inertial loads that will arise during the task relevant movements, imbalance of forces between the oppo-

sition axis and the object's center of mass, hand–induced moments created by the virtual fingers themselves, etc). For two–phase tasks, such as the shake cylinder task, the *preshape schema* creates an opposition space to account for the initial lifting forces and not the later inertial loads; however, in the grasp mug task the opposition space created accounts for both the initial lifting forces and the later inertial loads (which arise when the mug is rotated toward the mouth).

The units on the dimensions of all the above must be scaled to the dimensions of the hand.

Schemas for Preshaping Virtual Fingers

We suggest that the *preshape schema* will activate, in parallel, opposition schemas which map virtual fingers into real parts of the hand. The three opposition schemas (*pad opposition schema, palm opposition schema, and side opposition schema*) compete and tune their behavior based on values of the task parameters listed above. The behavior of these schemas, all competing for the control of the hand, will produce particular configurations of virtual fingers. *Move schemas* will move the virtual fingers, within a particular time frame and tactile contact expectation, to locations and orientations relative to the object.

We can now reanalyze the two tasks described above in terms of virtual finger configurations available to a schema controller working within opposition space. To complete the analysis, the grasp mug task will also be reviewed once more.

Place Cylinder Task Revisited

In the place cylinder task (Fig. 1a–c), the available opposable surfaces of the cylinder are parallel to gravity. The object is light and long with a moderate radius of curvature, relative to the conformation potential of the hand surfaces. The task of placing it on the circle calls for flexible control of multiple *dofs*, with emphasis on small horizontal translations and rotations about horizontal axes. The center of mass of the object might not remain above the base during the task; however, it is light and so the resulting torques are easy to control. The perceived weight of the object can be overcome by the friction force available parallel to the pads of the fingers and thumb. Therefore, since the many *dofs* available are preferred in this task, and since the normal force required to avoid dropping the object does not exceed that available in the flexible grasp, the constraints converge on a grasp that uses pad opposition. This opposition provides the needed flexibility, in terms of available translational and rotational *dofs* to more precisely fit the cylinder base to the circle, as well as sufficient force to oppose the anticipated light weight of the object. The *pad opposition schema* becomes activated, mapping the thumb into VF1 and the index and long finger into VF2. Opposition space is created by moving the pad of VF1 into opposition with the pad of VF2, with a distance between them larger than the width of the cylinder. An *enclosing schema* will then bring VF1 and VF2 together along the opposition axis.

Shake Cylinder Task Revisited

In the shake cylinder task (Fig. 1d–f), the weight of the object and the reaction forces that will arise during the rapid movement of the object must be cancelled. The length of the object along the direction of the translation axis is longer than the hand width. A more powerful grip is required which will overcome these forces, and which necessarily locks the *dofs* of the hand, leaving only wrist and arm movements. Nevertheless, since these forces will arise later in the task, initially grasping the object in the finger and thumb pads allows the hand better access to the object without requiring adjustment of more proximal elements of the reaching system. It also allows the wrist to stay oriented generally adducted and dorsiflexed, a comfortable and effective position (Kapandji 1982). The result is that opposition space is created for the lifting subtask using the *pad opposition schema*, mapping the thumb into VF1 and the index and long fingers into VF2. The *enclose schema* brings VF1 and VF2 together along the opposition axis. Subsequently, the *shake schema* shifts the hand into palm opposition for the shaking subtask, mapping the palm into VF1 and the four fingers into VF2. The large surface area provided by palm opposition allows the application of both passive (friction) and active (flexor muscles) forces, as well as redundant sensory knowledge about unwanted object movements. The action of the thumb will depend on the competition between the *side opposition schema* and the *palm opposition schema*. The first will try to drive it to the radial side of the object, while the latter will try to drive it into thumb opposition. If the anticipated forces are significant (as they most likely are if the shaking is vigorous), the *palm opposition schema* will move the thumb to a place across the backs of the fingers, thus increasing the surface area of the palm, and creating a stronger grip by helping VF2.

During the transition between subtasks, a gravity–induced torque will rotate the cylinder as the hand turns with it between the thumb and index finger. In order to overcome the torque, the palm is mapped into VF3. Near the end of the transition, the *palm opposition schema* becomes more active, and the new opposition space emerges.

Grasp Mug Task Revisited

In the grasp mug task (Fig. 3a), one functional *dof* is the rotation of the mug when it reaches the mouth. If it is an extremely delicate teacup, the *pad opposition schema* will be active and the rotation will be done at the finger level between VF1 (the thumb) and VF2 (the index finger). If the mug is somewhat heavier and larger, pronation at the wrist would be better, in which case equal activation would occur of the *side opposition schema* (to maintain the correct orientation for and during the rotation) and the *palm opposition schema* (to stabilize the handle against the palm and volar finger surfaces during the rotation). However, a gravity–induced torque will arise directed toward the hand when the mug is lifted, due to the fact that the handle is not above or centered around the center of mass. If any real fingers are available, they are mapped into VF3, and curled in order to cancel the torque. If no real fingers are available, the force being applied on the handle at VF2 is increased. Opposition space is created when the pad of VF1 moves to oppose VF2 (at the side if the *side opposition schema* is active), VF2 curls (driven by the *palm opposition schema*), and VF3 curls to oppose the anticipated torque. The *enclose schema* will then bring VF1 and VF2 together along the opposition axis through the top of the handle, VF2 will enclose around the side of the handle (however, in this case, not moving along the opposition axis, but instead following the contour of the handle), and VF3 will extend opposing the torque.

FUTURE RESEARCH

In the previous section, we have outlined how a schema controller might be mapping functional requirements of tasks onto physical constraints. While still only speculations at this point, we are using these concepts to guide further research in order to verify them. Specifically, we see the basic problems in extracting the relevant features of prehensile behavior as follows:

1. Schema interaction with respect to functional requirements
2. Competition and selection of motor schemas
3. Minimization criteria for opposition space selection
4. Detailed description of opposition in terms of the biomechanics of the hand
5. Center of mass perception and development of grasping strategies to account for its use in hand postures
6. Relative contribution of passive vs active forces

CONCLUSIONS

This paper describes an initial approach to problems in the control of prehensile movements through the use of coordinated control programs involving both parallel and sequential activation of schemas. Preshaping the hand into a posture suitable for interaction with objects forces the controller to have a model of the physical properties of the object and the hand working within a task. We describe flexible functional units called virtual fingers, which are groupings of real fingers or the palm. We define opposition space as the area where three basic oppositions can take place, alone or in parallel, so that opposing forces can be exerted between virtual finger surfaces to effect a stable grasp. We describe opposition schemas activated by the *preshape schema* that implement virtual finger configurations based on such task constraints as object properties, anticipated forces, and functional degrees of freedom. This research will be further developed to model other aspects of human prehensile behavior, and will go on to suggest models for neural mechanisms for control of hand movements.

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