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The bilateral reach to grasp movement

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This study investigated the kinematic organization of bilateral reach to grasp movements. In Experiment 1 non-homologous bilateral movements were performed. One limb reached to grasp an object using whole hand prehension; the contralateral limb simultaneously reached to grasp an object using precision grip. Corresponding unilateral movements were assessed. Movement duration for each limb in the bilateral condition was similar. However, with earlier temporal settings for peak wrist acceleration and velocity, the limb performing precision grip showed a longer approach (deceleration) phase to the object. Unilateral precision grip movements showed a longer movement duration and deceleration phase than unilateral whole hand prehension movements. In Experiment 2 homologous bilateral movements were assessed. Both limbs performed either a reach and whole hand prehension or a reach and precision grip. Again the precision grip movements showed longer movement and deceleration times. Experiment 3 consisted of bilateral non-homologous pointing movements and a pointing movement with one limb while reaching to grasp with the contralateral limb. It was found that the earlier temporal settings of peak acceleration and velocity with the precision grip limb of the non-homologous bilateral task (Expt. 1) were largely due to the performance of distal grasping actions. It is concluded that a kinematic parameterization which is independent to each limb is evident for bilateral tasks which require functionally independent actions.

INTRODUCTION

In interacting with an object, the upper limbs work in a coordinated manner. One often acts in a stabilization capacity, while the other acts in a manipulative capacity. For example, in order to open a can of soft-drink both limbs transport the hands to the can however the prehensile task performed by each hand differs. One hand adopts a gross grasp in order to stabilize the can; the other adopts a precision grasp in order to pull open the tab. This study will investigate a bilateral movement which resembles that of opening such a can. The primary aim is to investigate the coordination of the upper limbs when each performs a reach to grasp movement.

The performance of a reach to grasp movement with *one* limb has been well characterized. Jeannerod[15,16] described two main components of this movement. One is the transport whereby the hand is brought to the target by the reaching arm. The other is the manipulation whereby the hand prepares for and then grasps the target. These components are thought to be subserved by independent neural channels[28,32] which are activated in parallel. However, it has been demonstrated that the kinematic parameterization of transport is not completely independent from that of manipulation. For example, recent studies have shown that the organization of *both* components when a subject performs a reach with a precision grip differs from that organization for a reach with whole hand prehension[6,7,11]. This finding also suggests that the neural channels which subserve precision grip differ from those which subserve whole hand prehension[28,32].

Previous studies of bilateral tasks have largely focussed on pointing or simple component movements. Typically it has been found that the spatio-temporal characteristics of one limb influence those of the other. For example, Kelso et al.[18] found that for the performance of non-homologous Fitts' aiming tasks, the longer movement duration of the limb with the higher index of difficulty was also evident for the limb with the lower index. Swinnen et al.[38,39] compared the performance of a unidirectional elbow movement with the simultaneous

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performance of a bidirectional elbow movement by the contralateral limb. They found that when subjects first attempted this task, the pattern of the bidirectional movement was imposed upon the limb which was performing a unilateral movement. Similarly, Franz et al.[10] reported that when subjects drew a circle with one hand and a straight line with the other, the circle began to resemble a straight line and the line began to resemble a circle.

Various theories have been proposed to explain the central mechanisms which underlie the control of bilateral movements. On finding that movement duration and other temporal aspects of bilateral non-homologous pointing tasks were similar for both hands, Kelso et al.[18] proposed that the limbs were constrained to act as a single unit. As dictated by the end-goal, muscles temporarily group to act as functional units[41] or "coordinative structures"[8]. This theory implies that the central control can flexibly alter synergic interactions according to the required motor output[1,41]. Marteniuk et al.[26] did not find that movement duration was similar for the two limbs when subjects performed a non-homologous bilateral task with styli. Given, however, that the movement duration of one limb was influenced by that of the other, they proposed that the commands for the left and right limbs were delivered via separate channels. With transmission of the output signals, the two channels engaged in "neural cross-talk" at various levels of the central nervous system. The bilateral projection of cortical neurons to the motoneurones of proximal arm musculature could thus be a means by which the neural impulses to one arm could influence those of the other[5,22,23]. Another concept developed to explain bilateral motor control uses the theory of motor programmes[17,43]. For example, Schmidt et al.[34] suggested that the framework for a bilateral movement was determined by a central motor programme. In the execution of this programme some controls are common to both limbs (e.g. movement duration; c.f. "global" aspects of Heuer[14]) while others are individual to each limb (e.g. movement distance; c.f. "local" aspects[14]).

When learning a motor skill, the ability to produce one movement with the left limb while the other limb performs a different movement may be limited by the tendency to minimize the number or complexity of control parameters[10]. This could dictate that the temporal and spatial coupling of the two limbs is stronger, that a greater amount of "neural cross-talk" is incorporated[26] and/or that the number of parameters under "global" control is greater. A novice piano player thus shows difficulty in producing a particular rhythm with one hand while the contralateral limb performs a different rhythm[37]. With a well-rehearsed task the tendency to control the limbs as one unit may lessen. For example, a skilled pianist shows independent specifications of rhythm for each hand[39]. The same finding may apply for tasks which are familiar to the subject. For example, bilateral reach to grasp movements are an integral part of the activities of daily living. It is thus proposed that for a non-homologous reaching to grasp movement, the limbs will show a greater amount of spatio-temporal independence than has been found for non-homologous bilateral pointing or drawing tasks.

The current study consisted of three main experiments. Both reach to grasp and pointing movements were assessed in order to distinguish how the performance of a grasp influences kinematic patterning. The bilateral tasks were either homologous or non-homologous. For the homologous reach to grasp tasks both upper limbs reached to grasp a small object or both reached to grasp a large object. This assessment, together with that of corresponding unilateral tasks, aimed to determine kinematic parameterization according to the type of grasp performed (i.e. precision grip—small object; whole hand prehension—large object). A comparison to homologous pointing tasks aimed to dissociate the effects of accuracy requirements, such as object size, from those effects generated by the type of grasp adopted. Non-homologous tasks consisted of one hand pointing to or reaching to grasp the small object while the other hand pointed to or reached to grasp the large object. This assessment aimed to determine whether the task performed by one limb influenced the kinematic parameterization of the contralateral limb. Overall, this study thus attempts to address several issues concerning the performance of bilateral upper limb movements.

EXPERIMENT 1

In this experiment subjects performed a non-homologous bilateral reach to grasp task. With one hand the subject was required to grasp a large diameter cylinder. With the contralateral hand, the subject grasped a small diameter pull tab which was attached to the upper surface of the cylinder. The task was to pull upon the tab with this latter hand and thus the subject was required to stabilize the cylinder with the contralateral hand. The kinematic profiles of the transport and manipulation components of each limb during this bilateral task were compared to corresponding unilateral reach to grasp tasks.

The kinematic assessment of a bilateral task which requires a reach and precision grip (tab) with one hand and a reach and whole hand prehension (cylinder) with the other, allows a number of issues to be addressed. It is of interest, for example, to determine whether each limb will retain the unique kinematic organization dictated by the grasp or whether one limb will show a kinematic arrangement which is similar to that of the contralateral limb. If the former finding applies, it would be expected that the duration of the approach phase of the hand to the object would be longer for the limb which performs a precision grip[6,7]. If the latter finding applies, it is of interest to determine whether the global kinematic organization will resemble that for the more accurate task (i.e. precision grip) or that for the more gross task (i.e. whole hand prehension).

Materials and Methods

Subjects

Six right-handed subjects (3 males and 3 females) ranging in age from 18 to 31 years gave their informed consent to participate in the experiment. All were naive as to the purpose of the experiment. None reported visual, neurological or skeletomotor abnormalities.

