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EFFECTS OF TASK CONSTRAINTS ON REACHING KINEMATICS BY HEALTHY ADULTS [1]

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Summary.—Understanding the control of movement requires an awareness of how tasks constrain movements. The present study investigated the effects of two types of task constraints—spatial accuracy (effector size) and target location—on reaching kinematics. 15 right-handed healthy young adults (7 men, 8 women) whose mean age was 23.6 yr. ($SD=3.9$ yr.) performed the ringing task under six conditions, formed by the crossing of effector size (larger vs smaller size) and target location (left, right, or a central position). Significant main effects of effector size and target location were found for peak velocity and movement time. There was a significant interaction for the percentage of time to peak velocity. The findings suggested that task constraints may modulate movement performance in specific ways. Effects of effector size might be a consequence of feedforward and feedback control, and location effects might be influenced by both biomechanical and neurological factors.

In daily life, we perform a tremendous variety of functional tasks requiring movements with various constraints that determine in part the type of movement needed. Constraints are viewed as boundaries or features that limit or guide motion of the person under consideration and may arise from the environment or the human body (Newell, 1986). In neurorehabilitation, therapeutic intervention is viewed as a constraint on action that interacts with boundary conditions already present in the environment, individual, and task to channel change in movement (Newell & Valvano, 1998). For these

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reasons, understanding the control of movement requires an awareness of how tasks constrain movements (Shumway-Cook & Woollacott, 2001). Among numerous task constraints, two are of particular interest, spatial accuracy and target location, because the planning and execution of goal-directed movements involving different visuomotor processes is based upon their spatial requirements (Barthelemy & Boulingues, 2002). The present study focused on effects of these two types of task constraints in motion analysis—spatial accuracy demands and target location—on kinematic performance during upper-limb reaching movements by healthy adults.

Reaching movements are subserved by visuomotor mechanisms with feedback and feedforward control (Keele, 1981). According to these controls, reaching movements are separated into acceleration and deceleration phases. The first is driven by preplanning of the movements, in part, according to task constraints, and ensures rapid transport of the hand to the vicinity of the target. The second depends on sensory feedback loops to perform online corrections and allows the hand to hit the target when the movement velocity becomes low (Jeannerod, 1988; Milner, 1992; Haaland, Prestopnik, Knight, & Lee, 2004). By integrating information on task constraints, motor output, and sensory input, the time spent in completing the task and velocity of the hand can be measured (Desmurget & Grafton, 2000).

When the task demands for spatial accuracy increase, the person may need to scale the spatial relations between the person and the target precisely, perform the task carefully, and require more on-line corrections to hit the target accurately (Fisk & Goodale, 1989). As a consequence, demands for increased accuracy lead to longer time to finish the task, i.e., longer movement time (Fitts, 1954; Adam, 1992; Berthier, Clifton, Gullapalli, McCall, & Robin, 1996; Roy, Kalbfleisch, Bryden, Barbour, & Black, 2000; Saoud, Coello, Dumas, Franck, d'Amato, Dalery, & Rossetti, 2000), lower peak velocity (Adam, 1992; Berthier, *et al.*, 1996; Garry & Franks, 2000; Roy, *et al.*, 2000), and less percentage of time to peak velocity, i.e., a longer deceleration phase (Adam, 1992; Berthier, *et al.*, 1996; Roy, *et al.*, 2000). A number of studies (Adam, 1992; Berthier, *et al.*, 1996; Teixeira, 1999; Garry & Franks, 2000; Roy, *et al.*, 2000; Saoud, *et al.*, 2000) investigated the effects of spatial accuracy demands by manipulating target size or width. Demands for higher spatial accuracy are associated with smaller size of the target. Some of these studies (Fitts, 1954; Adam, 1992; Berthier, *et al.*, 1996; Teixeira, 1999; Garry & Franks, 2000; Roy, *et al.*, 2000; Saoud, *et al.*, 2000) have used highly controlled laboratory tasks such as pointing to circular plates of different sizes in the vertical or horizontal plane. Sparse studies (e.g., Teixeira, 1999) have looked at the effect of target size by employing functional or daily tasks such as kicking balls of different sizes.

