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Motor Strategies in Lifting Movements: A Comparison of Adult and Child Performance

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ABSTRACT. The experiment compares the performances of children six to nine years old and adults in a simple, monoarticular lifting task. Overt behaviors, as described by the kinematic features of the movement, do not differ qualitatively in the two groups. The patterns of motor commands, as expressed by the electromyographic recordings, are however strikingly different. Adults plan the movement with a careful balance between agonist muscle activity and passive, viscoelastic forces, whereas children use both agonist and antagonist active forces. It is argued that the motor strategy adopted by adults depends upon an internal representation of the properties of the motor system and of the size/weight covariation in natural objects, and that this representation is not yet fully developed at nine years of age.

A WELL-ESTABLISHED notion in motor control theory posits that the successful accomplishment of purposive movements is predicated upon some central representation of the properties of the motor system itself (Bernstein, 1967; Glencross, 1980; Matthews, 1972; Paillard & Brouchon, 1974; Schmidt, 1975; Teuber, 1972). In particular, motor commands issued to the muscles undoubtedly take into account—and take advantage of—the properties of the biomechanical system upon which they impinge (Viviani & Terzuolo, 1973; Viviani, Soechting, & Terzuolo, 1976).

Equally important and perhaps not as sufficiently emphasized in recent studies is the notion that any successful motor performance also re-

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quires a representation of the properties and constraints of the physical world within which the movement is executed and, in particular, of the objects that are acted upon (Hauert, 1980; Mounoud & Hauert, 1982; Mounoud, Mayer, & Hauert, 1979). Such representation must concern not only the immediate perception of the properties of the object per se (such as weight, size, etc.), but also, and primarily, the relationships among the properties of several objects (relational schemata). For instance, as Claparède (1902) pointed out a long time ago, the planning of lifting movements is largely based on the predicted relationship between size and weight which can only be defined over a class of objects.

It has been suggested that both the representation of the properties of the motor system and the relational schemata and inferences concerning the external world evolve into a fully developed perceptuo-motor representation during the various stages of child development (Mounoud & Bower, 1974; Mounoud & Hauert, 1982). In this paper, we present experimental evidence that the planning of a specific simple movement changes from childhood to adulthood, and we argue that this change is consistent with the hypothesis, discussed above, of an underlying evolution of the representational schemata.

The motor task considered here is the lifting of a series of objects whose weight and size increase linearly. Such a task is not a skill that requires learning, and any normal adult can be expected to have fully mastered the representation of an orderly covariation of weight and size. On the other hand, it is quite unlikely that such representation is inborn. We can therefore predict some major difference between the performance of children and adults.

A previous study of the lifting movement of children (Hauert, 1980) emphasized the qualitative characterization of the overt behavior (trajectory and kinematics). In the present study, we will consider both the overt behavior and the underlying motor activities. Since a number of different motor patterns can result in virtually indistinguishable movements, the study is based on the analysis of both the movement kinematics and the EMG activity in the main agonist and antagonist muscles.

This work is concerned only with the global comparison of child and adult performance. In a subsequent report, we will focus on the age-dependent differences in children's performance.

Method

Subjects. Forty male elementary school children (6 to 9 years old) and 10 young male adults participated in the experiments.

Apparatus. The objects to be lifted were metal parallelepipeds with constant square section (4 × 4 cm) and variable height (see Table 1).

The objects were each attached with a velcro strap to a rod connected to an angular potentiometer through a 2°-of-freedom mechanical link (see Figure 1). Thus, the lifting movement was unimpeded. Frictional

Table 1
Weight and Height of the Objects.

Objects	1	2	3	4	5	6	7	8	9
Weight (g)	375	625	875	1125	1375	1625	1875	2125	2375
Height (cm)	3	5	7	9	11	13	15	17	19

forces were negligible with respect to the weight of the objects. The amplitude of the movement was limited to 20 cm by an abutment which was positioned before each trial, taking into account the length of the subject's forearm.

Procedure. Subjects sat in front of the object with the shoulders maintained in a fully upright position by the chair's back. Before beginning a movement, the forearm lay horizontally on a properly positioned platform while the half-prone hand grasped the object with the thumb in opposition to the fingers.

The movement required a pure flexion of the forearm to bring the wrist in gentle contact with the abutment, followed by the maintenance of this final position for 4 sec. Subjects were free to choose the time of initiation and the velocity of the movement and were encouraged to perform the movements in what they felt to be the most natural manner. However, we eliminated and repeated those trials in which the elbow had been lifted during the movement. In all cases, subjects used their dominant hand. The objects were placed and removed by the experimenter. Adults lifted six times the entire series of nine objects from the lightest to the heaviest. Children only lifted the seven lightest objects of the series in the same order as the adults; moreover, the number of repetitions was reduced from six to five. The large weight difference between the last object lifted in one sequence (number 7 or 9) and the first object in the next sequence could introduce an artefact. Therefore, we discarded the results concerned with the lifting of the lightest object. At the end of the experiment, subjects had to maintain each object at a height of 10 cm for a duration of 30 sec in adults and 20 sec in children. This isometric condition was used for calibration purposes (see Results Section).