Recording technique

Movements were recorded with an Optotrak three-dimensional system equipped with three cameras placed 3 m above and around the horizontal working surface of a table. The camera monitored the displacements of active markers (infrared emitting diodes, IREDS) which were attached to the skin overlying the following areas on the dorsal surface of the right and left arms: (1) distal styloid process of the radius (wrist IRED); (2) medial to the lower ulnar corner of the thumb nail (thumb IRED); and (3) lateral to the lower radial corner of the index finger nail (finger IRED). The wrist IRED was used to measure the displacement, velocity and acceleration of the wrist. The finger and thumb IREDs were used to measure the displacements of the finger and thumb and the size of the grip aperture (finger–thumb distance). A spatial error of 0.3 mm was determined by dynamic accuracy tests. Position of the IREDS was sampled at 250 Hz. These recordings were stored on an IBM 386 computer.

Apparatus and procedure

Each subject was seated comfortably and without restraint facing the working surface. The ulnar edge of each hand rested upon a starting switch. These two switches were positioned 10 cm apart directly anterior to the subject. For each limb the forearm was semi-pronated, the wrist joint in the neutral position and the tips of the index finger and thumb were held in a relaxed opposed position. The target was a cylindrical aluminium object, similar to an empty container, with a pull tab on its top surface (Fig. 1A and B). This was placed vertically and in the subject's midline, 35 cm from each of the starting switches. The diameter of the cylinder was 7.5 cm (height 20 cm) and the diameter of the pull tab was 2 cm (height 2 cm; thickness 0.4 cm). Each trial began with an acoustic signal representing the "go" command for the subject to reach, grasp the cylinder and lift only the tab. In ten practice trials, the subjects were required to grasp the cylinder with the right or left hand and open the lid using the pull tab with the contralateral hand. No instructions were given as to the speed of movement or as to its spatial boundaries. Neither were the subjects explicitly required to simulta-

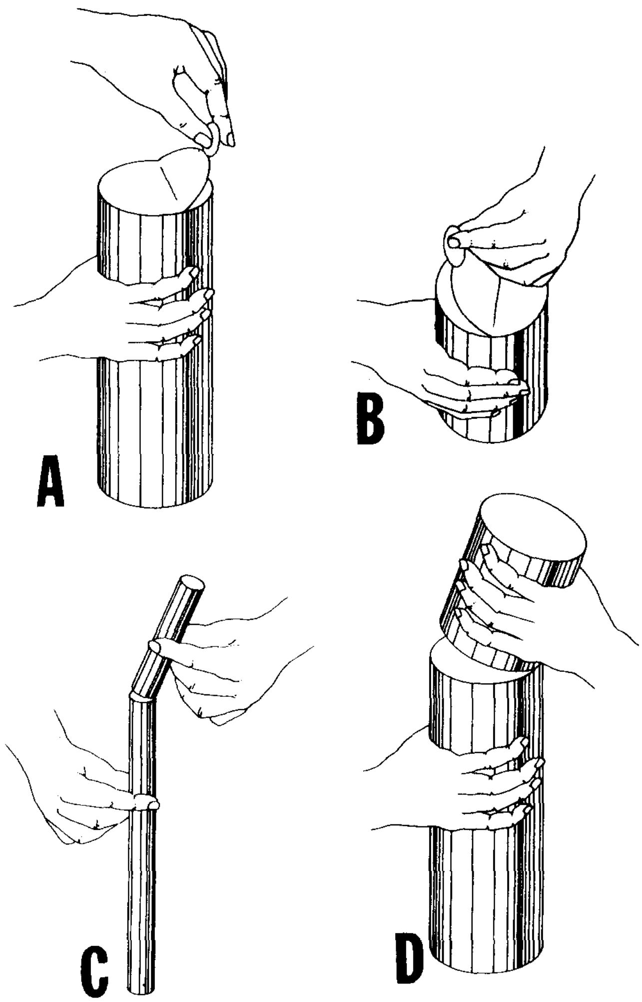

Fig. 1. A and B show the apparatus used for Expt. 1 viewed from the side (A) and from above (B) as a subject performs the bilateral task. One hand adopts a precision grip between the index finger and thumb to grasp the pull-tab. The other hand adopts a whole hand prehension to grasp the cylinder. C and D illustrate the apparatus used for Expt. 2. In C subjects grasped two small diameter cylinders (2 cm) with each hand adopting a precision grip. In D both hands adopt whole hand prehension to grasp two large diameter cylinders (7.5 cm).

neously make contact with both the tab and the cylinder. Following the practice trials, all subjects adopted patterns of grasp which were specific to the target diameter: The pull tab was grasped and lifted with a precision grip (PG) consisting of opposition between the index finger and thumb[29]. The cylinder was grasped with a whole hand prehension (WHP) characterized by flexion of all the digits around the cylinder[32] (Fig. 1A and B).

The recorded trials were performed in blocks of twenty, with the sequence of blocks counterbalanced across subjects in order to exclude practice effects. Unilateral control trials consisted of four blocks: left hand grasping the tab or cylinder; right hand grasping the tab or cylinder. For unilateral trials to the "tab", the cylinder was secured to the working surface. Bilateral tasks consisted of two blocks: right hand grasping the cylinder while the left hand grasped the tab; left hand grasping the cylinder while the right hand grasped the tab.

Data processing

The X, Y and Z trajectories of each IRED and the velocity of the wrist IRED were computed following filtering (Butterworth dual pass filter; cutoff frequency 10 Hz). Acceleration data were derived by differentiating the velocity data. Movement onset was taken as the time, shortly after release of the starting switch, at which the wrist IRED consistently exceeded displacement of 0.3 mm. The end of the movement was taken as the time at which the distance between the thumb and index finger was constant (i.e. the IREDs showed displacements of <0.3 mm). Movement duration for each limb was thus measured as the time from wrist movement onset to contact of the fingers with the object. (Note that the movement duration of the manipulation component, as measured from onset of aperture to contact with the object, and that of the transport component, as measured from onset to end of wrist IRED displacement, showed no statistical differences). This latter contact was established by analyzing the grip size profile to determine the point of constant aperture. The lifting of the "tab" was not assessed.

The following parameters were determined for the transport component: (a) the time from movement onset to the peak of acceleration; (b) the time from movement onset to the peak of velocity; (c) the time from movement onset to the maximum trough of the acceleration profile, that is, time to peak deceleration; and (d) the time from the velocity peak to the end of the movement, that is, deceleration time. The following parameters were computed for the manipulation component: (a) the time from movement onset to maximum grip aperture; and (b) the amplitude of the maximum grip aperture.

Movements performed to grasp the cylinder are referred to as whole hand prehension (WHP) trials; movements performed to grasp the pull tab are referred to as precision grip (PG) trials. Movement duration and kinematic parameters of the transport and manipulation components are shown in Table I: each value represents the inter-subject mean. For each parameter, an analysis of variance (ANOVA) was performed with the following factors: condition (unilateral or bilateral), Type of Grasp (PG or WHP) and Hand (right or left). Post-hoc comparisons using a Newman–Keuls procedure were carried out on the means of interest. Prior to

TABLE I

Expt. 1: kinematic parameters of the transport and manipulation components

Inter-subject mean for each parameter. SD is indicated in parentheses. Note that the time of the peak aperture is also expressed as a percentage of movement duration. Left and right refer to the hand used.

