

# Body Scale and the Development of Prehension

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This study examined whether common dimensionless ratios define the critical point in the shifts in the grip coordination pattern of preschoolers and adults engaged in a displacement grasping activity with cubes that varied in object size. The findings indicated that there was an interaction between task constraints and organismic constraints in determining the grasping pattern utilized. However, when the object size is scaled to hand size there are common dimensionless ratios that correspond to the grasping patterns and the limb orientations employed across the age range utilized. Furthermore, 5 grip configurations accounted for the majority of grip variance in both age groups. The findings suggest a strong role for the impact of body scale on the development of coordination and provide preliminary evidence for the view that the development of prehension is a reflection of the constraints imposed on action.

Prehension is the act of grasping. Typically humans utilize the hand for prehensile activity although other anatomical units such as the foot and mouth may also be employed for grasping actions. The hand contributes immensely to the adaptability of the prehensile act in humans, in large part due to the relatively large number of biomechanical degrees of freedom (28) in each arm and hand biokinematic linkage.

Traditionally, developmentalists have reported an orderly and regular sequence of the development of prehension (e.g., Connolly, 1973; Connolly & Elliott, 1972; Gesell, 1928; Halverson, 1931; Hooker, 1938), in much the same way that developmental sequences have been reported for other so-called phylogenetic activities such as posture and locomotion. The normative developmental progression for prehension extends from a primitive grasp reflex to a voluntary type of prehension and from a crude clawing type of hand closure to a precise index finger-thumb opposition that allows a sequential "dictionary" of grips to emerge through infancy and over the early years of childhood. This relatively invariant

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order in the development of grasping skills has been traditionally viewed as consistent with the tenets of maturation theory (Gesell, 1928), although later studies have attributed the prehensile development of early childhood to be due to increased cognitive capacity of the older child (Connolly & Elliott, 1972). The maturational and cognitive accounts of the development of coordination are both prescriptive in the sense that they have some symbolic knowledge based system specifying the details of the dynamics of the movement sequence.

Napier (1956, 1962) claims that all the movement configurations of the hand fall basically into either a power or precision category. Other grip classification schemes have been proposed by Elliott and Connolly (1984), Landsmeer (1962), and van Gemert (1984), that are all based to varying degrees on anatomical and/or functional schemes of classification. A key question regarding prehensile development has been the emergence in infancy of a precision index finger–thumb opposition grip from the imprecise power grip where the object is held between the undersurface of the fingers and the palm. Halverson (1931) in his classic study of infant prehension reported that a precision grasp in infants does not emerge until the age of 9 months. Subsequent studies have demonstrated more precocious prehensile activity (e.g., Bower, 1972; von Hofsten, 1982; 1983), but our understanding of the development of the grip pattern per se in infancy and early childhood still rests primarily on the work of Halverson (1931, 1932, 1937) and Connolly and Elliott (1972), respectively.

The developmental prehensile studies published to date have been confined to a very narrow range of task constraints (Newell & Scully, 1987), in spite of the fact that task constraints have been implicated many times as the key factor determining the prehensile pattern (e.g., McGraw, 1943; Napier, 1962; Shirley, 1931). For example, Halverson (1931) primarily used a 1-in. cube as the object to assess the grasping patterns of infants. Similarly, the comparisons of prehension in early childhood and adulthood has usually been confined to a single object size that most naturally conforms to the body scale of the adult (Connolly & Elliott, 1972). Thus, the impact of task constraints on the development of prehension has not been examined empirically or considered sufficiently in theoretical accounts of the sequential progressions of motor development (Newell, 1986; although see Thelen's [1986] discussion of the role of constraints on the development of locomotion).

In this study we compare the grasping patterns utilized in early childhood with those of adults in performing a simple displacement task as a function of object size. Although the most interesting developmental aspects of coordination probably emerge during infancy, sequential developmental progressions for prehension have been reported in early childhood by Connolly and Elliott (1972) and Connolly (1973), in their examination of 3–5-year-old grasp patterns. To begin our examination of the role of body scale on the development of prehension, we decided to study a similar age group. It was anticipated that the influence of neural constraints would not be a significant factor in producing grip pattern differences in preschoolers and adults and would allow a more independent test of the influence of body scale on the development of different grip patterns during early childhood.