Data recording and processing. In all cases, the trajectory of the object was roughly an arc of a circle (see Figure 1). Because of the geometry of the mechanical link, the output of the potentiometer provided an instantaneous measure of the chord of this arc. Within the small angles approximation, such a measure was confounded with both the vertical and angular displacement of the object. The analog signal was filtered (cut off: 100 Hz) and sampled at 125 Hz. Velocities and acceleration were computed digitally after some further smoothing with a (double-sided) exponential low-pass numerical filter.

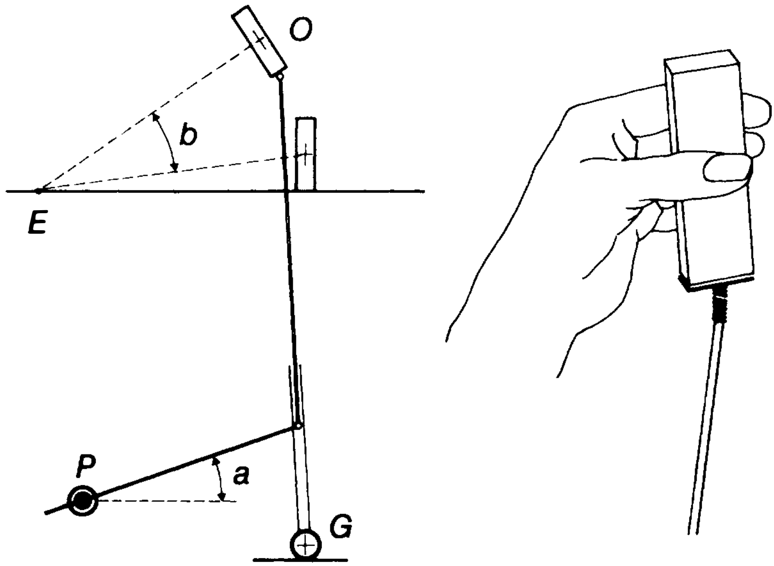

Fig. 1—Experimental setup. In the left panel, a schematic view of the mechanical link between the lifted object (0) and the angular potentiometer (P). A pure flexion of the forearm around the elbow (E) imposes a circular trajectory to the object. The rod attached to the object slides in a rail mounted on a 2°-of-freedom gimbals (G) and produces a rotation of the potentiometer axis. The correspondence between the rotation angle at the elbow (b) and the measured angle (a) is established by a proper calibration of the system. Since the amplitude of the movement was limited to 20 cm, the rotation angle (b) can be confounded with the arc length. The left panel shows the finger grip used to seize the object.

Surface EMG was recorded with Beckmann electrodes (silver-silver chloride pellet, 17 mm diameter; bipolar detection) from three groups of muscles: Biceps brachii, deltoid (anterior part), and triceps brachii (long head). The correct placement of electrodes was tested against resistance (Basmajian, 1967). After filtering (band pass from 50 Hz to 1000 Hz), the raw EMG signals were converted into a train of 1 msec impulses. The Schmitt trigger threshold was individually adjusted for each subject and each group of muscles with the criterion that no pulses were triggered during resting activity. Finally, the train of pulses was converted into an average frequency signal with a binning technique (bin width: 96 msec). The rationale and the details of such a binning procedure have been given elsewhere (McKean, Poppele, Rosenthal, & Terzuolo, 1970; Viviani, Soechting, & Terzuolo, 1976). Displacement and EMG signals were recorded from 960 msec before to 3136 msec after the initiation of the movement.

Results

Analysis of adult performance. The parameters relevant to the description of the movement are identified in Panel A of Figure 2 which shows a representative example of a mechanogram. Panel B in the same figure shows the time of occurrence of the first two peaks of acceleration (T_{a_1} and T_{a_2}), of the first peak of velocity (T_{v_1}), and of the total duration of the movement (T_d), as a function of the object rank order in the series. Data points are averages over all repetitions and all subjects. Bars indicate the intersubject variability (standard deviation of individual means). Neither the peak times, T_{a_1} and T_{v_1}, nor the total duration of the movement varied significantly with the object weight, ($F(1,72) = 1.49$, $p > .01$, $F(1,72) = 5.38$, $p > .01$, and $F(1,16) = 0.19$, $p > .01$, for the linear trend, respectively). On the other hand, the time of occurrence, T_{a_2}, of the second peak of acceleration increased linearly with the weight ($F(1,72) = 6.24$, $p < .01$).