	Unilateral				*Bilateral*			
	Precision grip		*Whole hand prehension*		*Precision grip*		*Whole hand prehension*	
	Left	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*	*Right*
Movement duration (ms)	829 (65)	800 (39)	775 (38)	777 (43)	813 (87)	810 (84)	810 (77)	800 (56)
Transport component								
Time to peak acceleration (ms)	209 (16)	217 (26)	188 (15)	217 (16)	180 (21)	194 (14)	220 (19)	229 (32)
Time to peak velocity (ms)	355 (33)	375 (36)	350 (24)	352 (30)	357 (39)	360 (32)	375 (38)	384 (36)
Time to peak deceleration (ms)	505 (58)	543 (20)	504 (41)	507 (35)	516 (41)	560 (58)	555 (58)	564 (43)
Deceleration time (ms)	474 (47)	425 (27)	432 (43)	415 (44)	475 (51)	450 (43)	435 (45)	426 (30)
Manipulation component								
Time to peak grip aperture (ms)	453 (43)	458 (22)	485 (51)	476 (35)	437 (56)	481 (58)	514 (49)	531 (51)
Time to peak grip aperture (%)	54	57	62	61	53	72	63	63
Amplitude of peak grip aperture (mm)	59 (7)	58 (5)	120 (22)	113 (10)	51 (5)	56 (3)	119 (12)	115 (16)

the ANOVAs which were conducted on the means of each parameter, a mixed design ANOVA was performed in order to assess inter-subject variability (this was also conducted for Expts. 2 and 3). In this analysis, each subject was a between factor (i.e. a six level between-factor analysis was conducted upon each parameter). No significant interactions were found when assessing the pattern of each parameter across the six subjects thus the results from the ANOVAs which were performed upon the means will be presented.

Results

Movement duration

For the unilateral trials, movement duration varied according to the type of grasp, $F_{1,5} = 26.54$, $P < 0.001$. The average time for a PG movement was 815 ms while for the WHP movement it was 776 ms. A post-hoc comparison performed on the mean values of the significant interaction between Condition and Hand, $F_{1,5} = 8.10$, $P < 0.01$, showed that in the unilateral condition, movement duration for PG movements performed with the left hand was longer than those performed with the right hand ($P < 0.05$). No differences of movement duration were found in the bilateral condition: the movement duration for the limb adopting a PG movement (812 ms) was similar to that for the limb adopting a WHP movement (805 ms).

Transport component

For either hand and under either the unilateral or bilateral conditions the arm movement displayed a typical single peak velocity profile (Fig. 2). Differences of the transport component between the unilateral and bilateral conditions were more apparent during the first or acceleration phase of the movement. The shortening of this phase when a PG was used by one hand during the bilateral task seemed to allow for a prolonged deceleration phase. Analysis of the time to peak velocity showed a significant interaction between the factors Condition (unilateral and bilateral) and Type of Grasp (PG and WHP), $F_{1,5} = 6.39$, $P < 0.05$. Unlike findings for the unilateral condition, in the bilateral condition peak velocity was earlier for PG than for WHP movements (358 vs. 380 ms, respectively). The interaction Condition by Type of Grasp was also significant for the time of peak acceleration, $F_{1,5} = 8.25$, $P < 0.05$. In the bilateral condition this peak was earlier for PG than for WHP movements (187 vs. 225 ms, respectively; Fig. 2).

The deceleration phase of the transport component showed similar patterns under both the unilateral and bilateral conditions. The interaction between Condition, Type of Grasp and Hand was significant, $F_{1,5} = 8.14$, $P < 0.05$. Thus, peak deceleration for PG movements performed with the left hand in the unilateral and bilateral conditions (505 and 516 ms, respectively) was earlier than for the same movements performed with the right hand (543 and 560 ms, respectively; Fig. 2). Deceleration time (from peak velocity to end of movement) showed a significant interaction between Type of Grasp ($F_{1,5} = 10.04$, $P < 0.01$) and Hand ($F_{1,5} = 8.05$, $P < 0.05$). It was longer for PG than for WHP movements (449 vs. 431 ms, respectively) and longer for the left than for the right hand (453 vs. 427 ms, respectively). Deceleration time for PG movements performed by the left hand in the unilateral condition showed the longest duration ($P < 0.05$). These results indicated that a longer approach was needed for greater precision and/or when using the non-dominant limb.

Grasp component

During transport of the hand, grip size increased to a maximum aperture before closing around the object (Fig. 2). As expected, the amplitude of maximum grip aperture was related to the type of grasp adopted (56 mm for PG; 116 mm for WHP), $F_{1,5} = 66.08$, $P < 0.0001$. The time to maximum grip aperture was also related to the type of grasp, ($F_{1,5} = 19.13$, $P < 0.001$). Thus, the maximum grip aperture for PG movements (470 ms) was earlier than for WHP movements (489 ms; Fig. 2). The interaction between Condition, Type of Grasp and Hand was significant, $F_{1,5} = 7.09$, $P < 0.05$. Post-hoc comparisons showed that maximum grip aperture was earlier for PG than for WHP movements under both unilateral (455 ms PG vs. 480 ms WHP) and bilateral (459 ms PG vs. 522 ms WHP) conditions. For the left hand, the maximum grip aperture for PG was reached earlier ($P < 0.05$) than for any other trials and conditions. When the time to maximum grip aperture was expressed as a percentage of the movement duration, these results were further confirmed (Interaction Condition, Type of Grasp and Hand, $F_{1,5} = 9.08$, $P < 0.05$): Maximum grip aperture was relatively earlier for PG than for WHP movements under both unilateral and bilateral conditions and it was earliest for PG movements performed with the left hand ($P < 0.05$).

Relationship between the two limbs

A series of correlation coefficients was calculated in order to compare the temporal setting of each parameter across the two limbs. The Fisher-*Z* transformation of data was used for homogeneity of variance and to counteract any non-normal distributions. The signifi-