Elaborating from the coordinative structure notion of coordination and control (Kugler, Kelso, & Turvey, 1980, 1982) and principles of dimensional analysis (Buckingham, 1914; Stahl, 1961) one might expect some dimensionless body size/

object size ratio to specify the grasp employed in prehension for a given set of task constraints. This postulate implies that there is a stable and perhaps optimal grip configuration for a given set of task constraints that humans typically gravitate toward using, not that a child or adult cannot or will not employ many grip patterns in the same task situation. Dimensionless body-scaled ratios that correspond to shifts in gait patterns (e.g., Alexander, 1984), the perception of preferred stair riser height (Warren, 1984) and sitting height (Mark, 1987; Mark & Vogele, 1987), the perception by adults of the optimal size of objects for grasping (Hallford, 1984), and the perception of passable apertures in walking (Warren & Whang, 1987) have previously been reported. Furthermore, the onset of voluntary locomotion in infancy appears to be related to the weight/height ratio and leg/trunk ratio (Norval, 1947; Shirley, 1931). Thus, dimensionless ratios can define the critical points of behavior that correspond, in this study, to shifts in the grip coordination pattern.

These critical points for action categories are viewed as emergent properties of the way in which the response dynamics are channeled by organismic, environmental and task constraints (Newell, 1986). In the coordinative structure perspective (Kugler et al., 1980, 1982), the assembly and disassembly of coordinative movement patterns is modelled in terms of the generation and annihilation of equilibrium regions of the response dynamics as a function of changes in thermodynamical, mechanical, geometrical or logical constraints. These equilibrium regions correspond to stable movement patterns of coordination and control, although they may not reflect the additional criterion of being optimal regions, in the sense of also being preferred regions of energy expenditure. The approach to modelling the physical processes underlying change in the layout of the equilibrium regions supporting the movement patterns is consonant with the physical design principles for self-organizing systems (see Kugler & Turvey, 1987).

In the current study, it was anticipated that there are dimensionless object/hand size ratios that specify the grasping pattern employed for a given set of task constraints, *independent* of age between early childhood and adulthood. The task selected was a displacement task in which cubes of varying sizes were to be placed into another slightly larger open-faced cube. Grip patterns were classified on a variety of dimensions according to their anatomical contact with the object and examined for their frequency as a function of an object/hand size ratio and age.

## Method

### Subjects

The subjects were 26 preschoolers with an age range of 3 years 3 months to 5 years 4 months ( $M = 4$  years 4 months), and 22 adults ranging from 18 to 46 years ( $M = 31$  years 2 months).

### Apparatus and Procedures

The adults were tested individually in a soundproof testing room at the University. The children were tested in a quiet room at their school. A number of

anthropometric measures of hand size, arm length and finger span range of motion were recorded using standard anthropometric techniques (Snyder, Schneider, Owings, Reynolds, Golomb, & Schork, 1977).

The subjects sat at a table of normal height for their body size, but table height was not manipulated directly with respect to the height of each individual. That is, preschoolers sat at a preschool-size table and adults sat at a table with a height that was normal for adult use. The experimenter sat on the opposite side of the table from the subject. The grasping routine that subjects performed was videotaped by two cameras placed at right angles to each other to allow a split screen image for subsequent coding of the grip patterns utilized by subjects.

The subject's task was to complete a series of prehension trials in which a cube was to be grasped and displaced into another, slightly larger cube that had an open side face-up. The cube for each trial was presented to the subject on a flat board by the experimenter and placed directly on a table in front of the seated object, on a line extending from the body mid-line. The cube was delivered to the subject on a board to prevent the subject from seeing the experimenter grasp the cube. The object was brought to rest so that subjects could comfortably reach the cube with their elbow(s) flexed at about 90°. The subjects were told to grasp the cube and to place it into another cube which had an open side face-up and that was also on the body mid-line, but further away from the subject than the cube to be lifted. There was an intertrial interval of about 15 s. No instructions were provided to guide subjects' selection of grasping patterns.

Ten cubes with one side open were created out of cardboard. The width of the cubes was 0.8, 2.2, 4.2, 6.2, 8.2, 10.2, 14.2, 16.2, 20.2, and 24.2 cm. The 24.2-cm-width cube weighed 275 g. Additional cubes of width 1.4, 12.2, 18.2, and 31.1 cm were made so that each of the 10 cubes to be grasped could be placed into another cube that was 2 cm larger in width. The only exception was the 0.8-cm cube that was placed into the 1.4-cm cube. Thus, there was only one object shape and task goal that required the subject to pick up a cube of varying size and place into another cube. Subjects completed 3 rounds of testing in which each round had the 10 cube sizes in random order.

