RESEARCH ARTICLE

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The coordination between trunk and arm motion during pointing movements

Abstract The coordination between the trunk and arm of six subjects was examined during unrestrained pointing movements to five target locations. Two targets were within arm's length, three were beyond. The trunk participated in reaching primarily when the target could not be attained by arm and scapular motion. When the trunk did contribute to hand transport, its motion started simultaneously with arm movement and continued until target contact. Redundancy in the degrees of freedom used to execute the movement had no effect on the configuration of joints and segments used to attain a specified target; no difference in variability was noted regardless of whether redundancy existed. However, different configurations were used to achieve the same wrist coordinates along a common endpoint path, depending on the final position of the hand. The addition of trunk flexion, rotation and scapular motion did not alter the coupling between the elbow and shoulder joints and had no effect on the path of the hand or the smoothness of its velocity profile. Thus, trunk motion was integrated smoothly into the transport phase of the hand. As the trunk's contribution to hand transport increased, it played a progressively greater role in positioning the hand close to the target during the terminal stage of the reach. Of the movement components measured, trunk flexion was the last component to complete its motion when target reaches were made beyond arm's length. Hence, the trunk not only acts as a postural stabilizer during reaching, but becomes an integral component in positioning the hand close to the target.

Key words Coordination · Arm movement · Posture · Trunk · Human

Introduction

Reaching has been studied extensively from both a hand and joint level of analysis. The primary finding from the

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hand level of analysis is that the hand moves in a relatively straight path with a smooth, bell-shaped velocity profile (Morasso 1981; Abend et al. 1982; Kaminski and Gentile 1986, 1989). The majority of investigations that have focused on the joint level of analysis have confined motion to the elbow and shoulder joints. If motion of an additional joint was included, it has been typically the wrist (Lacquaniti and Soechting 1982; Cruse and Bruwer 1987; Cruse et al. 1993). The major findings indicate that shoulder and elbow motion is strongly coupled (Soechting and Lacquaniti 1981; Kaminski and Gentile 1986, 1989), while wrist motion has no clear relationship to that of the other two joints (Lacquaniti and Soechting 1982).

The observation that wrist motion appears to be independent of motion at the more proximal joints is not surprising when considering the roles of these joints during reaching. The primary function of the shoulder and elbow joints is to transport the hand to the target, while wrist motion primarily orients the hand for grasping (Jeannerod 1988). The hand can attain the desired final location regardless of the degree of wrist participation. Unlike motion at the wrist joint, trunk and scapula motion can extend the range of the workspace and have a substantial impact on the hand's trajectory. Consequently, the coordinative patterns observed when trunk and scapula motions are coupled with arm motion may be quite different than those observed when shoulder and elbow motion are coupled with wrist motion.

Previous research concerned with the relationship between the trunk and the arm during movement has focused primarily on the trunk's role as a postural stabilizer when the arm is used to reach to a target (see Massion 1992 for a recent review). However, when the target is located beyond arm's length, the trunk must change its role from a postural stabilizer to prime mover of the hand. Although trunk motion has been studied extensively by Oddsson and Thorstensson (Thorstensson et al. 1985; Oddsson and Thorstensson 1986, 1987, 1990; Oddsson 1988, 1989), the coordination between arm and trunk motion has received little attention. The relationship between

scapula and arm motion has been extensively studied, but the movements under analysis have been limited to elevation of the arm through its range of motion (Lucas 1973; Dvir and Berne 1978; Blakely and Palmer 1984; Bagg and Forest 1988; Culham and Peat 1993) and have not been concerned with the coupling that occurs between the trunk, scapula and arm during goal-directed activities. The purpose of this study was to assess the coordination between the trunk, scapula and arm during reaching movements. The role of the trunk was varied by placing targets within and beyond arm's length. When the target was within arm's length, the trunk was required to act only as a postural stabilizer and the target could be attained by motion at the shoulder and elbow joints. When the target was beyond arm's length, the trunk and scapula had to move in conjunction with the shoulder and elbow joints for goal attainment. This arrangement permitted an analysis of the coordination between the trunk and arm as well as an assessment of the component coupling used during goal-directed movements.

Methods

Subjects

Six adults (two men, four women) between the ages of 23 and 38 years with no known histories of neurologic or orthopedic impairments volunteered to serve as subjects. All subjects signed informed consent forms prior to their participation in the study. Approval for conducting this study was granted by the institution's Committee on Human Research.

Procedures

Subjects were seated in a straight back, wooden chair with their knees flexed to 90 deg and their feet resting firmly on the floor. To minimize forward translation of the thigh while performing reach-

es, an adjustable strap was placed across the proximal tibia of both legs and secured to the chair. The target was a ball, 2.5 cm in diameter, which was threaded through a string and fastened to a frame at both ends to minimize movement. Prior to reaching to the target, subjects were placed in the following position: trunk (unsupported by the chair) aligned with a plumb line, shoulder in 0 deg flexion, elbow in 90 deg flexion, forearm in 0 deg supination, index finger extended and all other fingers flexed (see Fig. 1).

Subjects were required to reach to five target locations placed in the sagittal plane in front of them. The farthest target (T5) was set at a distance requiring maximum comfortable forward excursion of the trunk and upper extremity. Consequently, the number of joint configurations available to reach the target was very limited and redundancy in the number of degrees of freedom available was minimal. Target location two (T2) was set at a distance requiring maximum forward excursion of the upper extremity without any displacement of the scapula or trunk. The other three target distances were based on a percentage of the distance to T2 and T5: T1 was 50% of the distance between the initial position and T2; T3 and T4 were 33% and 66% of the distance between T2 and T5, respectively.