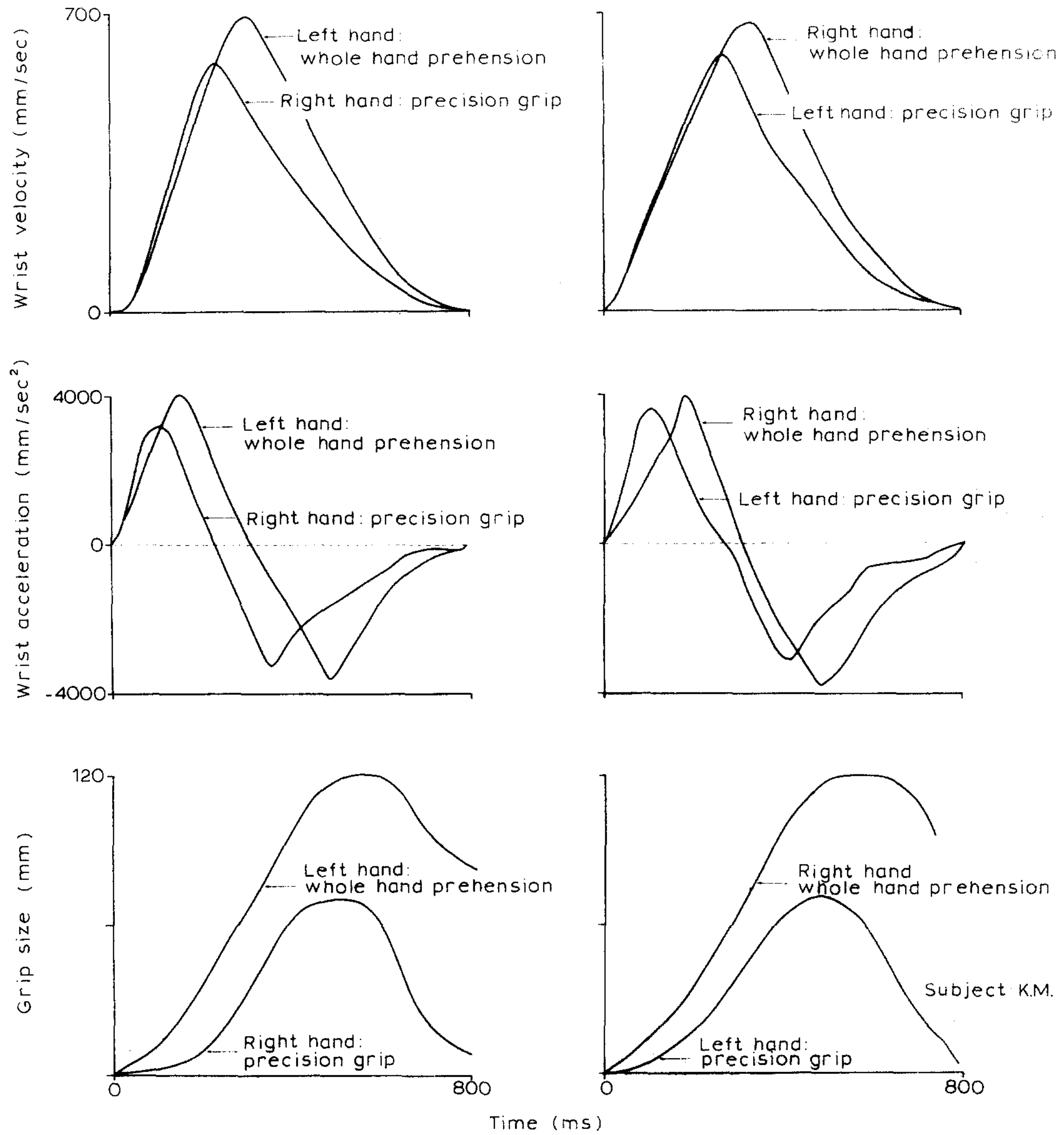

Fig. 2. Expt. 1: non-homologous bilateral reach to grasp. Left: a single trial recorded when the left hand performs a reach and whole hand prehension while the right hand performs a reach and precision grip. Right: a single trial for the opposite bilateral condition. Wrist velocity curves (upper row) show bell-shaped profiles. Peak velocity is earlier for the precision grip movement. The acceleration curve (middle row) shows the peak of acceleration followed by the peak of deceleration. Both peaks are earlier for PG than for WHP movements. Grip size (lower row) refers to the distance between the thumb and index finger – maximum grip aperture is smaller and earlier for precision grip.

cance of each correlation was assessed with Student *t*-test. The results indicated that under the bilateral condition, the parameters of the left limb were not correlated in time with those of the right limb (peak velocity $r = 0.12$; peak acceleration $r = 0.21$; peak deceleration $r = 0.14$; maximum grip aperture $r = 0.10$).

EXPERIMENT 2

In this experiment, subjects were required to perform homologous reach to grasp tasks. For one task, the subject used both limbs to reach for and grasp large diameter cylinders. For the other task, both limbs were used to reach for and grasp small cylinders.

The results from Expt. 1 indicated that during a bilateral task, movement duration for a reach and precision grip movement with one limb was similar to that for a reach and whole hand prehension movement with the contralateral limb. However, the kinematic parameterization for each limb differed. In particular, the limb which performed the precision grip movement showed a longer deceleration time (approach phase) than the limb which performed the whole hand prehension movement.

Expt. 2 was thus conducted in order to further elucidate the effect of the end-grasp upon the kinematic features of the movement. It was anticipated that the kinematic parameterization of the limbs should be similar when both perform a precision grip movement. Similarly, both limbs should show a similar parameterization for the whole hand prehension movement. Further, the precision grip bilateral movements should show a pattern which differs from that for the whole hand prehension tasks. If, however, the patterning of bilateral movements is determined by other factors, it was anticipated that differences between the right and left limbs should be apparent for the homologous tasks. This would indicate, for example, that elements such as handedness may play a more important role in movement planning.

Materials and Methods

Subjects

The six subjects of this second experiment did not participate in the first experiment. They nevertheless showed the same gender, age, handedness and general health characteristics.

Apparatus and procedure

The recording technique, starting position and placement of the IREDs were the same as described for Expt. 1. For Session A of this experiment two large diameter cylinders were used. One cylinder (height 8 cm, diameter 7.5 cm) was placed to stand vertically upon the other (height 12 cm; diameter 7.5 cm). Refer to Fig. 1D. For Session B, two small diameter cylinders were used. One cylinder (height 8 cm; diameter 2 cm) stood vertically upon the other (height 12 cm; diameter 2 cm). Refer to Fig. 1C. For each session the subject performed 10 practice trials whereby the requirement was to reach for the two cylinders with both limbs, to grasp the lower cylinder with one hand and to grasp and lift the upper cylinder with the contralateral hand. For Session A, subjects used whole hand prehension in order to grasp either cylinder. For Session B, subjects used a precision grip in order to grasp either cylinder.

The recorded trials were then performed in blocks of twenty. As for Expt. 1, an acoustic signal indicated to commence the bilateral movement. In order to avoid practice effects, the order of the two sessions (A and B) was counterbalanced across subjects.

Data processing

The bilateral movements of Session A are referred to as WHP trials; those of Session B are referred to as PG trials. The parameters determined for each limb are the same as those described in Expt. 1. Movement duration and the kinematic parameters of the transport and manipulation components are shown in Table II. For each parameter an ANOVA was performed with Session (WHP or PG) and Hand (right or left) as factors. Post-hoc comparisons were with the Newman–Keuls testing procedure.

Results

Movement duration

As was found for the unilateral condition of Expt. 1, the duration of WHP movements was less than that for PG movements, $F_{1,5} = 8.80$, $P < 0.05$. For WHP the

TABLE II

Expt. 2: kinematic parameters of the transport and manipulation components

Inter-subject mean for each parameter. SD is indicated in parentheses. Note that the time of the peak aperture is also expressed as a percentage of movement duration. Left and right refer to the hand used.

	Bilateral			
	Precision grip		*Whole hand prehension*	
	Left	*Right*	*Left*	*Right*
Movement duration (ms)	882 (88)	886 (73)	835 (88)	823 (100)
Transport component				
Time to peak acceleration (ms)	233 (22)	243 (24)	229 (36)	234 (21)
Time to peak velocity (ms)	354 (32)	361 (45)	371 (29)	369 (31)
Time to peak deceleration (ms)	521 (52)	534 (53)	534 (55)	538 (59)
Deceleration time (ms)	528 (52)	525 (50)	476 (61)	454 (42)
Manipulation component				
Time to peak grip aperture (ms)	505 (58)	504 (49)	518 (51)	525 (63)
Time to peak grip aperture (%)	57	56	62	63
Amplitude of peak grip aperture (mm)	54 (9)	58 (8)	110 (11)	117 (10)

movement duration was 829 ms while for PG the movement duration was 874 ms.

Transport component

No differences were found between the PG and WHP movements during the first or acceleration phase of the movement (Table II and Fig. 3). However, and as was found for both the unilateral and bilateral conditions of Expt. 1, the deceleration time was longer for PG than for WHP movements (526 vs. 465 ms, respectively), $F_{1,5} = 15.01$, $P<0.001$. The temporal settings of peak velocity, peak acceleration and peak deceleration showed no differences according to the hand used.