The videotapes of the prehension trials were coded by an experimenter on a number of hand dimensions including: hand(s) used (right, left, both); number of fingers along with thumb in contact with object; depth of finger contact (distal finger phalanx or more proximal use of finger); palm contact (yes, no); and orientation of hand grip on object (side, top, side/top). A second experimenter independently coded 25% of both the adult and preschoolers trials. There was 100% agreement between the coders on three of the 5 hand dimensions and 98% agreement on the other 2 dimensions. Thus, the coding of the data appears very reliable which was expected given the relatively discrete categories used for describing hand function.

## Results

The frequency of trials per age group employing the grip dimensions was calculated as a function of object size. The frequency data are primarily presented as a function of the ratio of the cube size/index finger–thumb range of motion. There are a variety of hand parameters on which the frequency data could be body

scaled. A range of motion measure was chosen instead of an anatomical length as it was anticipated that range of motion will generalize across population groups more readily than length of hand or fingers, particularly at the extremes of the age continuum where anatomical length and range of motion are less likely to covary. We examined several possible range of motion parameters, but index finger–thumb provided as good a picture of the shifts in the grip patterns as a function of object size, as any of the possible body-related measures. Anthropometric measures of the hand tend to be highly correlated, particularly in young children ( $r$ 's > .70), and, thus, a similar set of frequency data emerge across a variety of object/hand size ratios. The index finger–thumb measure is also appealing as it intuitively sets the limits to the use of a precision index finger–thumb opposable grip.

An analysis of the proportion of trials on which one or two hands were employed revealed a significant age group by hand interaction,  $F(1,46) = 47.08$ ,  $p < .01$ . Adults on average used one hand on 60.00% and two hands on 40.00% of the trials. The children used one hand on 38.59% and two hands on 61.41% of the trials. Thus, adults used one hand significantly more often than the children used a single hand which is to be expected when one employs the absolute hand size as the means to analyze the frequency data.

However, Figure 1a reveals that the frequency curves for hand use by children and adults are very similar both in pattern and absolute frequency when plotted against the object/hand ratio. This suggests that object to hand size ratio is a significant factor in the use of one or two hands in grasping an object for a given set of task constraints, independent of age. There was a slightly higher percentage of right hand use by adults than the preschool children, which is consistent with the general finding that hand dominance may not be fully developed at the age of 4 years (Corballis & Morgan, 1978; Gesell & Ames, 1947; Ingram, 1975). When single right and left hand grasps are summed to form a single hand condition (see Fig. 1b), it can be observed that a common dimensionless ratio specifies for the two age groups the shift in grasp pattern from one to two hands.

A similar body scaled trend is observed in Figure 2 that depicts the number of fingers in the dominant hand that grasps the object as a function of the same object/hand size ratio. The frequency data again reveal very high similarity between preschoolers and adults in both the shape and the absolute size of the frequency trends. As anticipated, one finger is used with the thumb at very small object sizes and all 4 fingers are combined with the thumb at the larger object sizes. There was evidence of 2 and 3 fingers being combined with the thumb at the intermediate object sizes, but the preference for this grip configuration existed only over a small intermediate range of object sizes.

A more detailed analysis of finger use is provided in Table 1 where the frequency of the total number of fingers used irrespective of the number of hands employed is shown as a function of the object size. These data confirm the expectation that total number of fingers increases as object size increases, but, in addition, reveal some insights as to the influence of task constraints on grip patterns. It is clear that only a few grip patterns were utilized out of the large number of potential hand and finger configurations. This trend is particularly evident at the extremes of object size where presumably the constraints eliminate the majority of configurations of fingers and thumbs as a viable solution to the task. For example, with the .8-cm cube, over 92% of the grasps in both age groups