The three graphs in Panel C of Figure 2 show the relation between the maximum values of both velocity and acceleration and the object's weight. Data points are averages over all repetitions and all subjects normalized to the respective mean values for all objects (a_{1M}, v_{1M}, a_{2M}). Bars indicate $\pm$ 1 standard deviations of individual means. Each set of data

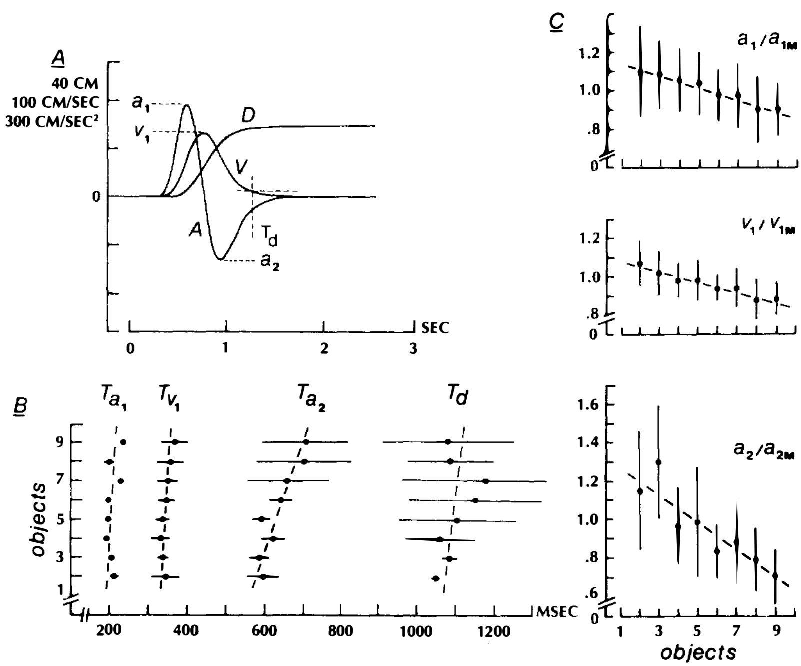

Fig. 2—Kinematic description of adult performance. Panel A: Displacement (D), velocity (V), and acceleration (A) curves for a typical trial. Panel B: Effects of the object weight on the time of occurrence of the velocity and acceleration peak values. Bars indicate the standard deviations of the individual means. Panel C: Effects of the object weight on velocity and acceleration peak values. Data points are averages over all repetitions and all subjects, normalized to the mean value for all objects (a_1/a_{1M}, v_1/v_{1M}, a_2/a_{2M}).

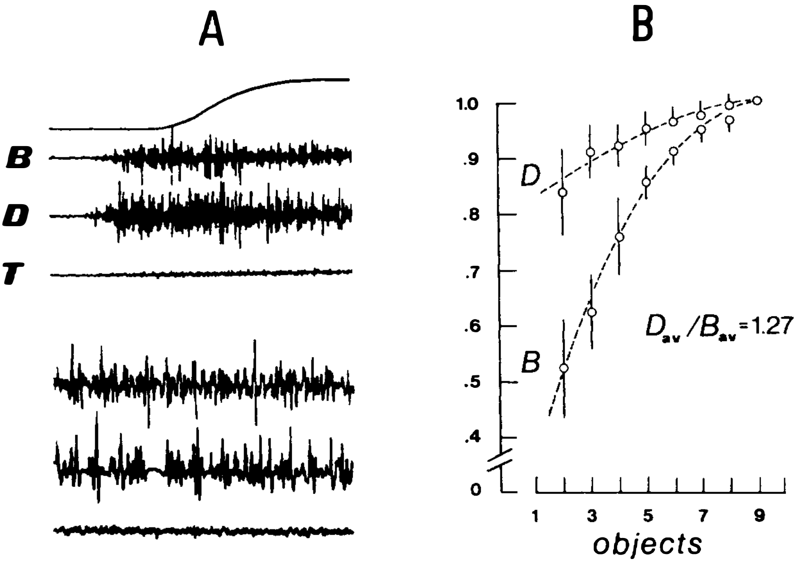

Fig. 3—EMG recordings of adult performance. Panel A: Examples of raw EMG data under dynamic (upper tracing) and isometric (lower tracing) conditions, respectively, for biceps brachii, deltoid (anterior part), and triceps brachii (long head). Panel B: Average EMG activity under isometric conditions in biceps (B) and deltoid (D) muscles for all objects. Data points are normalized to the maximum value, attained for object number 9. D_{av}/B_{av} indicates the ratio between the average (un-normalized) activities in the two muscles across all objects.

points reveals a significant linear decrease of the maximum values (a_1/a_{1M}: $F(1,72) = 6.14$, $p < .01$; v_1/v_{1M}: $F(1,72) = 8.60$, $p < .01$; a_2/a_{2M}: $F(1,72) = 8.78$, $p < .01$). However, it should be stressed that the manifold increase in object weight (380%) results in only a rather small (linear) variation in the kinematic parameters of the order of 30%. Thus, adult performance is characterized by a clear tendency to invariance vis-à-vis changes of the external conditions. However, this compensatory behavior is more apparent in the timing of the kinematic parameters (T_{a_1}, T_{v_1}, T_{a_2}, T_d) than in their amplitude. The relative invariance of the timing of the movement is reminiscent of the Isochrony Principle which expresses a built-in tendency, observed in many motor performances, to make execution time less variable than movement size (Kelso, Southard, & Goodman, 1979; Turvey, Shaw, & Mace, 1978; Viviani & Terzuolo, 1982; Viviani & McCollum, in press).