Grasp component

The pattern of the manipulation component in a bilateral homologous task was similar to that of a unilateral or a bilateral non-homologous task. The amplitude of maximum grip aperture was 114 mm for WHP and 56 mm for PG movements ($F_{1,5} = 88.03$, $P<0.0001$). The time to maximal aperture between the digits was significantly related to Session ($F_{1,5} = 16.08$, $P<0.001$) being later for WHP (524 ms) than for PG movements (504 ms; Fig. 3). This finding was confirmed when the time of peak aperture was expressed as a percentage of movement duration, $F_{1,5} = 10.09$, $P<0.01$ (63% WHP; 56% PG).

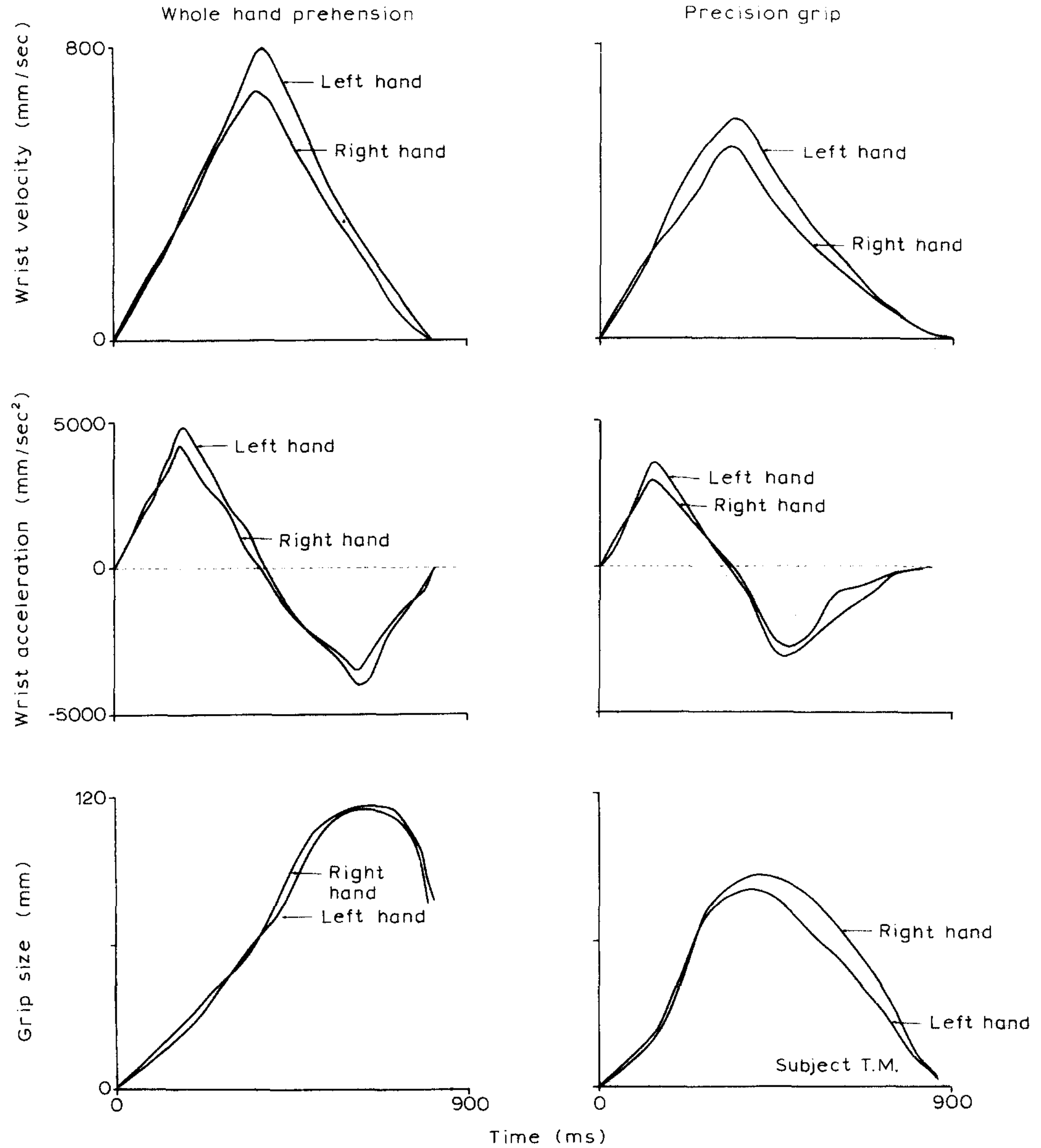

Fig. 3. Expt. 2: homologous bilateral reach to grasp (single trials). Left: both limbs perform reach and whole hand prehension (WHP) movements. Right: both limbs perform reach and precision grip (PG) movements. Peak velocity for either PG or WHP movements occurs at the same time for both limbs (upper row). The peaks of acceleration and deceleration of one limb also concur with those of the contralateral limb (middle row). The Grip Size curves (lower row) show that the maximum grip aperture is earlier for PG movements.

Relationship between the two hands

As the kinematic profiles were similar for both arms, each temporal landmark of the transport and manipulation components for one limb was compared to that of the other. A series of correlation coefficients were calculated using the same methods as described in Expt. 1. The time of peak acceleration for one limb was correlated to that for the contralateral limb ($r = 0.52$, $P < 0.001$). Such significant bilateral correlations were also found for the times of peak velocity ($r = 0.48$, $P < 0.001$), of peak deceleration ($r = 0.38$, $P < 0.001$) and of maximum grip aperture ($r = 0.52$, $P < 0.001$).

EXPERIMENT 3

In this experiment, subjects were required to perform both reach to grasp and pointing movements. Three conditions were assessed. For one, the subject performed a bilateral movement with one limb pointing to the tab and the contralateral limb pointing to the cylinder of Expt. 1. For the two other conditions, the subject performed a reach to grasp movement with one limb and a pointing movement with the contralateral limb. These movements were directed either to the two large or to the two small cylinders (as described in Expt. 2).

The results from Expt. 2 indicated that the movement patterning for bilateral movements was influenced by the type of grasp utilized by the manipulation component. Both limbs of the bilateral precision grip (PG) movements showed a longer deceleration (or approach) time than either limb of the bilateral whole hand prehension (WHP) movements. The settings of the kinematic landmarks for one limb of the homologous bilateral task showed temporal coupling to the same kinematic landmarks of the contralateral limb. Overall, these results suggested that the patterning and thus the central control for the two limbs was similar for a homologous bilateral task. In addition, it was evident that the patterning for PG bilateral movements differed from that for WHP bilateral movements.

Expt. 3 was conducted in order to determine where the differences between PG and WHP movements lay. Characteristics of the target stimuli may have dictated the kinematic parameterization. Alternatively, or in addition, the differences between PG and WHP movements could be attributed to the peculiarities of performing each grasp. The greater accuracy required for a precision grip may be the determinant for a longer deceleration time for the transport component. Similarly, the performance of a whole hand prehension grasp may dictate a parameterization for the transport component which differs from that for a movement with only a transport component (such as pointing).

Materials and Methods

Subjects

Six individuals, who had not been previously tested and who did not know the purpose of the experiment volunteered for this experiment. They showed the same gender, age, handedness and general health characteristics of the subjects in Expts. 1 and 2.