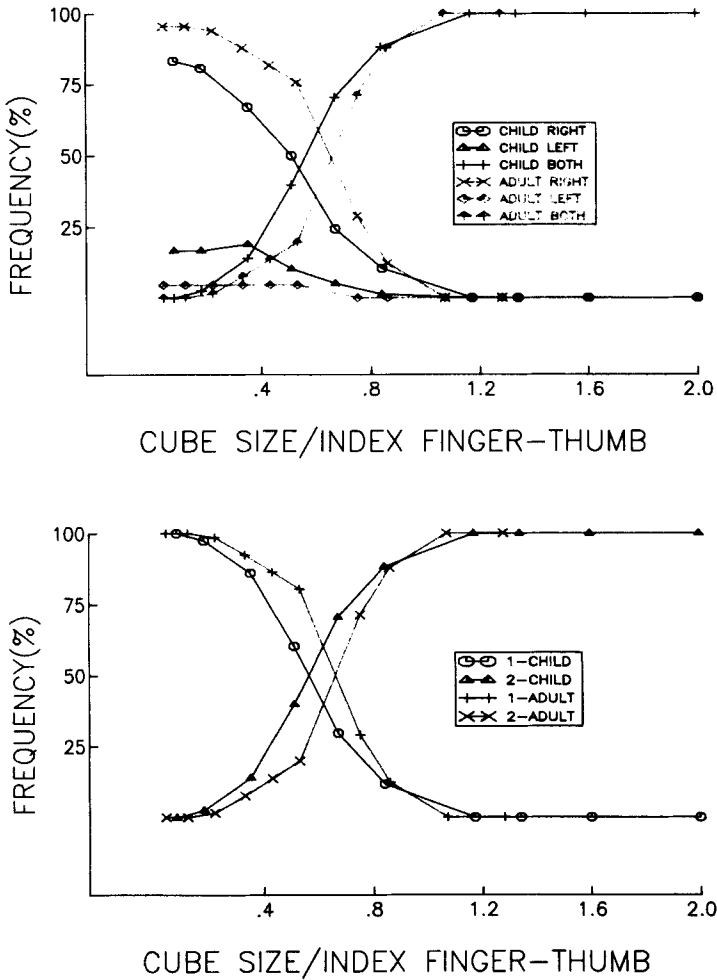


Fig. 1. (Top) Frequency of hand use (right, left, both) as a function of age group and object/hand ratio. (Bottom) Frequency of single and two hand use as a function of age group and object/hand ratio.

are with one finger and thumb, whereas with the largest 24.2-cm cube, over 98% of the grasps are with all the fingers and thumb of both hands. The absolute object size that induces the grip pattern shifts between age groups is different. For example, the shift to 2 hands and all fingers occurs with the 8.2-cm cube in children, whereas the shift point is the 14.2-cm cube in adults. However, as shown previously, the relative data in the form of dimensionless ratios confirm that the hand grip shifts are similar between age groups when the object is scaled to hand size.

There are 1013 potential combinations of fingers and thumb (without respect to order) when considered across the 2 hands. This figure is derived from the sum of the number of combinations of 10 digits taken 2 at a time, 3 at a time and so on up to 10, without respect to order or permutation. However, subjects only utilized a small subset of this possible total. Adults used 14 combinations of finger and

TABLE 1. Frequency (%) of Fingers Used as a Function of Age and Object Size.

Number of Fingers	Object Size (cm)									
	.8	2.2	4.2	6.2	8.2	10.2	14.2	16.2	20.2	24.2
A. Children										
1	74 (94.87)	28 (35.90)	2 (2.78)	1 (1.28)	2 (2.56)					
2	4 (4.13)	38 (48.72)	23 (29.48)	9 (11.54)	5 (6.41)	4 (7.6)				
3		8 (10.26)	32 (41.02)	21 (26.92)	11 (14.10)	4 (5.12)				
4		3 (3.85)	16 (20.51)	17 (21.79)	5 (6.41)	2 (2.56)				
5				1 (1.28)	1 (1.28)	1 (1.28)				
6		1 (1.28)	1 (1.28)	11 (14.10)	10 (12.82)	10 (12.82)	6 (7.69)	3 (3.85)	1 (1.28)	
7			1 (1.28)	5 (6.41)	5 (6.41)	12 (15.38)	4 (5.13)	5 (6.41)	5 (6.41)	1 (1.28)
8			3 (3.84)	15 (16.66)	38 (48.72)	43 (55.12)	68 (87.18)	70 (89.74)	72 (91.3)	77 (98.72)
B. Adults										
1	61 (92.4)	40 (60.61)	11 (16.67)	6 (9.09)	2 (3.03)	2 (3.03)				
2	5 (6.75)	26 (39.39)	33 (50.00)	15 (22.73)	7 (10.60)	4 (6.06)	6 (9.09)	1 (1.52)		
3			20 (30.30)	30 (45.46)	26 (39.39)	24 (36.36)	3 (4.55)	2 (3.03)		
4			2 (3.03)	12 (18.18)	25 (37.87)	23 (34.85)	10 (15.15)	5 (7.58)		
5						1 (1.52)		1 (1.52)		
6				2 (3.03)	1 (1.52)	2 (3.03)	4 (6.06)	4 (6.06)	1 (1.51)	
7						1 (1.52)	3 (4.55)	4 (6.06)	4 (6.06)	1 (1.52)
8				1 (1.51)	5 (7.58)	9 (13.64)	40 (60.61)	49 (74.24)	61 (92.42)	65 (98.49)