Target height was set at the same level as the subject's right hand prior to initiation of movement and remained at that height for all five locations. Maintaining a constant target height increased the probability that an arm movement to a farther target location would result in passage through the same wrist coordinates used when moving to closer target locations. This target arrangement permitted comparisons of the configuration of the body segments and joint angles when the spatial coordinates of the wrist were the same, but the goal of the movement (distance to be traversed) was different.

Subjects were instructed to move as fast as possible and contact the target with their right index finger when given verbal cues to move (ready, go). Twenty-five practice trials (five to each of the five target locations) were performed prior to a set of 25 test trials, which were videotaped for analysis. Trials were blocked in groups of five, with one movement made to each target location (in random order). The target was manually shifted to one of the other locations after each trial.

Data collection and reduction

All reaching movements were videotaped at 60 Hz using a Panasonic 2XC camcorder positioned 10 m away from the subjects in

Fig. 1 Starting position for all subjects. *Black circles* on the body indicate points used for digitizing. Subjects pointed to each of the five target locations (*T1–T5*)

Movable Frame
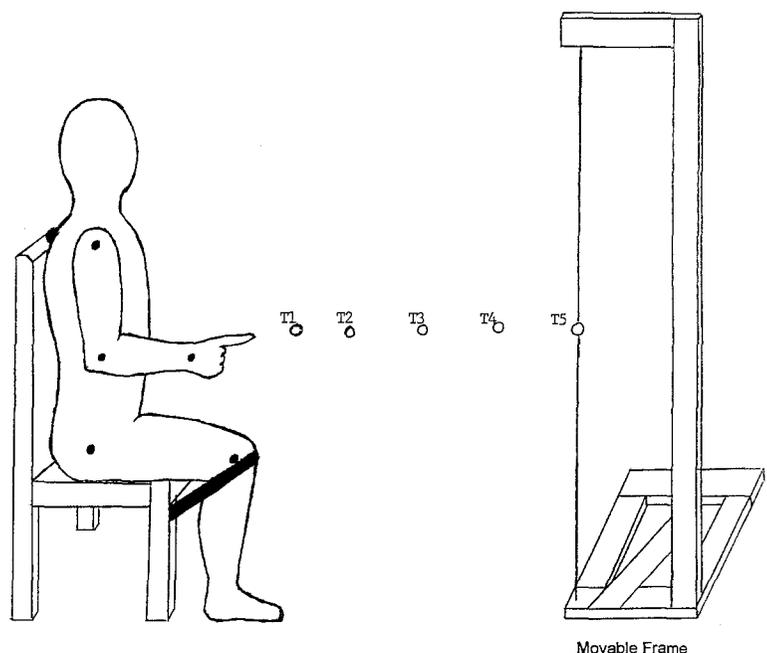
the sagittal plane to record movements in the X and Y directions. For three of the subjects, a second camcorder was positioned overhead, perpendicular to the first camera, which recorded motion in the X and Z directions. The two camcorders were genlocked and synchronized using an event synchronization unit (Peak Performance Technologies, Englewood, Cdo). Reflective markers were placed over the right lateral femoral epicondyle, greater trochanter, lateral humeral epicondyle,midway between the styloid processes of the radius and ulna, tip of the index finger, left and right acromion processes and over the third thoracic vertebrae. To derive X, Y and Z coordinates, these markers were manually digitized from the videotape using Kinematic Analysis software (R.A. Schleihauf, City University of New York) or automatically digitized using the Peak Performance system. These data were smoothed by a fourth-order zero-phase-shift Butterworth low pass digital filter with a cutoff frequency of 7.48 Hz (Winter 1990), then differentiated to obtain velocity values.

Data analysis

Multiple regression analyses were carried out using movement time, peak wrist velocity, movement onset and termination, displacement and peak velocity of the scapula, trunk, shoulder, elbow and hip joints as the dependent variables. Because there were between-subject differences in reach distances and velocities, measures of the dependent variables were standardized by converting to Z scores prior to regression analysis. Two sets of displacement standard deviations were calculated. Between-subject standard deviations were derived from mean displacements of the wrist, scapula, trunk and each of the joints for movements to each target location. These scores represented variability across subjects due to individual morphologic differences in range of motion. Average within-subject standard deviation scores were derived by: (a) calculating the standard deviation of the dependent measures for the five trials to each target location, and then (b) averaging these scores across subjects. These scores depicted the degree of dispersion for movements to each of the five target locations. Because the joint configurations were well controlled prior to the start of each trial, the values obtained also represented the variability in segment and joint configurations at movement termination.

Hip joint angular motion was considered a reflection of trunk forward segmental motion. The hip angle was derived by measuring the angle made by the knee, hip and back markers. Although trunk segmental motion is actually a resultant of motions at the hip joint, pelvis, lumbar and thoracic vertebrae, it was used as a way of approximating the contribution of trunk forward motion in transporting the hand to the target. Shoulder flexion was determined from the angle created by the hip and back markers and the acromion and elbow markers. Using these points to determine shoulder motion minimized measurement inaccuracies that could result from scapular protraction and trunk rotation.

The combined contribution of trunk rotation and scapular protraction on hand transport was determined by subtracting the forward displacement of the marker over the right acromion process from the displacement of the marker over the vertebrae as viewed from the sagittal plane. Scapula protraction, defined as forward movement of the scapula around the thoracic wall is a fairly complex motion which combines linear translation of the scapula away from the vertebral column, rotation of the scapula around the the end of the clavicle and anterior movement of the lateral end of the clavicle (Culham and Peat 1993). An estimation of the contribution of scapula motion separated from trunk rotation was made from the overhead view of the reaches. In addition to the markers placed on the body, two stationary reference points were digitized from the overhead view. These two points created a reference line to assess the degree of angular rotation of the two acromion processes about the spine. Since the spinal column is the axis for trunk rotation, it was assumed that forward rotation of the right acromion process equals backward rotation of the left acromion process when motion is limited to trunk rotation. During reaching movements of the right arm, the motion of the right acromion pro-
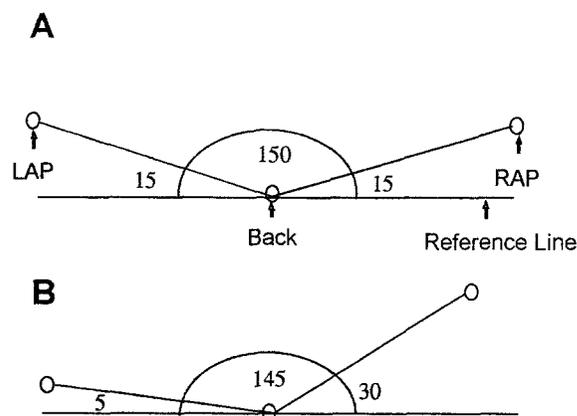