Apparatus and procedure

The recording technique and starting position were the same as in Expt. 1. For Expt. 3, only the wrist IRED was sampled during the pointing tasks. All three IREDs, as described in Expt. 1, were sampled for the reach to grasp movements. For Session A, the pull tab and cylinder (as described in Expt. 1) were the target stimuli. The subject was required to perform either a unilateral or a bilateral pointing movement in order to touch the target stimulus with the index finger. Under the unilateral condition, the subject used one limb to point at either the pull tab ($n = 20$ trials for each of the right and left limbs) or at the cylinder ($n = 20$ trials for each limb). Under the bilateral condition, the subject used the left limb to point at the tab and the right to point at the cylinder ($n = 20$) or the left limb to point at the cylinder and the right to point at the tab ($n = 20$). For Sessions B and C, the subject was required to perform a pointing movement with one limb and a reach to grasp movement with the contralateral limb. For Session B, the two large cylinders were positioned as for Expt. 2. The subject was required to point and to touch the upper cylinder (which was secured to the lower cylinder) with one limb and to reach to grasp the lower cylinder with the contralateral limb ($n = 20$). The opposite movement, pointing to touch the lower cylinder (which was secured to the table) and grasping the upper cylinder, was also assessed ($n = 20$). For Session C, the same blocks of trials as in Session B were assessed but the two small cylinders of Expt. 2 were used.

During the practice trials ($n = 10$) prior to each of Sessions B and C, all subjects adopted a whole hand prehension to grasp the large cylinder and a precision grip to grasp the small cylinder. These are respectively referred to as WHP and PG movements. The sequence of the ten blocks of recorded trials was counterbalanced across subjects.

Data processing

The data was processed in the same way as described for Expt. 1. The inter-subject means and standard deviations of the parameters measured in Expt. 1 were determined for the reach to grasp movements of Sessions B and C. For the pointing movements of all three sessions, the displacement, velocity and acceleration profiles for only the wrist marker were assessed. Movement duration for the pointing task was taken as the time of onset of the transport component until the time at which the index finger touched the cylinder. For Session A, the main factors for the ANOVAs were Condition (unilateral or bilateral), Hand (right or left) and Stimulus (pull tab or cylinder). For each of Sessions B and C, the main factors for the ANOVAs were Hand (right or left) and Type of Movement (prehension or pointing). A separate analysis was performed for the comparison of the time and amplitude of the maximum grip aperture across the two types of prehension utilized in Sessions B and C. Thus, the two main factors were Type of Grasp (WHP or PG) and Hand (right or left).

RESULTS

Session A—unilateral and bilateral pointing

Movement duration.

Movement duration for the bilateral movement was longer than for the unilateral movement ($F_{1,5} = 28.12$, $P < 0.0001$, 780 vs. 733 ms, respectively; Table III). It was similar for the right and the left hands in the bilateral condition. Unlike the findings for the unilateral reach to grasp tasks of Expt. 1 to the tab and cylinder, movement duration for the unilateral pointing movement to the tab was similar to the movement duration for the unilateral pointing movement to the cylinder.

Transport component

The kinematic parameters are presented in Table III. For the unilateral task of pointing to the large cylinder, peak velocity occurred at the same time as that for the task of pointing to the pull tab (223 ms). However, deceleration time was longer for pointing movements directed to the tab than to the large cylinder (446 vs. 410 ms, respectively), $F_{1,5} = 15.08$, $P < 0.0001$. As was found for the reach to grasp movements of Expt. 1, the accuracy of the task thus influenced the approach time. In the bilateral condition, the kinematic parameters of one limb showed no differences according to the size of the target stimulus. Note that this was in contrast to the results for the bilateral non-homologous reach to grasp tasks.

Relationship between the two limbs

Assessment of the temporal coordination between the two limbs in the bilateral task was determined in the same manner as described for Expts. 1 and 2 (correlation coefficients). The peaks of acceleration, velocity and deceleration of one limb were correlated in time to those of the contralateral limb ($r = 0.48$, $P < 0.001$; $r = 0.39$, $P < 0.001$; $r = 0.42$, $P < 0.001$, respectively).

Sessions B and C—bilateral task: pointing with one limb, reach to grasp with the other limb

Movement duration

No differences of movement duration were found when comparing the pointing limb to the grasping limb (Table IV).

Transport component

The kinematic parameters are presented in Table IV. The peaks of acceleration, velocity and deceleration

TABLE III

Expt. 3 (pointing task only): kinematic parameters of the transport component

Inter-subject mean for each parameter. SD is indicated in parentheses. Small and large refer to the size of the target stimulus. Left and right refer to the hand used.

	Unilateral				*Bilateral*			
	Small		*Large*		*Small*		*Large*	
	Left	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*	*Right*
Movement duration (ms)	773 (72)	738 (71)	735 (65)	727 (62)	787 (72)	779 (68)	770 (79)	784 (83)
Transport component								
Time to peak acceleration (ms)	221 (18)	224 (21)	218 (15)	227 (21)	218 (18)	227 (23)	221 (26)	217 (19)
Time to peak velocity (ms)	318 (28)	321 (31)	319 (22)	324 (35)	323 (28)	334 (32)	338 (34)	319 (36)
Time to peak deceleration (ms)	525 (50)	518 (48)	531 (45)	533 (51)	538 (46)	542 (47)	539 (41)	544 (53)
Deceleration time (ms)	455 (38)	437 (48)	416 (51)	403 (40)	464 (44)	455 (41)	452 (43)	465 (51)

TABLE IV

Expt. 3: pointing task with one limb and a reach to grasp movement with the other. Kinematic parameters of the transport and manipulation components

Inter-subject mean for each parameter. SD is indicated in parentheses. Note that the time of peak aperture is also expressed as a percentage of movement duration. Small and large refer to the size of the target stimulus. Left and right refer to the hand used. "–" indicates no value.

	Small				*Large*			
	Pointing		*Precision grip*		*Pointing*		*Whole hand prehension*	
	Left	*Right*	*Left*	*Right*	*Left*	*Right*	*Left*	*Right*
Movement duration (ms)	791 (80)	794 (82)	800 (75)	795 (74)	788 (68)	788 (77)	802 (88)	789 (67)
Transport component								
Time to peak acceleration (ms)	221 (17)	229 (21)	193 (18)	188 (19)	217 (21)	231 (25)	209 (20)	206 (22)
Time to peak velocity (ms)	342 (36)	347 (37)	302 (28)	299 (32)	364 (35)	359 (36)	311 (31)	313 (33)
Time to peak deceleration (ms)	525 (56)	532 (56)	498 (53)	488 (48)	532 (77)	537 (65)	510 (50)	515 (49)
Deceleration time (ms)	449 (38)	447 (39)	498 (45)	496 (46)	424 (41)	429 (42)	471 (54)	466 (53)
Manipulation component								
Time to peak grip aperture (ms)	–	–	448 (45)	453 (41)	–	–	494 (41)	489 (47)
Time to peak grip aperture %	–	–	56	57	–	–	62	61
Amplitude of peak grip aperture (mm)	–	–	55 (3)	57 (6)	–	–	113 (9)	118 (12)