thumb categories and children used 22 finger and thumb categories. Within the finger combinations used, there were common grasp preferences by both age groups with 5 grip configurations accounting for a large percentage of the total. These 5 grip configurations with their frequency of use as a function of age group are shown in Table 2. A graphic depiction of these 5 grip patterns is provided in Figure 3. The 5 grip patterns account for approximately 62% of the grips used by children and approximately 89% in adults. If playful behavior by the young children could be eliminated in data collection, one might anticipate the 5 grips to account for a higher percent of grip variance in the young children. The finger data also reveal a high degree of symmetry when 2 hands are used. Indeed, a symmetrical grip with respect to finger configuration was employed by each hand approximately 89% with the children and 92% with adults in 2 hand grasps.

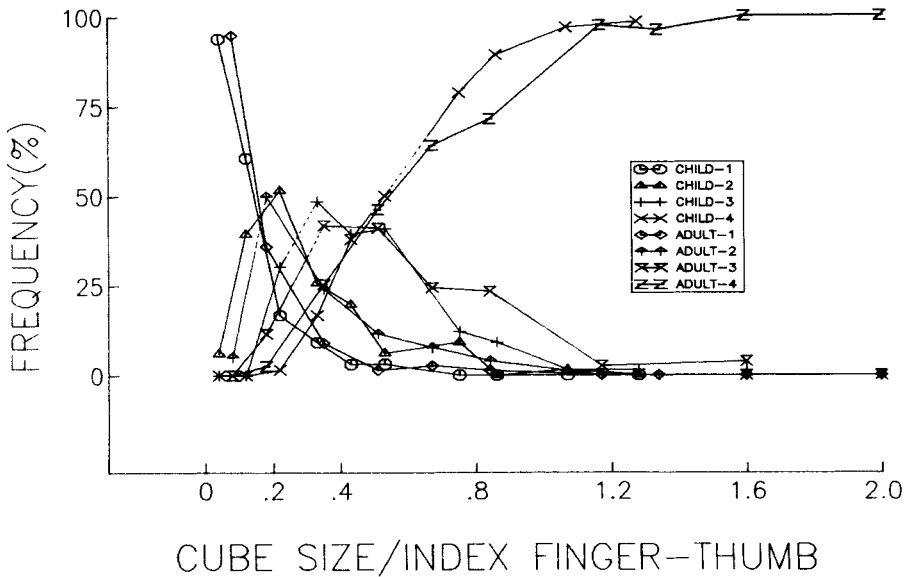


Fig. 2. Frequency of the number of fingers used in the dominant hand as a function of age group and object/hand ratio.

Figure 4 depicts the orientation and depth of finger contact for children and adults as a function of the object/hand ratio. Figure 4a shows that children and adults adopted a similar strategy to orientation given the same relative object size in that the object was picked up from the top when the object was small and as the