Fig. 2A, B Method for measuring the rotatory portion of scapula protraction and trunk rotation. **A** Overhead view of markers on the vertebra, left (*LAP*) and right (*RAP*) acromion processes and the angles created relative to a stationary reference line prior to movement onset. As subjects reached for a target, LAP and RAP would rotate counterclockwise. **B** Final position of markers after completion of a reach. In this example, trunk rotated through an angular displacement of 10 deg and scapula protracted 5 deg

cess results from a combination of both scapular motion and trunk rotation, while motion of the left acromion process results primarily from rotation of the trunk. By subtracting the angular displacement of the right acromion process from that of the left, a rough approximation of scapular rotation around the thorax was obtained (see Fig. 2). Estimates of this scapular motion could also be made directly by measuring the angle created by connecting the two acromion processes to the vertebral marker. The translation and elevation of the scapula could not be measured with the analytic techniques used in this study. These motions also contribute to hand transport and need to be measured in order to more precisely quantify scapular movement. It is recognized that the dichotomy of scapular and trunk motions used in this study is a simplification of the actual movement. However, this analysis provides a rudimentary estimate of the relative contributions of these two components during reaching movements that are made to locations greater than arm's length away.

For qualitative analyses, the velocity of one joint was plotted against the velocity of another joint. The topology of these plots gave a visual depiction of the relationship between the movement of two joints.

Results

Displacements and configurations

For movements to the closer targets (T1 and T2) transport of the hand was accomplished primarily by motion at shoulder and elbow joints. Hip, trunk and scapular motion became more evident when reaching to the farther targets (T3, T4 and T5), with hip flexion and trunk rotation reaching their maximum during reaches to T5. The mean amplitudes and standard deviations of displacement for the various components which contributed to hand transport are reported in Table 1. Note that the standard deviations for movements to T1 through T4 in which a large range of configurations could be used to attain the same final position of the endpoint were no greater than those observed for movements to T5, in

Table 1 Mean values (*n*=6) and between- and within-subject standard deviations (*SD*) for segment and joint displacements to the five targets

Component	Target	Mean	SD between	SD within	Component	Target	Mean	SD between	SD within
Wrist	T1	18.1	3.8	1.8	Elbow	T1	25.1	12.3	2.4
forward motion	T2	31.8	0.7	1.6	extension	T2	36.3	12.5	3.6
(cm)	T3	51.0	3.9	2.3	(deg)	T3	42.6	9.5	2.2
	T4	69.7	7.7	2.5		T4	47.9	7.8	2.7
	T5	90.1	10.7	2.1		T5	90.1	10.7	2.1
Acromion	T1	2.0	0.8	0.4	Shoulder	T1	25.8	10.2	2.4
forward motion	T2	4.8	1.7	0.6	extension	T2	42.0	8.1	2.5
(cm)	T3	10.2	3.8	1.2	(deg)	T3	62.7	8.0	2.9
	T4	11.8	5.9	1.8		T4	83.3	13.5	2.5
	T5	11.2	6.8	2.2		T5	109.3	20.6	2.6
Scapula	T1	3.9	2.8	1.3	Hip	T1	0.5	0.2	0.3
angular motion	T2	6.9	4.0	1.8	flexion	T2	2.2	1.9	0.7
(deg)[a]	T3	6.4	3.0	3.0	(deg)	T3	11.4	8.1	2.1
	T4	−6.0	8.6	7.1		T4	28.0	13.0	3.0
	T5	−13.0	11.6	5.3		T5	46.6	13.3	2.9
Trunk	T1	2.1	0.9	1.6					
rotation	T2	6.2	2.6	2.2					
(deg)[a]	T3	21.5	6.1	3.3					
	T4	29.3	7.0	3.6					
	T5	38.0	9.4	3.0					