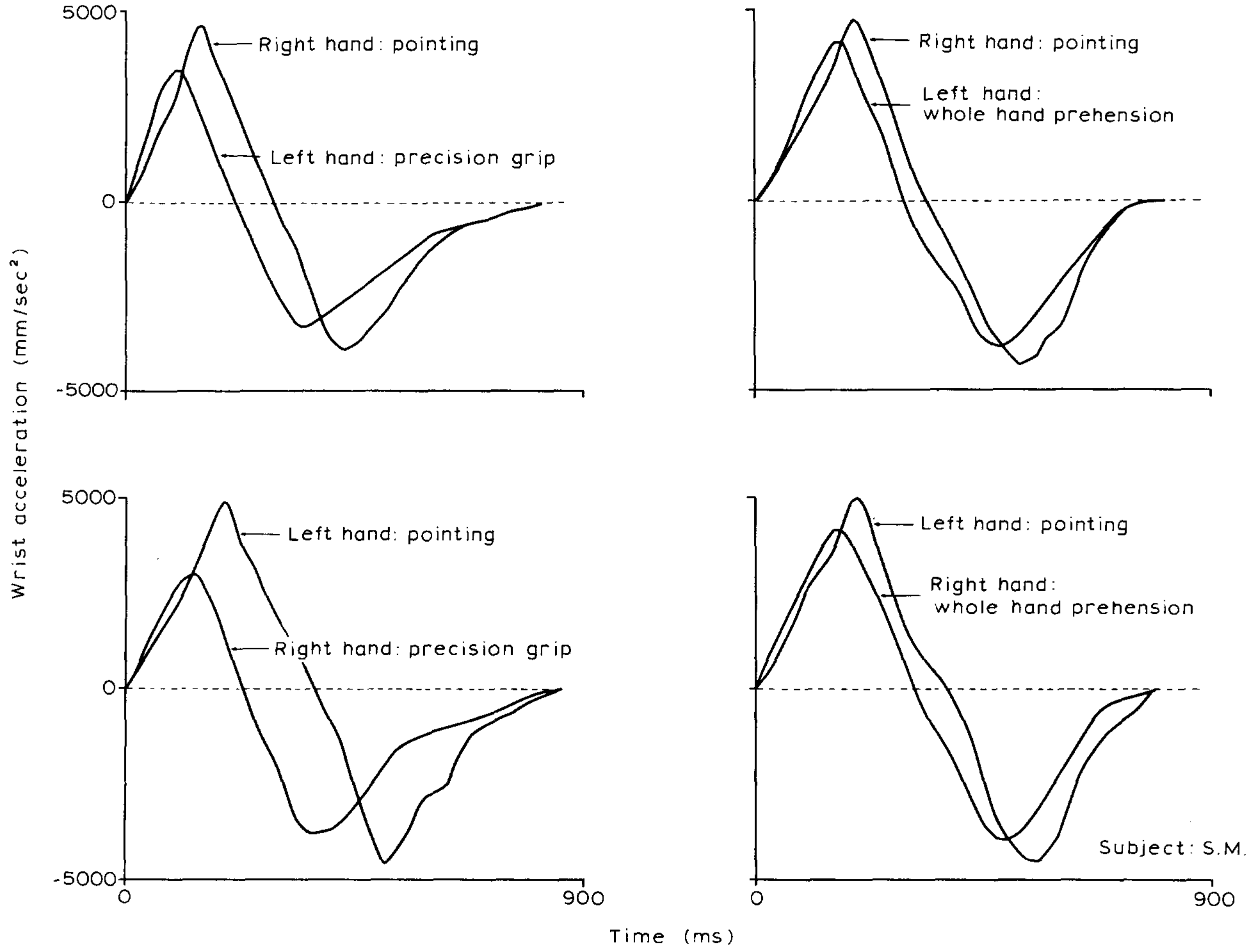

Fig. 4. Expt. 3: bilateral pointing and reach to grasp (single trials). The pointing and prehension combinations are indicated for each set of traces. Thus the upper left trace shows the left hand performing a reach and precision grip movement while the right hand performs a pointing movement to a similar small diameter cylinder. The acceleration and deceleration peaks are earlier and the deceleration phase is greater for PG than for pointing movements. The same pattern for the comparison of whole hand prehension and pointing illustrates the significance of the performance of a distal program.

were all earlier for prehension than for pointing movements (Fig. 4). Thus, peak acceleration was at 199 ms for prehension but at 225 ms for pointing movements ($F_{1,5} = 10.04$, $P < 0.001$). Peak velocity was at 306 ms for the former and at 354 ms for the latter movements ($F_{1,5} = 17.04$, $P < 0.0001$). Similarly, peak deceleration was at 503 ms for prehension and at 532 ms for pointing movements ($F_{1,5} = 18.76$, $P < 0.0001$). Because of these earlier kinematic temporal settings the deceleration time for prehension movements was greater than that for pointing movements ($F_{1,5} = 8.05$, $P < 0.05$). Thus, deceleration time was 497 ms for PG movements but 449 ms for pointing movements to the small cylinder ($P < 0.05$). Similarly, deceleration time was greater for WHP movements (469 ms) than for pointing movements to the large cylinder (427 ms; $P < 0.05$).

In addition for the prehension movements, all three peaks were earlier for PG than for WHP movements. Peak acceleration was at 191 ms for PG but at 208 ms for WHP ($P < 0.05$). Peak velocity was at 300 ms for the former but at 312 ms for the latter ($P < 0.05$). Similarly, peak deceleration was at 493 ms for PG but at 513 ms for WHP movements ($P < 0.05$). Deceleration time for PG movements was longer than that for WHP movements ($P < 0.05$). This time was also greater for pointing movements to the small than to the large cylinder ($P < 0.05$; see values above).

Grasp component

Maximum grip aperture was earlier for PG (441 ms) than for WHP movements (492 ms; $F_{1,5} = 17.08$, $P < 0.0001$). Further, and as indicated by the significant interaction between Type of Grasp and Hand ($F_{1,5} = 7.05$, $P < 0.01$), maximum grip aperture was earlier for PG movements performed with the left hand than for those performed with the right hand (428 vs. 453 ms, respectively). The maximum grip aperture was 56 and 116 mm for PG and WHP movements, respectively, $F_{1,5} = 73.01$, $P < 0.0001$.

Relationship between the two limbs

An assessment of the coordination between the limbs showed that the times of peak acceleration, velocity and deceleration for the pointing limb were not correlated to those for the grasping limb ($r = 0.06$, 0.12, 0.08, respectively).

DISCUSSION

This work uses the reach to grasp movement for the study of bilateral tasks. It assesses the coordination of the proximal (transport) and distal (manipulation or grip) components when each limb simultaneously performs different grasping actions (whole hand prehension and precision grip). The results indicate that movement duration for the limb performing the reach and precision grip movement equals that of the limb performing the reach and whole hand prehension movement. Movement duration can be thus considered as a control parameter which is common to both limbs during non-homologous reach to grasp tasks. Once prescribed, it provides the temporal framework for parameterization of the kinematic parameters of each limb. The grasp with the greater accuracy requirements may have more influence upon this prescription: movement duration for the non-homologous bilateral reach to grasp task is similar to that for the unilateral reach and precision grip task. A similar result was reported by Kelso et al.[18]. Under a bilateral condition, the limb which performed the pointing movement with a low index of difficulty showed a movement duration that more approximated the limb which performed the movement with the higher index of difficulty.

Despite the common control parameter of movement duration, kinematic parameterization is individual to each limb during the non-homologous bilateral reach to grasp task. The temporal measures of one limb show no correlation to those of the contralateral limb and deceleration time is greater for the limb performing the reach and precision grip. The transport component can be divided into an initial acceleration phase and a deceleration phase (from velocity peak to end of movement). For the limb performing the precision grip, the peaks of arm acceleration and velocity are earlier than those peaks for the limb performing whole hand prehension. Adjustment to the acceleration phase of the movement thus promotes the longer deceleration phase for precision grip. Features of the manipulation component (the grasp pattern) determine early effects within the transport component and by promoting such early adjustments meet the individual kinematic requirements of each limb.

The greater deceleration time for precision grip than for whole hand prehension movements is observed whether it is performed under unilateral or bilateral conditions or whether, under bilateral conditions, the task is homologous or non-homologous. However, kinematic modifications to the acceleration phase only occur for the non-homologous bilateral reach to grasp task. The means of achieving the longer deceleration time under all other conditions is not with changes to the acceleration phase but with an extension of movement duration and thus to the later phase of the movement. The acceleration phase for unilateral precision grip movements shows no difference when compared to that for unilateral whole hand prehension movements.