Panel A in Figure 3 illustrates two typical examples of raw EMG recordings in adult subjects under dynamic (upper tracing) and isometric (lower tracing) conditions. In isometric conditions, both biceps and deltoid activity increase monotonically as a function of the object's weight ($F(1,72) = 79.11$, $p < .01$, $F(1,72) = 10.63$, $p < .01$, respectively), while the triceps show no trace of activity. Data points in Panel B represent the average EMG activity (see Methods Section) for each ob-

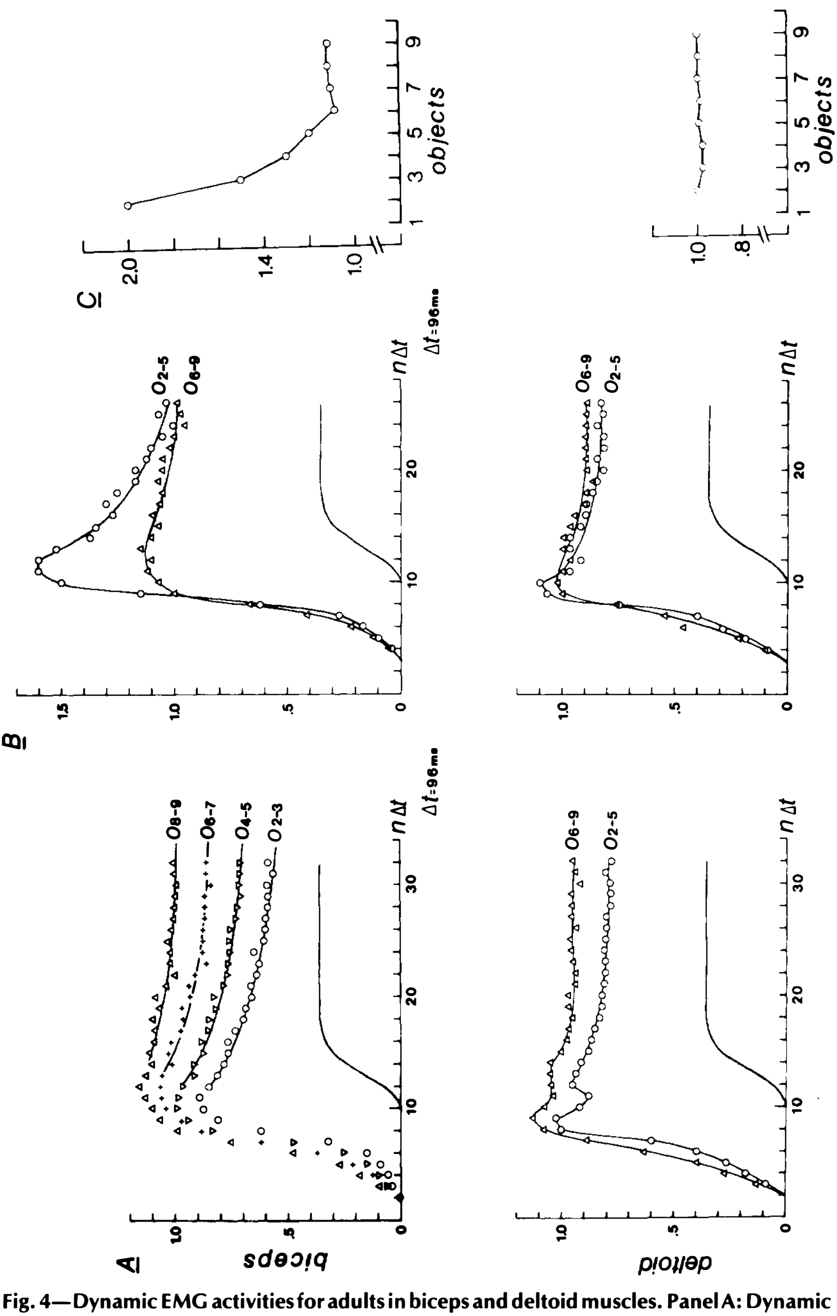

Fig. 4—Dynamic EMG activities for adults in biceps and deltoid muscles. Panel A: Dynamic EMG activities normalized to the final maintenance position value for the heaviest object (number9). Panel B: EMG normalized to the isometric values. Notice the large overshoot in the biceps for the lighter objects. Panel C: Average amplitude of the overshoot as a function of the object weight.

ject in the biceps (B) and deltoid (D), normalized to the maximum value which was consistently obtained for the heaviest object (number 9). Note that, although the deltoid is not directly involved in the task as an agonist muscle, its level of activity depends on the weight of the objects.