[a] Values based on results from three subjects

Fig. 3 Stick figures illustrating the movement patterns used during reaches to three target locations. Figures on the *left* are derived from the sagittal view, while those on the *right* are derived from the overhead view. Elapsed time between stick figures was 83 ms (*LAP* left acromion process, *RAP* right acromion process)
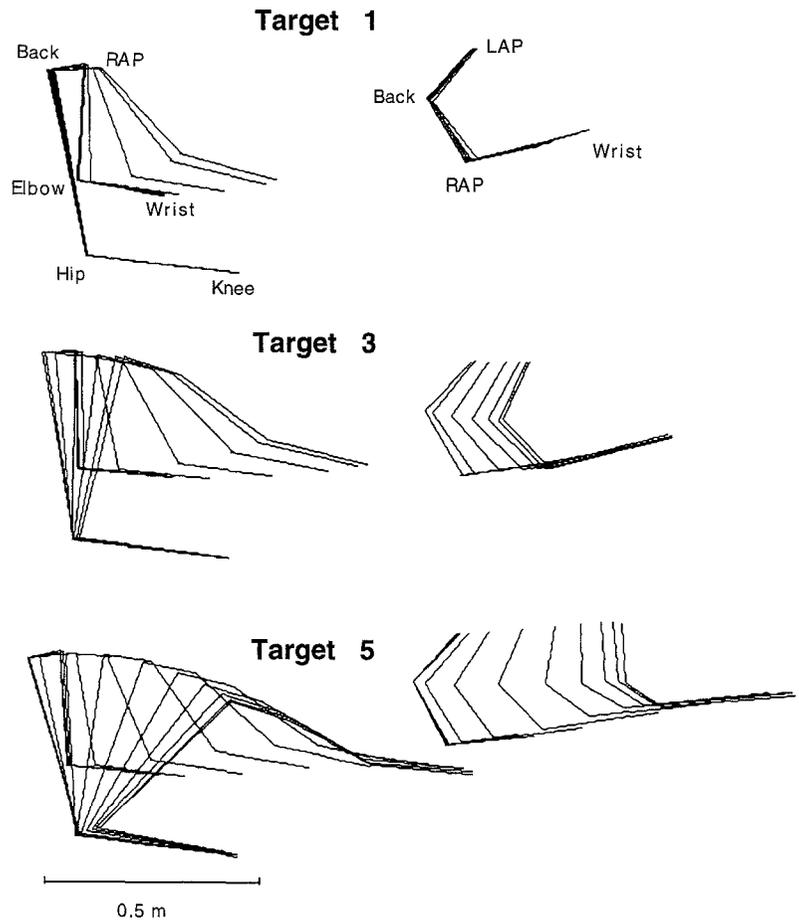
Fig. 4A–C Five overlapped
trials of one subject's move-
ment to T2. **A** Tangential
velocity profiles of wrist and
acromion. Acromion velocity
profiles represent the combined
forward motion of the scapula
and trunk relative to the verte-
bral marker as observed from
the sagittal view. **B** Hand paths
as observed from the sagittal
(Y and X directions) and over-
head (Z and X directions)
views. **C** Component velocity
profiles of the movements.
Scapula and trunk were derived
from the overhead view, while
hip, shoulder and elbow were
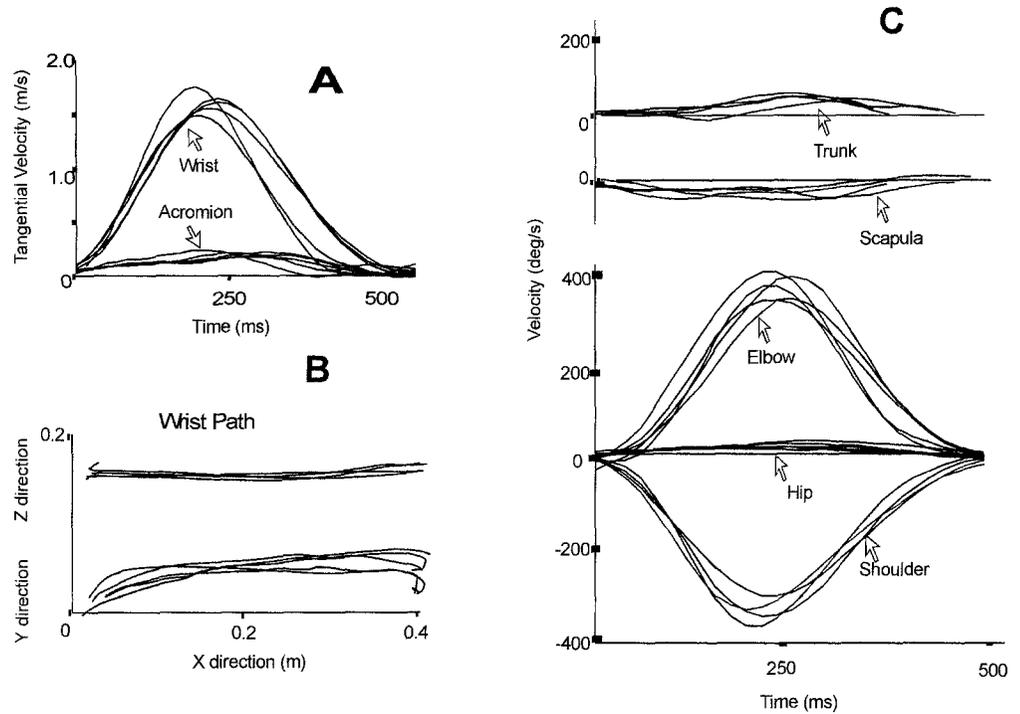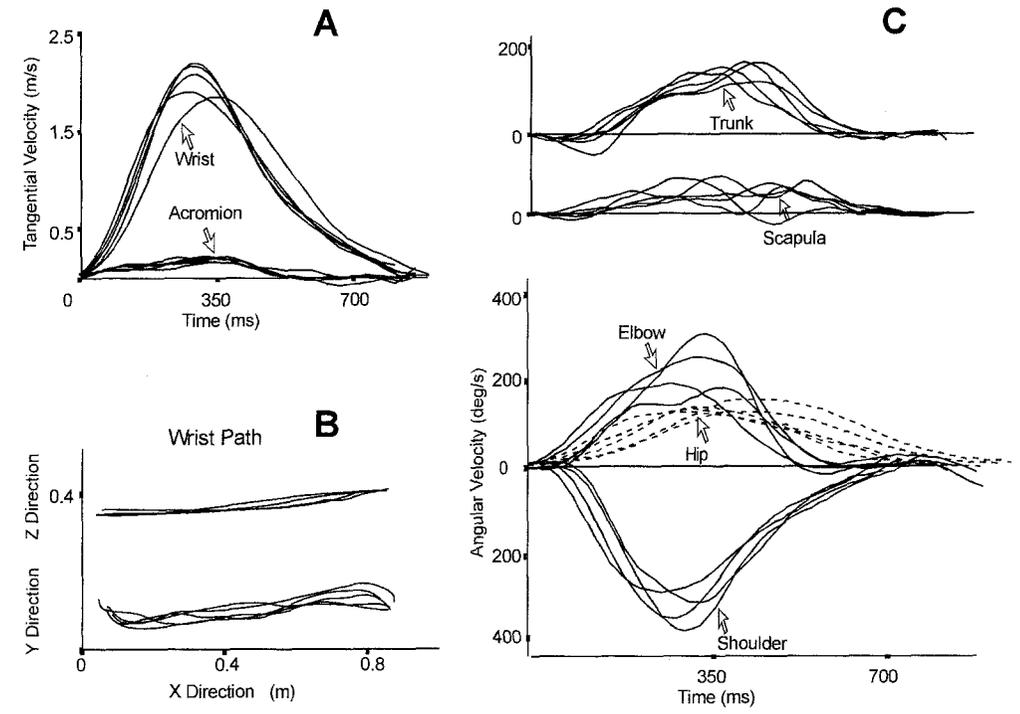derived form the sagittal view