Similarly, when comparing bilateral homologous tasks, the acceleration phase shows no differences but movement duration is greater for bilateral precision grip than for bilateral whole hand prehension movements. This allows for a greater deceleration time for precision grip than for whole hand prehension movements.

The prolonged deceleration phase together with the earlier time of maximum grip aperture for precision grip movements is in accordance with previous studies of prehension movements: the time from peak velocity to the end of the movement is greater when using a precision grip and when reaching to grasp more fragile or smaller objects[6,7,11,27]. It has been postulated that this greater approach phase allows sufficient time for effective error correction. Additional time is given to utilize feedback in order to adjust for the requirement of the more "precise" object and to allow for independent use of the index finger and thumb. The comparison between right and left unilateral reach to grasp movements supports the theory that the deceleration phase reflects the amount of correction which may be required. In general, movement duration and deceleration time were greater for the left hand. Further, the earliest timings of both deceleration and peak grip aperture and the longest deceleration times were with left hand precision grip movements. A similar result was reported by Todor and Cisneros[40] for a stylus-aiming task—with the requirement to reduce error rate the difference in the duration of the late movement phase between left and right hand was augmented (see also[13]). Marteniuk et al.[27] even suggested that the duration of the deceleration phase can be used as a reliable index of the precision needed for the performance of a prehension task.

What is the main determinant for a longer deceleration time with precision grip movements? Is it the size of the target stimulus or the type of grasp which is utilized by the manipulation component? In the unilateral pointing tasks, where no grasping action is performed, the deceleration phase when pointing to a small object is greater than that when pointing to a large object. Intrinsic properties of the stimulus, such as size, thus influence movement patterning[6,7,11,24]. However, for the non-homologous bilateral tasks, it appears to be more the performance of a precision grip than the small target size stimulus that determines the independence of parameterization for each limb. During the non-homologous pointing task, the kinematic patterning for one limb does not differ from that of the other and the limbs show a high degree of synchrony. The acceleration phase for the limb pointing to the small target shows similar temporal features to that pointing to the large stimulus. The deceleration phase is of similar duration for both limbs. This equivalence of patterning contrasts to that found for the bilateral non-homologous reach to grasp tasks. Further, the finding that the deceleration time for prehension is greater than that for pointing indicates that the duration of the approach phase is related to the performance of a manipulative action.

With each limb executing the same distal grasping action, the kinematic parameters do not demonstrate differences between the two hands: the acceleration and deceleration phases show the same profiles and the limbs are coupled in time. For these homologous tasks, the proximal and distal components require the activation of similar sets of muscles for each limb. Similarly, and as found by Kelso et al.[18], for the bilateral pointing studies the kinematic profiles of each limb are very similar. Kelso et al.[18] proposed that this "fixed and reproducible" interlimb coordination reflects the concept of a coordinative structure[41]: control signals act to group the muscles of both limbs as a single functional unit for the purpose of attaining the bilateral goal. The high degree of interlimb kinematic coordination was not thought to favor the concept of a separate programming for each limb.

Consider, however, the rarity of performing the same task simultaneously with both hands. What purpose is served by synergic groupings which largely ignore differences between the limbs? The results from the current bilateral experiment whereby a different grasp is required by each hand do not entirely support the idea of both limbs acting as a single unit. Despite the activation of corresponding muscle groups for the transport component and consequently the bilateral recruitment of the same neural pathways, kinematic organization differs according to grasping action. The patterning of the transport component for one limb does not resemble that of the other. The manipulation component also shows independent and appropriate specifications for the temporal and spatial properties of the grip aperture[6,7,11,15,16,25,42,44]. For these non-homologous reach to grasp bilateral movements there was also no evidence to suggest that one limb is influenced by the kinematic organization of the other[10].

Given the multiple requirements of operating both hands for manipulation of and interaction with objects in the environment, a control mechanism which groups muscles as a single unit does not seem feasible for most functional tasks. This does not imply that a "coordinative structure" does not operate. It is clear from the results of the current study that the limbs adopt the same parameterization for homologous tasks. The patterning is also similar when the same component is activated by both hands. Thus, when one limb points to a small object and the other to a large object, both limbs perform only a reaching component. Similarly, in the Kelso et al.[18] experiment, despite reaches of different distances, bilateral activation is also only of the transport component. With a low criterion for individual programming of each limb in a bilateral task, the number of globally controlled parameters thus appears to increase. Movement duration and temporal settings for kinematic landmarks of the transport and manipulation components are processed as if for a single unit. Control is thus simplified by minimizing the number of output process requirements. With a high criterion for individual programming of each limb, the number of globally controlled parameters decreases. Movement duration remains the common parameter however temporal settings for kinematic landmarks such as peak velocity or maximum grip aperture are processed separately for each limb. The system thus determines what can be independently specified for each limb but, where possible, retains output requirements which are common to both limbs.

Abnormalities of bilateral coordination assist in revealing the neuroanatomical substrates of its control. It has been found, for example, that primates with unilateral supplementary motor area (SMA) lesions showed inappropriate mirror-symmetric movements in tasks which required independent use of the limbs[2,4]. With subsequent section of the corpus callosum the lesioned animals regained the ability to perform these bilateral tasks[2]. On the basis of these results and those obtained from neurophysiological[3] and regional cerebral blood flow studies[30,33], Goldberg[12] proposed that under normal circumstances both SMAs are active for non-homologous bilateral movements. Each functions not only to influence the ipsilateral primary motor cortex and thus contralateral motor control but also, via callosal connections, to suppress the influence of the contralateral SMA. When one SMA is damaged the activity of the undamaged SMA is unchecked and via its ipsilateral and contralateral connections to the motor cortex[31] can promote the passage of one output response to both sides of the body. With lesion of the corpus callosum, the influence on the contralateral motor cortex and thus of ipsilateral motor control, is largely forfeited. In the undamaged system, Goldberg[12] proposes that the neural influence of SMA activity from one hemisphere upon that of the other may function to establish "an overall temporal structure for the task". If this is the case, results from the current study indicate that structural temporal parameters which may be subject to this inter-hemispheric SMA influence can vary according to the degree of functional independence required by the limbs.

Anatomically, the nervous system provides for both independent limb control and for control which is common to both limbs. The lateral corticospinal system projects predominantly to contralateral motoneurone pools[20,35] and thus allows for independent limb use. With abnormal development of this system such that neurones branch to both sides of the spinal cord (Klippel-Feil syndrome[9]) distal movements of the upper limb are mirrored by the contralateral limb. The independence of each limb is thus disrupted. Other systems normally promote control which is common to both limbs. Callosal connections are thought to support neural synchrony at the cortical level[19] while descending pathways such as the medial corticospinal and brainstem projections which influence motoneurones on both sides of the spinal cord[21] could ensure synchronous bilateral activation of the upper limbs. The processing for both homologous and non-homologous bilateral tasks presumably reflects a balanced recruitment between these independent and common pathways. For homologous bilateral tasks the activation of pathways which are common to both limbs predominates. For non-homologous bilateral tasks requiring greater limb independence processing presumably involves the activation of independent pathways and greater suppression of common pathways.

In conclusion, when a subject performs a reaching task which requires the distal programming of a gross grip with one hand and a precision grip with the other hand, central processing normalizes the bilateral task to a common movement duration. The nervous system is given a defined temporal space to work within and can use this to normalize the appropriate timing and spacing of the proximal and distal components for each limb[36]. It is thus "compelled" to ensure that the limb responsible for the more precise task is given sufficient approach time and thus that the kinematic parameterization of this limb differs from that of the contralateral limb.

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