As for the dynamic conditions, the EMG activities varied considerably from subject to subject, depending on skin resistance, electrode placement, and other uncontrollable factors. Two normalizing techniques were used to eliminate this variability from the results. The first procedure, which permits one to represent all the results in a unique ratio scale, consists in expressing the binned activity, for each subject, as a fraction of the average activity calculated over the last second of the movement (the "hold" phase) for the heaviest object (number 7 or 9). Panel A in Figure 4 shows the results of such a procedure for both biceps and deltoid muscles. In this figure, different symbols are used to represent the time course of the normalized electromyographic activity averaged over all subjects and the indicated groups of objects. The results show an orderly relation between the weight during the force build-up that precedes the onset of the movement, the movement itself, and the hold period. However, this relation is much clearer for the biceps which—at least in the adult—bear the primary responsibility for the adaptation of the motor plan to changes in the external load, than for the deltoid muscles which contribute a far less specific stabilizing component. This adaptive increase of the motor command in response to increases in weight clearly corresponds to the general compensatory tendency suggested by the analysis of the kinematic parameters.

The second normalization procedure for the individual EMG data consists in expressing the EMG activity as a fraction of the isometric value for the same subject and the same weight. Notice, however, that the average EMG activity during the total phase does not necessarily coincide with the value in the isometric condition for the same weight. Such representation emphasizes the dynamic component of the motor activity during the movement. The application of the procedure to the binned data already shown in Panel A is illustrated in Figure 4B where different data points are again used to represent the averages over all subjects.

The results for the biceps indicate the presence of a considerable dynamic overshoot above the isometric value whose amplitude decreases with an increase in weight (Panel C of Figure 4). The activity in the deltoids, in contrast, show little or no overshoot. Although dynamic components greater than 1 cannot automatically be identified with the resulting acceleration, the trend of the normalized EMG data in Panels B and C are consistent with the fact that both velocities and accelerations were found to be significantly higher for the lighter objects than for the heavier ones (cf. Panel C in Figure 2).

In conclusion, the EMG data are in reasonable agreement with the results of the kinematic analysis and demonstrate that the movement is performed almost exclusively by the biceps while the deltoid is mainly used to stabilize the shoulder. Aside from the general compensatory behavior discussed above, both types of analysis point to the fact that light weights are both accelerated and decelerated more energetically than heavy ones. However, the deceleration does not involve the active intervention of the antagonist muscle (triceps).

Analysis of children's performance. Figure 5 summarizes the analysis of the kinematic parameters for the children's group with the same modalities as in Figure 2 for adults.

Panel A shows the evolution of the timing parameters T_{a_1}, T_{v_2}, T_{a_2}, and T_d as a function of the object rank order in the series. Data points are averages over all repetitions and all subjects. The times of occurrence of T_{v_1} and T_{a_2} are constant (F (1,235) = 1.97, $p > .01$, and F (1,235) = 1.63, $p > .01$, for the linear trend, respectively). The time of occurrence of the first peak of acceleration (T_{a_1}) decreases linearly with the weight (F (1,235) = 17.44, $p < .01$). In contrast, the duration parameter (T_d) increases linearly with the weight (F (1,66) = 5.67, $p < .02$).

The three graphs in Panel B of Figure 5 show the relation between the maximum values of both velocity and acceleration and the object rank order. Data points are averages over all repetitions and all subjects nor-