Fig. 5A–C Five overlapped
trials of the same subjects's
movements to T5 (for an expla-
nation of **A–C** see Fig. 4). Note
that the velocity profiles of the
scapula are above the 0 refer-
ence line, indicating that
it was moving in the opposite
direction (retracting) compared
to its displacement during
reaching to T2 (see Fig. 4C)

which the range of possible configurations was reduced
considerably. Thus, the final configuration attained at
target contact was constant from trial to trial regardless
of the amount of redundancy in the available degrees of
freedom.

Trunk rotation and scapular motion exhibited an inter-
esting relationship. When trunk rotation was meager the
scapula protracted. As the amplitude of trunk rotation in-
creased, scapula motion reversed direction and retracted.

This pattern of scapular retraction can be observed in the
overhead view of the stick figure representations illus-
trated in Fig. 3. The angle created by the two acromion
processes and the vertebral marker increased slightly
from the beginning to the end of the trial for the move-
ment to T5. This pattern was observed across trials of the
three subjects analyzed from the overhead view. Note in
Table 1 that scapula motion was negative for movements
to T4 and T5. These negative numbers indicate that scap-

ula retraction occurred during reaches to the farther target locations. The end result of this interaction between trunk and scapular motion was to lessen the contribution of the shoulder girdle to hand transport for the farther target locations.

Wrist kinematics

Wrist paths were straight and highly reproducible from trial to trial for movements in the Z direction, while a greater degree of variability was noted for movements in the Y direction (see Figs. 4, 5). Wrist velocity profiles were smooth and variability of the wrist's path remained low regardless of the degree of trunk and scapular participation in the movement. Thus, the addition of trunk and scapular motion was well integrated with that of the shoulder and elbow joints.

A prolongation in the deceleration phase of the movement was frequently observed for movements to the further target locations (movements to T3, T4 and T5). This prolongation can be seen when comparing the wrist velocity profiles of Figs. 4 and 5. Regression analysis indicated that two variables made a significant contribution to increasing the percentage of time spent in the deceleration phase: target distance and amplitude of hip displacement. Although hip displacement was correlated with target distance, it produced a significant prolongation in the deceleration phase of the wrist beyond that attributed to target distance alone ($F_{1,27}$=4.45, $P<0.05$).

Temporal coupling of component motions

There was no consistent pattern of temporal coupling that linked all the components involved in the reaches. However, coupling between individual pairs of components was observed. The onset of shoulder motion preceded motion of the acromion by 29±12 ms, averaged across subjects, and remained constant across target distances. Cessation of these two motions showed a significant linear relationship dependent upon amplitude of wrist displacement ($F_{1,25}$=5.22, $P<0.05$). When wrist displacement was small (movements to T2), the acromion stopped moving on the average of 107±78 ms prior to cessation of shoulder flexion. For the largest wrist displacements (movements to T5), the acromion ceased moving 277±33 ms before the shoulder stopped flexing.

Hip and shoulder motion demonstrated a unique pattern of coupling at movement termination. This relationship is illustrated in the scatterplot of Fig. 6. When the target was close and hip displacement was small, hip motion either stopped simultaneously with or preceded the termination of shoulder motion. As reach distance increased and hip flexion increased, the hip completed its motion at a progressively later point in time relative to shoulder motion. Thus, when hip flexion was incorporated into the reaching task, trunk motion was the primary component used to bring the hand to the target during the terminal stage of the movement.

Shoulder and elbow motion were strongly coupled for all reaches. Of particular note was the one-to-one ratio between shoulder and elbow angular velocity observed