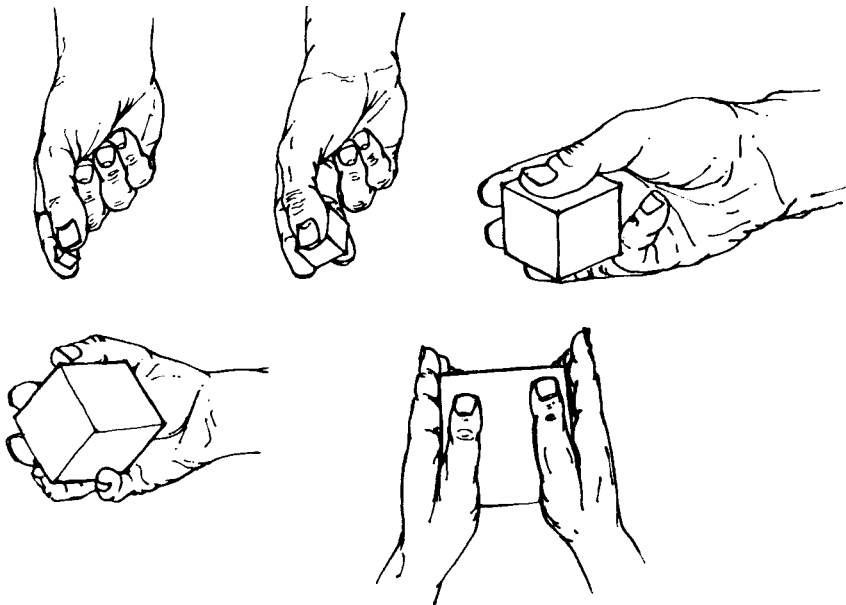


Fig. 3. Schematic of the 5 grip patterns that accounted for the majority of grip variance.

TABLE 2. Frequency of Five Grip Patterns in Children and Adults.

Age Group	Grip Pattern					Total
	One Hand				Two Hands	
	Index & Thumb	Index, Middle & Thumb	Index, Middle, Ring & Thumb	All 4 Fingers & Thumb	8 Fingers & 2 Thumbs	
Children	87	52	66	42	235	482
Adults	112	86	85	73	229	585

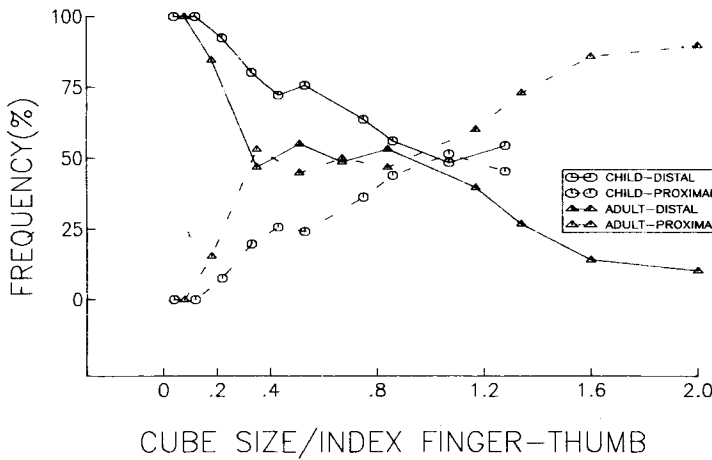
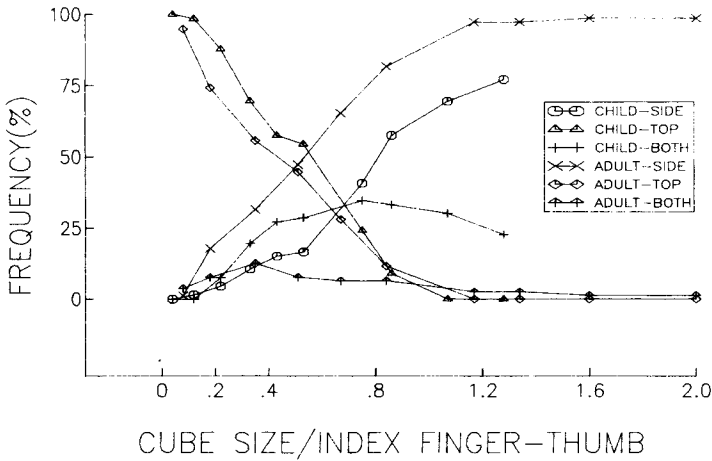


Fig. 4. (Top) Frequency of hand orientation as a function of age group and object/hand ratio. (Bottom) Frequency of depth of finger contact as a function of age group and object/hand ratio.

relative size of the object increased, a side orientation strategy was used increasingly. There was a tendency for the children to grasp both the top and side in the middle range of object size.

Children and adults adopted a similar strategy with respect to depth of finger contact (Fig. 4b). That is, at small relative object sizes the distal phalanges are used, but as the relative object size increases, more proximal finger contact is made with the object. The functions for each age group depart somewhat around the object/hand ratio of .4. This could be due to the differential finger shifts that occur between groups at this dimensionless ratio, which would suggest that there is some hierarchy to the significance of different hand dimensions in specifying grip configurations. However, the similarity of the frequency profile of the orientation and finger depth dimensions, when considered in conjunction with the similarity of hand and finger use (Figs. 1, 2), confirms that when body scale is considered on a relative basis there are common dimensionless ratios that specify the grip pattern utilized, across the age groups.