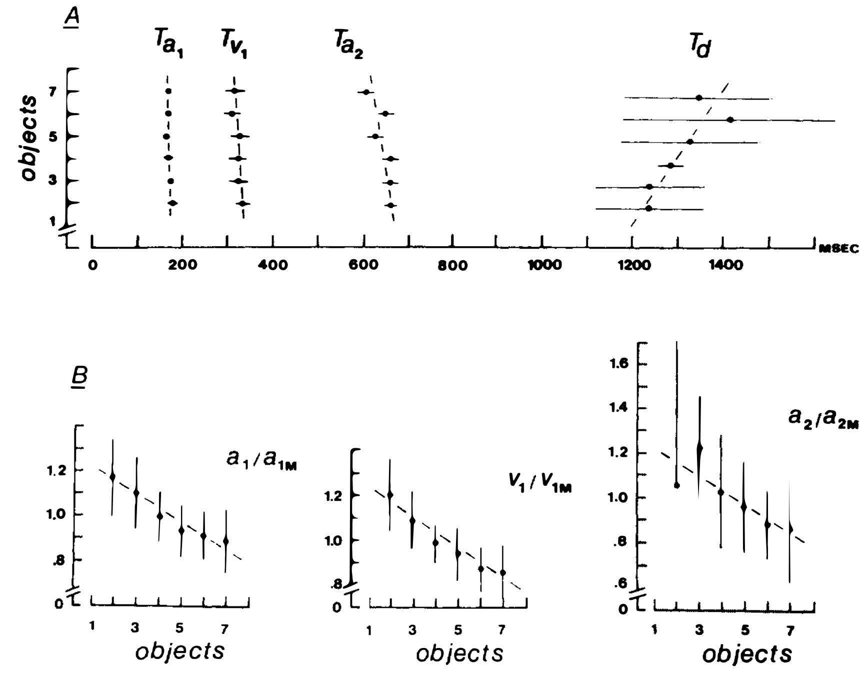

Fig. 5—Kinematic description of child performance. Panel A: Effects of the object weight on the time of occurrence of the velocity and acceleration peak values. Data points are averages over all repetitions and all subjects, normalized to the mean value for all objects (a_1/a_{1M}, v_1/v_{1M}, a_2/a_{2M}).

malized to the mean values for all objects. The acceleration and velocity peak values (a_1/a_{1M}, v_1/v_{1M}, a_2/a_{2M}) all decrease with weight in much the same way as in the adult control group (a_1/a_{1M}: F (1,235) = 29.43, $p <$ .01; v_1/v_{1M}: F (1,235) = 39.55, $p <$ .01; a_2/a_{2M}: F (1,235) = 23.72, $p <$ .01); the decrease of the kinematic parameters is rather small (of the order of 40%) in comparison to the increase in the object weight (300%).

The kinematic analysis of the performance reveals that children between the age of 6 and 9 years display the same compensatory behavior whereby large variations in weight result in comparatively small changes in the acceleration and velocity peak values. However, the children's performance differs from the adult control group in terms of the timing of the kinematic events: While the total duration of the movement in children (T_d = 1306 ± 73 ms) is longer than in adults (T_d = 1097 ± 43 ms), the first peaks of acceleration and velocity occur earlier (T_{a_1} = 175 ± 5 ms; T_{v_1} = 317 ± 7 ms, respectively, versus T_{a_1} = 205 ± 10 ms and T_{v_1} = 371 ± 44 ms in adults; all differences are significant at the .01 level for the *t*-test). The earlier occurrence of the first peak of acceleration may suggest a breaking action which curtails the initial upswing, before the target position is attained (to be discussed below). This early breaking action of the antagonist muscle would then explain the lengthening of the movement duration.

The analysis of the motor commands in children was conducted as for the adults and revealed much more profound differences between the two groups than those found at the behavioral level.

Figure 6 shows the relation between the weight of the objects and the average isometric EMG activity (see Methods Section) in the biceps, triceps, and deltoid muscles. As in Panel B of Figure 3, data points are averages, again normalized to the maximum value attained for the heaviest object (in this case, number 7). The activity in both the biceps and the deltoid still increases with weight (respectively, F (1,54) = 17.81, $p <$ .01, and F (1,54) = 8.36, $p <$ .01, for the linear term), but the dependency is much weaker than the one observed in adults. More important, however, is the presence of a considerable amount of triceps activity (in absolute terms, ⅓ of either biceps or deltoid activity) which increases steeply with weight (F (1,54) = 317.18, $p <$ .01), and which was never present in adults. Thus, even in the isometric maintenance of a weight, children in the age range considered here resort to a co-contraction strategy involving both agonist and antagonist muscles.

Figure 7 summarizes the results for the lifting movement. Panel A shows the EMG activity normalized to the average value during the last second of hold and averaged over the two indicated groups of objects. During the force build-up that precedes the movement, a clear relation exists between the weight and the activity in the agonist muscles. However, during the actual movement and the subsequent hold phase, the biceps contribution becomes insensitive to the object weight. Thus, the balance of forces, for each weight, after the onset of the movement

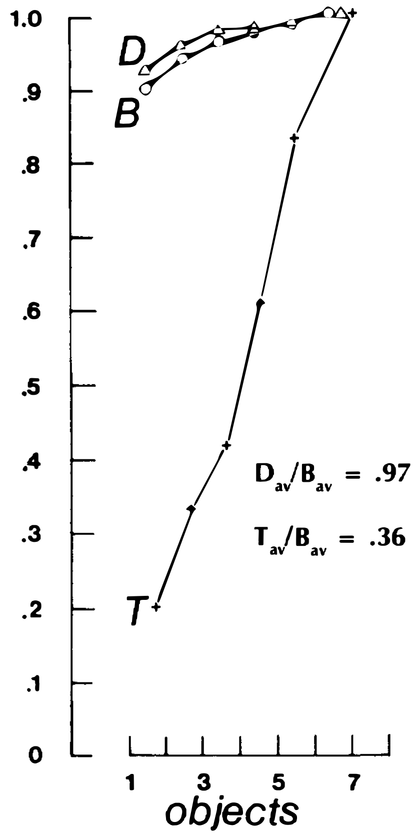

Fig. 6—Isometric EMG of children's performance (see Panel B of Figure 3). Notice the presence of considerable triceps activity.