Fig. 6 Relationship between the time difference of hip and shoulder joint movement termination and amplitude of hip displacement. As the amplitude of hip flexion increased (along abscissa), the hip stopped moving at a progressively later point in time relative to the shoulder. Each symbol represents the mean difference in movement termination for a subject reaching to an individual target. A positive value indicates that the hip stopped moving before the shoulder. A negative value indicates that the hip stopped moving after the shoulder
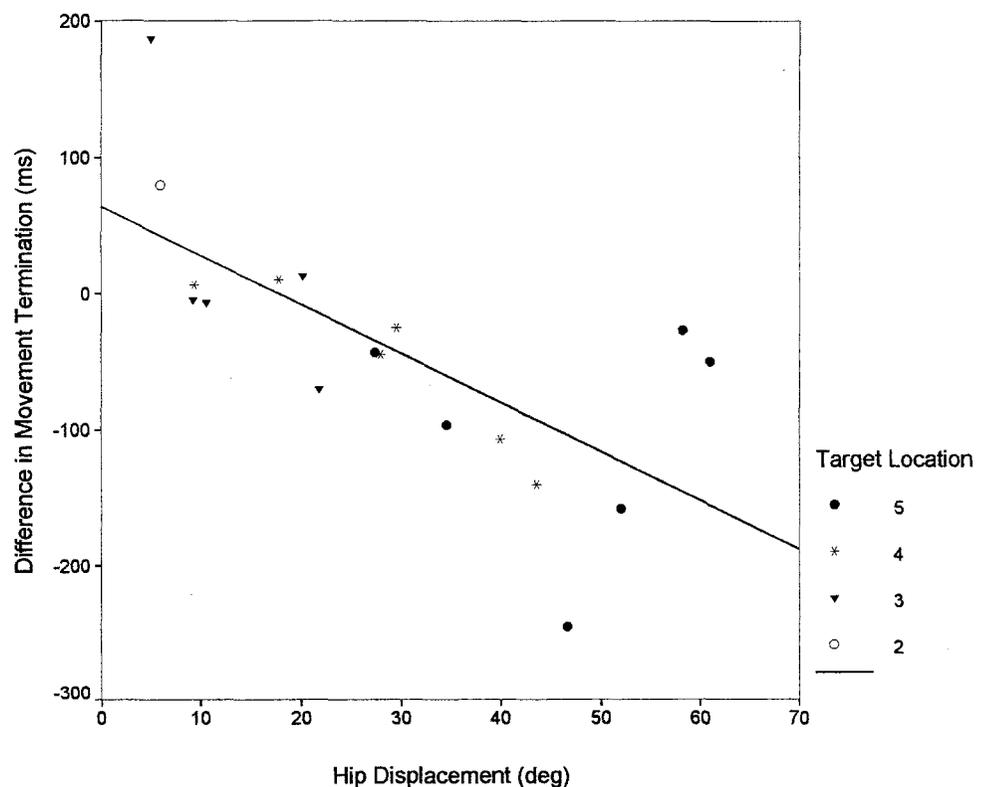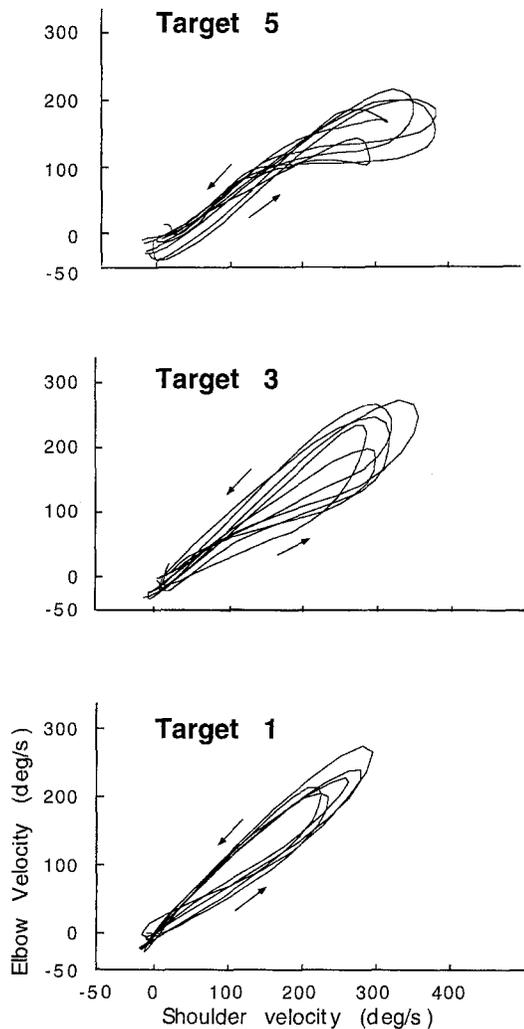
Fig. 7 Velocity plots of elbow (*ordinate*) vs shoulder (*abscissa*) for movements to T1, T3 and T5 derived from one subject's five trials to each target. Variations in the plots always occurred in the early part of the movement. The relationship between elbow and shoulder velocity remained the same during the deceleration phase regardless of amplitude of elbow and shoulder joint displacement or the the contribution from the other moving components (*arrows* indicate acceleration and deceleration phases)

during the deceleration. This ratio remained the same for all subjects for movements to all targets. Thus, the addition of trunk and scapular motion did not affect the coupling between the elbow and shoulder joints during the deceleration phase. This finding is illustrated in Fig. 7 in which shoulder velocity is plotted against elbow velocity.

Relationship between peak velocity and displacement

The linear relationship between peak velocity and displacement observed previously at both the endpoint and joint levels of analysis (Kaminski and Gentile 1986, 1989) was modified when hip flexion occurred (see Fig. 8). As the target distance increased, peak velocity increased in an asymptomatic fashion. This relationship

was virtually identical for movement of the hand and shoulder joint. When values for these variables were standardized by converting to Z scores, the respective best fit quadratic lines for the wrist and shoulder joint data almost attained a perfect overlap. The loss of linearity between displacement and peak velocity appeared to be related to amplitude of hip displacement. Separate regression analyses revealed that hip motion made a significant contribution in explaining the amount of variance in peak velocity for movements viewed from both the hand and joint level of analysis: R^2 increased from 0.794 to 0.867 ($F_{1,27}=14.69$, $P<0.001$) when assessing movement at the hand level and from 0.841 to 0.953 ($F_{1,27}=53.34$, $P<0.001$) when assessing movement at the joint level. Forward motion of the acromion made no significant contribution to explaining the variance in wrist or shoulder joint peak velocity.

Discussion

Trunk motion can make a significant contribution to the transport phase of the hand by extending the boundaries of the workspace and transporting the hand to the target during the terminal stages of the movement. Furthermore, the inclusion of hip flexion, trunk rotation and scapular motion as components of hand transport were well integrated with motion occurring at the shoulder and elbow joints; the wrist path was relatively straight and the velocity profile remained unimodal regardless of the participation from these additional components.