## Discussion

The findings of this experiment suggest a strong role for the influence of task constraints, in the form of object size, on grip patterns utilized in early childhood and adulthood. In essence, the experiment demonstrates that young children and adults predominantly use the same grip pattern when the object is scaled to hand size. Furthermore the subjects utilized only a very small number of the possible grip configurations, which suggests that there are a few optimal points that constrain grip patterns, in spite of the large number of degrees of freedom that need to be coordinated and controlled in the arm(s) and hand(s).

Synthesis of the grip pattern data across the dimensions of hand use, finger use, finger depth, palm use and hand orientation confirm that the grip pattern was predominantly identical when the task constraints were scaled to the body parameter of index finger—thumb range of motion. The evidence for common dimensionless ratios across the age groups was particularly compelling on the major dimensions that define the pattern of grip coordination; namely, the hand and finger configuration. The age groups trends for the dimensionless ratios were also similar on the hand orientation and depth of finger contact, but departures from a common function were apparent on these dimensions. The reason for these departures needs to be explored further. It is possible that these dimensions are of less significance than hand and finger configuration in determining grip organization, and thus, are susceptible to increased variability.

In this experiment, object size was manipulated within a given goal constraint of object displacement. It would be interesting to determine if these findings generalize across other action categories which are either designated externally, as they were in this study by the experimenter, or determined by the subject through perception of the environmental properties. The later condition is probably a stronger test of Gibson's (1979) notion of affordances, but the current findings suggest that the affordance concept may apply beyond global action categories of walking, grasping, etc. to very specific patterns of coordination.

Indeed, the current findings demonstrate that in spite of the 28 biomechanical degrees of freedom that are available in each arm and hand biokinematic linkage,

subjects gravitate to employ only a very few grip patterns. The 5 grip patterns accounted for approximately 62% of the grip pattern variance in young children and 89% of the grip pattern variance in the adult age group. This suggests that there are only a few optimal boundary points that reflect preferred regions of stability and energy expenditure (Kugler, 1986; Kugler & Turvey, 1987; Kugler et al., 1980, 1982), although further experimentation will be required to confirm an optimality interpretation to the critical dimensionless ratio points defining grip patterns. In the coordinative structure theory, the dimensionless ratios that define the critical points for the shifts in grip configurations are viewed as emergent properties of the constraints imposed on the dynamics of the biological system, rather than reflections of some prescriptive representation as required by both the maturational and cognitive accounts for the development of coordination.

The influence of task constraints on grip patterns has often been recognized (e.g., McGraw, 1943; Napier, 1962), but the various dimensions of task constraints have not been systematically manipulated in developmental studies of prehension. This has led to evaluations of the development of prehension in infancy (Halverson, 1931) and early childhood (Connolly & Elliott, 1972) to be limited to essentially a single object size condition. The current findings suggest that the developmental progressions reported for prehension, particularly the grasp configuration, may be reflective, to a large degree, of the task constraints imposed on the local experimental conditions. The implication, therefore, is that the development of prehension may be more precocious than traditional estimates and that it is more flexible and adaptive than the "dictionary-like" prescriptive progressions reported by Halverson (1931) for infants and Connolly and Elliott (1972) for children in early childhood.

This experiment only manipulated the task constraint of object size, but there are many other task factors, in addition to the geometry of the object, that will influence the coordination function (Newell, 1984, 1986). Other potentially significant object dimensions include form, mass, texture and surface coefficient of friction. In addition, the goal of the activity and the rules that may constrain or specify the response dynamics are other task factors. The full impact of these task constraints on the development of prehension has yet to be established. Furthermore, if the grip pattern employed is an emergent property of the confluence of constraints that exist (Kugler et al., 1980), then we also need to examine more completely the interaction of task, organismic, and environmental constraints (Newell, 1986).

From a developmental perspective, the more interesting tests of the influence of constraints on coordination, and, in this case prehension, probably will be found during the first year of life due to the relatively rapid development of the neuromotor system. Indeed, another thrust of our research is to examine the influence of task constraints on grip configurations on much younger children than used in this study with a view to reexamining the inferences drawn by Castner (1932), Halverson (1931) and others regarding infant prehension. The current data are, however, encouraging from the point of view of demonstrating the strong role for the impact of body scale on the development of coordination, and provide preliminary evidence for the view that the development of prehension is a reflection of the constraints imposed on action.

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