must be accounted for by the concomitant action of the triceps which, in all cases, opposes the movement with a downward torque. The activity in both triceps and deltoid increases with the weight, the increase being larger in the antagonist muscle than in the shoulder-stabilizing deltoid.

As mentioned above, the normalization of the absolute individual values to the corresponding isometric data (Panel B of Figure 7) emphasizes the time course of the acceleration-producing forces. In children, the dynamic overshoot of the biceps is much smaller than in adults and quite similar to the overshoot in the deltoid. Triceps activity during the hold phase terminating a movement decreases toward the same value obtained under isometric conditions. However, this asymptotic value is more quickly attained for the heavy objects than for the light ones. Indeed, as shown in Panel B of Figure 7, the normalized activities for objects 2, 3, and 4 are still higher than 1 at the end of the sampling period. Because of the long-lasting activity at the end of the

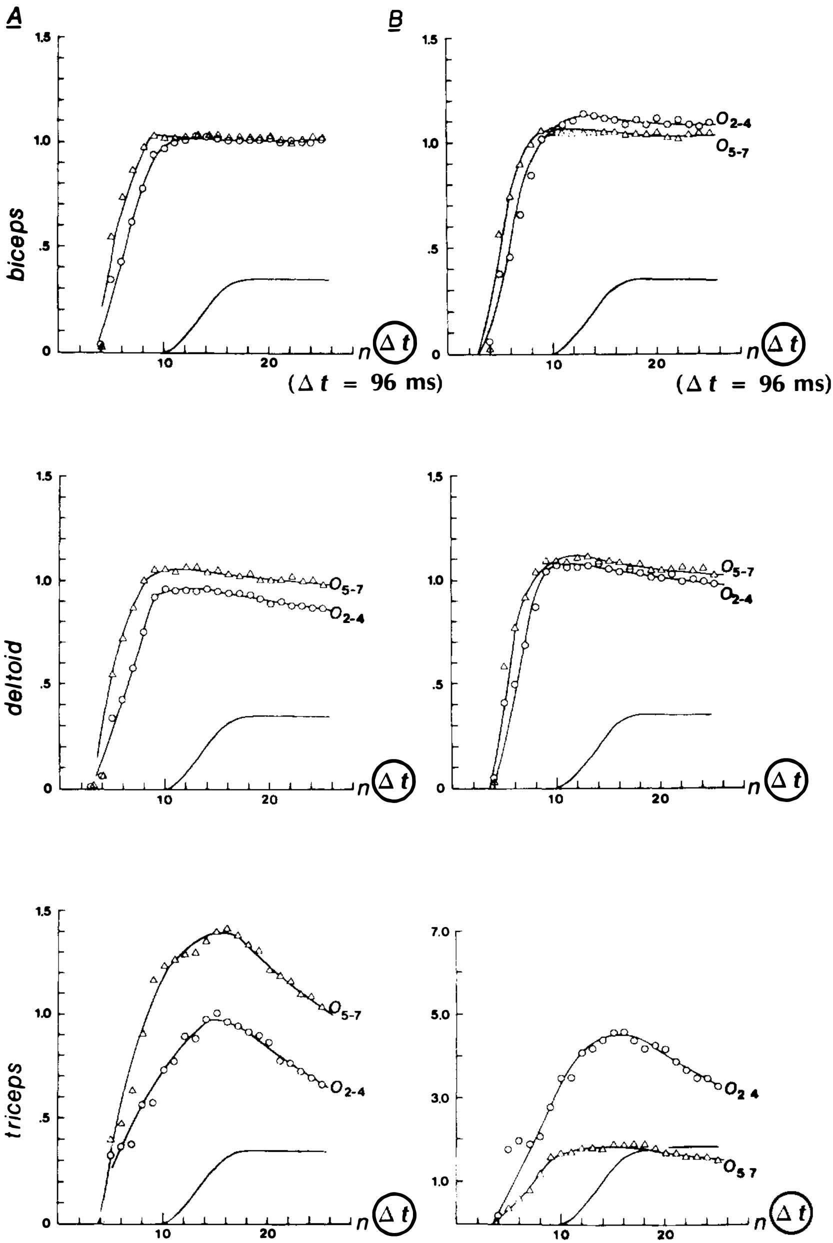

Fig. 7—Dynamic EMG activities for children in biceps, deltoid, and triceps muscles. Panel A: EMG normalized to the final maintenance position value for the heaviest object (number 7). Panel B: EMG normalized to the isometric values. Notice that both biceps and deltoid EMG are almost independent of the object weight. This is not the case for the triceps.

movement, the interpretation of the dynamic overshoot in this case is subject to caution. However, the asymptotes in the corresponding graph of Panel A suggest that the overshoot is relatively constant across the object series.