This study was not designed to be an anatomical analysis of the shoulder complex during reaching. The model used to analyze scapular motion has been simplified and may have produced some error in the values obtained. However, we believe the results remain valid in the sense that they highlight the elaborate interactions that exist between the components involved in a reaching task to produce a smooth, consistent movement of the endpoint. The observation that movement in the Z direction was straight and had minimal variability indicated that motion of the trunk, scapula and arm in the horizontal plane was coordinated with a high degree of precision. The integrated motion of the glenohumoral and scapulothoracic joints, frequently termed scapulohumeral rhythm, has been well documented in studies that have analyzed elevation of the arm without concerns for attaining a target with the hand (Codman 1934; Inman et al. 1944; Lucas 1973; Dvir and Berme). In the present study, this glenohumeral motion had to be combined with trunk rotation and scapula motion to move the hand forward to an anteriorly placed target. In order to keep the wrist moving consistently along a straight path in the horizontal plane, trunk rotation had to be countered by shoulder horizontal abduction. Any deviation from this tight coupling would result in a curved path. As the amplitude of trunk rotation and shoulder horizontal abduction increased for movements to the farther targets, the coupling between scapular and humeral motion resulted in scapula retrac-

Fig. 8 Relationship between peak velocity and displacement of the shoulder and wrist. The rate of rise in peak velocity decreased relative to displacement as hip flexion made a greater contribution to the movement. Velocities and displacements were standardized by converting to Z scores in order to place shoulder (an angular measurement) and wrist (a linear measurement) on the same scale. Each *symbol* represents the mean peak velocity derived from one subject's reaches to an individual target. The *dashed* and *solid lines* are the best fit quadratic lines for wrist and shoulder data, respectively (*WPV* wrist peak velocity, *WD* wrist displacement, *SPV* shoulder peak velocity, *SD* shoulder displacement)
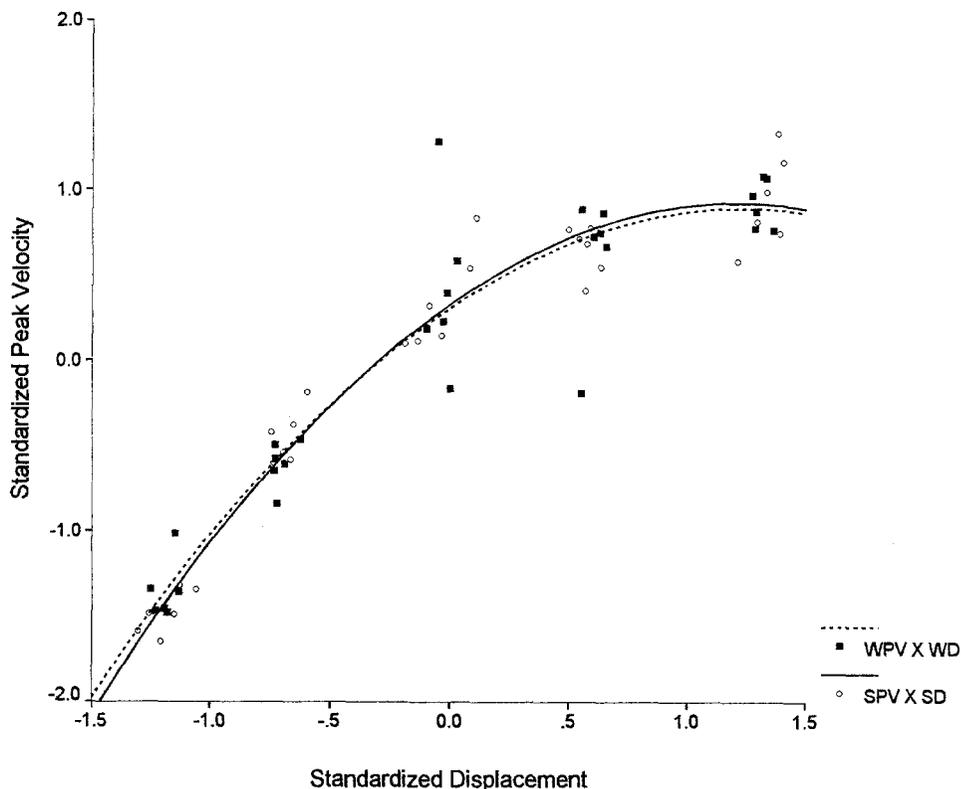
tion instead of protraction. Thus, the coupling between trunk, scapula and arm becomes much more complex when the task requires reaching for a target rather than simply elevating the arm.

Depending on the final desired location of the hand, a different combination of component displacements was used to position the hand at the same location along the wrist's path. Whenever redundancy exists in the number of degrees of freedom used to execute a movement, the components can be combined in different ways to attain the same goal. This phenomenon, commonly termed motor equivalence (Lashley 1930), has been observed previously for both oral (Abbs and Gracco 1984) and hand (Cole and Abbs 1986) movements and can be extended to movements involving redundancy of the trunk and upper extremity. When a target was placed relatively close to the body, it was attained primarily by motion of the shoulder and elbow, and the coordinates of the wrist were determined by motion of these two joints. For the further targets, trunk and scapular motions made significant contributions to hand transport. These components started moving in close temporal proximity to the shoulder and elbow joints and continued well into the deceleration phase of the wrist. Consequently, the only way the wrist could be positioned at the same Cartesian coordinates was by decreasing the displacement of the shoulder and elbow joints to compensate for the contribution to motion made by the trunk and scapula.

Rosenbaum et al. (1993) modelled three-segment reach movements similar to those analyzed in the present study and suggested that these movements are based on

an energy cost function derived from joint stiffness, friction and segmental moment of inertia. In their model, all three segments (trunk, upper arm and forearm) contributed to the reach, with each segment's displacement roughly proportional to its moment of inertia. Results from the present study indicate that the trunk flexion remained minimal if the target could be attained through use of the shoulder and elbow alone. Consequently, the trunk's contribution to a reach movement must be determined by factors other than those included in Rosenbaum's model. Maintenance of postural stability has been shown to be a major determinant of movement organization (Boisset and Zattara 1981, 1987, 1988, 1990; Friedli et al. 1988; Massion 1992). The trunk's large moment of inertia not only results in high energy costs whenever voluntary movement occurs, but also has a high potential for creating postural destabilization. Thus, the effect of each segment's motion on postural stability should also receive some weight in modelling the relationship between body configuration and target location.

In the present study in which trunk and scapular motion became additional degrees of freedom used to reach a target, the timing of these components relative to the upper extremity was predictable from trial to trial. Although there was no tight coupling between the trunk and limb velocities, trunk flexion always started at the beginning of the reach and persisted until target contact. Lacquaniti and Soechting (1982) looked closely at the coordination between the shoulder, elbow and wrist joints during three degrees of freedom pointing movements. They observed that the shoulder and elbow were

tightly coupled during the deceleration phase of the movement. However, there was considerable intertrial variability between timing and duration of motion at the wrist and the more proximal joints. The dissimilarity in coupling of the trunk and the wrist to the upper extremity can be explained by the different roles each plays during a reach. Wrist motion serves primarily to orient the hand for grasping and has little impact on the transport of the hand (Soechting 1984). In contrast, trunk motion makes a major contribution towards transporting the hand to the target and can affect both the path and velocity of the hand. By adopting a strategy of maintaining a low level velocity at the hip throughout the course of the movement, the consequences of trunk motion on hand trajectory are minimized with regard to both the kinematics and the interactional forces. Furthermore, this strategy also eliminates the need for altering the coupling between the shoulder and elbow joints. Plots of shoulder versus elbow velocity indicated that the addition of hip motion had no effect on the coupling between these joints. In fact, these velocity plots are comparable to those presented by Lacquaniti and Soechting (1982) when wrist motion was used as the third degree of freedom. Thus, the coupling between the elbow and shoulder joints remains unaffected by motion that is occurring either more proximally or distally to them.

Hollerbach and Atkeson (1987) suggested that the coupling between the shoulder and elbow may be simply a function of movements that approach the boundaries of the arm's workspace. This conclusion was derived from an assessment of the target locations used by Soechting and Lacquaniti (1981) which do appear to be situated roughly along the vertical edge of this workspace. In the present study, the shoulder and elbow joint displacements increased progressively in the horizontal direction from T1 to T5. Consequently, the boundaries of the joint workspace were attained only for movements to T5. The fact that the shoulder and elbow joint velocities had a one-to-one ratio throughout the deceleration phase of all movements and were virtually identical to those presented by Soechting and Lacquaniti (1981) is in opposition to the argument put forth by Hollerbach and Atkeson (1987). It is beyond the scope of this paper to explore alternative explanations for the coupling between the shoulder and elbow joints as the focus is directed towards the coordination between trunk and arm motion.

It has been demonstrated previously that as displacement increases, peak velocity increases linearly for medium range movements. This relationship is evident during movement of the hand as well as the shoulder and elbow joints (Kaminski and Gentile 1986, 1989). However, as the contribution of trunk motion to the reach increased, the linear relationship between displacement and velocity was modified at both the joint and hand level of movement. On the joint level of movement, the shoulder went through a large amplitude of displacement (a mean of 109 deg of flexion) when subjects reached to T5. Mashima et al. (1981) have demonstrated that as

movement amplitude increases, peak acceleration (and hence peak velocity) increases less rapidly and appears to reach a saturation point. As the subjects were instructed to move as rapidly as possible in the present study, the shoulder flexors may have reached their maximum speed of contraction while moving to the more proximal targets and could not produce enough additional force to accelerate the limb any faster when moving to the more distal targets.

This explanation cannot fully account for the change in the peak velocity/displacement relationship that occurred with motion of the hand. As trunk and scapula participation in hand transport increased (particularly movements to T3, T4 and T5), the rate of rise in wrist peak velocity decreased progressively in a manner similar to the shoulder. Trunk flexion, rotation and scapular protraction should summate with shoulder flexion and elbow extension in propelling the wrist to the target. As the contribution of the more proximal components increases, there should be an increase in the velocity of the wrist even when the velocity of the shoulder and elbow joints have saturated. Consequently, the slope of the peak velocity/displacement relationship of the wrist was expected to remain constant for movements to the further targets. The decrease in slope on the hand level may be explained by the fact that the hand was approaching the boundaries of postural stability for movements to the farther targets. As the hand reached to these targets there was a greater shift in the body's center of gravity, and a decrease in velocity may have been necessary to prevent momentum from causing a loss of balance.

When trunk motion assisted in bringing the hand to the target, the hip either stopped moving simultaneously with the shoulder and elbow joints or was the last joint to complete its motion. This observation points to an unexpected role for the trunk. During previous studies of arm movement, the trunk has been considered with reference to its role as a postural stabilizer (Bouisset and Zattara 1981, 1987, 1988, 1990). In the present study the trunk was not only committed to maintaining postural stability, but participated simultaneously in bringing the hand to the target during the final stage of the reach. Rather than merely stabilizing the body in an appropriate position that would permit the arm to complete the movement, trunk flexion and rotation was used as an integral component in the terminal stage of hand transport. Thus, posture and movement did not appear to be controlled separately, but were tightly integrated into a dynamic process of continuously balancing the forces acting on the body so as to control the resultant in ways compatible with the task (Riccio and Stoffregen 1988, Reed 1989).

In summary, current views of the trunk's contribution during reaching movements need to be reassessed. When the target is within arm's length, the trunk serves in its commonly accepted role as a postural stabilizer. However, when the target is beyond arm's length, the trunk's motion becomes smoothly integrated with that of the arm and plays a principle role in positioning the hand at the target location.

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