Discussion

The research has demonstrated profound differences between children and adults in the organization of motor commands, even for such a simple monoarticular movement as the lifting task considered here. These differences are all the more remarkable since, although the children's movements are somewhat slower, their main kinematic features are already the same as the adults', who represent a much later stage of development.

Our first point in this discussion is that the overt performance of adults can be construed as a form of optimal behavior. By definition, an object can only be lifted if the applied force exceeds its weight by some amount, the impressed acceleration being proportional to this amount. To simplify the argument, let us then define two (somewhat ideal) strategies for accomplishing the task and, more specifically, for planning the initial upward thrust that sets the object in motion. The first, which may be dubbed the "Constant Force Strategy," would apply to all objects the same net amount of upward force. The second, the "Constant Acceleration Strategy," would apply to each object a force which exceeds its estimated weight by a constant amount. Plainly, neither of these two idealized strategies predicts accurately the observed performance. However, the second hypothesis can better approximate reality than the first one, since the first peak values of both velocity and acceleration vary much less than the weight of the objects, while the timing parameters are almost constant. The following line of reasoning can then support the claim of the adults' behavior being optimal.

When the amplitude of the movement is constrained, as in our experiments, both strategies require some assessment—either before the movement or in the course of it—of the weight (or mass) of each object. The Constant Acceleration Strategy requires such assessment to ensure dynamic invariance in the accelerating phase of the movement; the Constant Force Strategy to stop the movement at the imposed height. The latter, however, also demands an *a priori* estimate of the weight of the heaviest object in the collection, to ensure that they shall all be lifted. Moreover, as already pointed out by other authors (Lestienne, 1979; Wallace, 1981), the arrest of an ongoing movement can occur without active intervention of antagonist muscles. If the momentum of the movement is not too large, the simple discontinuation of the agonist thrust and the passive forces due to the viscoelastic properties of the muscles will be sufficient to arrest the movement (in our case, we also have gravitational forces which must be opposed by a residual agonist activity). According to the Constant Force Strategy, light weights would be accelerated much more than heavy ones, requiring a properly tailored active intervention of the antagonist. In contrast, the Constant

Acceleration Strategy, by definition, adapts the agonist thrust to the weight of the objects.

The next point of discussion concerns the interpretation of the EMG data from the point of view of movement planning. As previously noted, one cannot expect a one-to-one correspondence between the electromyographic expression of the motor commands and the movement dynamics. Nevertheless, the EMG data for the adult control group appear to be one of the simplest patterns compatible with the observed kinematics. More specifically, the absence of triceps activity complies with the hypothesis that the impressed accelerations are carefully calibrated for each object to allow the arrest of movement solely by gravity and passive viscoelastic forces. In turn, this implies that adults possess an accurate internal representation of both the biomechanical properties of the limbs and the inertial properties of the objects.

Children obtain the balance of upward and downward forces through the coordinate action of the deltoid/biceps complex on the one side, and the triceps on the other. The earlier occurrence of acceleration peak values seems, then, due to the antagonist action which curtails the initial upward thrust. This suggests a push-pull type of operation in which the upward thrust is somewhat independent of the object, and the proper time course of the net forces is essentially taken up by the commands to the antagonist. This hypothesis is corroborated by the analysis of the EMG in the triceps (Figure 7A) which shows that the activity in this antagonist muscle increases *pari passu* with the weight of the object and, therefore, with the inertial force to be opposed to arrest the movement. In other words, the planning of the agonist motor commands in children would correspond to the Constant Force Strategy, but the breaking action of the triceps ultimately results in an overt performance compatible with the Constant Acceleration Strategy adopted by adults.

While it is likely that, in our experimental conditions, adults plan the motor commands before the inception of the movement, children seem to rely on the possibility of modifying the movement during its execution. Unless this can be ascribed to a difference in the overall approach to the task—unlikely in our context—one should then conclude that children as old as 9 years still lack a trustworthy representation of the size/weight covariation and of the properties of the motor system necessary for preplanning the lifting movement. In light of the previous argument, their performance must therefore be described as suboptimal.

Finally, one must ask how does such an adequate central representation form in the course of development. Although no definite answer is available at this stage, we would like to suggest that the use of antagonist muscles—typical of children's performance—not only provides the necessary balance of forces in the course of a single movement, but could also function in an active strategy that progressively attains proper calibration of the motor outputs. (Held & Hein, 1963; Paillard & Brouchon, 1968).

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