To extend the results of the studies altering target size (Fitts, 1954;

Adam, 1992; Berthier, *et al.*, 1996; Teixeira, 1999; Garry & Franks, 2000; Roy, *et al.*, 2000; Saoud, *et al.*, 2000), Bryden (2000, 2002) studied the effects of spatial accuracy by holding the target size constant and manipulating peg size or cursor size, that is, putting different sizes of pegs into the holes with equivalent size or moving different sizes of cursors onto a target on the computer screen. These two studies (Bryden, 2000, 2002) may, however, lack ecological validity. No study, to our knowledge, has manipulated spatial accuracy in terms of the body's effector systems. The present study employed a functional task of reaching to ring the desk bell and manipulated the spatial accuracy by varying the hand area of contact with the bell.

The target location is another spatial constraint to be considered during execution of movement. Reaching movements directed to lateralized targets may indicate performance with lateral asymmetries depending on which side the target appears (Jakobson, Servos, Goodale, & Lassonde, 1994). The basic proposition is that the visual hemifields and distal hand muscles are connected to the contralateral hemisphere. When the responding hand and the target location are on the same side, a single hemisphere is supposed to be involved in the processes occurring between visual input and motor output, i.e., the intrahemispheric processing. In contrast, when the responding hand and the target are on opposite sides, some information has to be transferred from the hemisphere receiving the visual input to the hemisphere emitting the motor output, i.e., the interhemispheric processing (Barthelemy & Boulingues, 2002). The former is more efficient than the latter (Jakobson, *et al.*, 1994; Velay, Daffaure, Raphael, & Benoit-Dubrocard, 2001), as empirically reflected in both shorter movement time and greater peak velocity (e.g., Fisk & Goodale, 1984, 1985; Roy, *et al.*, 2000).

However, one alternative interpretation of the advantage observed for movements into the ipsilateral hemispace was recently provided. Carey, Hargreaves, and Goodale (1996; Carey & Otto-de Haart, 2001) argued that the biomechanical factors might play a critical role in the kinematic differences between movements into the ipsilateral and contralateral hemispaces. Such differences could be accounted for by differences in the inertial forces operating at the hand for movements in different directions. Movements in which the hand path direction was parallel to the long axis of the upper arm, i.e., performing abductive movements into the ipsilateral space, have lower inertial loads that result in shorter movement time, higher peak velocity, and possibly a shorter time to achieve peak velocity, i.e., a longer deceleration phase, than more perpendicular hand paths, i.e., performing adductive movements into the contralateral space (Gordon, Gilhardi, Cooper, & Ghez, 1994; Carey, *et al.*, 1996; Carey & Otto-de Haart, 2001). Observation of the deceleration phase in these studies (Gordon, *et al.*, 1994; Carey, *et al.*, 1996; Carey & Otto-de Haart, 2001), but not in the studies by Fisk and Goodale (1984,

1985) and Roy and colleagues (2000), indicated that the percentage of time to peak velocity is primarily influenced by the biomechanical factors inherent in the functional anatomy of the moving limb. On the other hand, according to the visuomotor mechanisms with feedback control, the deceleration phase may represent the stage of on-line error correction and can be modulated by some constraints such as accuracy demands. How the visuomotor control and biomechanical model interplay to accomplish the task under accuracy and location constraints was investigated in the present study.

The present study evaluated the effects of effector size, i.e., the hand area of contact with the bell, and target location. It is unique in several ways. While most previous studies have conserved effects of target location, few have been focused on how the target location interacts with the effector size in reaching kinematics. Furthermore, few previous kinematic studies have included the deceleration phase of reaching so the difference in reaching toward various locations would be examined, and no study has explored the influence of spatial accuracy by changing the body effector's system. Finally, a functional activity was employed to enhance ecological validity, which was often ignored in the previous studies. Based on the concept of task constraints and previous empirical findings, we hypothesized that a smaller effector would require longer movement time and lower peak velocity and percentage of time to peak velocity than a larger effector. Among the three target locations, i.e., left, middle, or right, the movement using the right limb into the right side would elicit the lowest movement time and percentage of time to peak velocity, and highest peak velocity, and the movement into the left side the highest movement time and percentage of time to peak velocity and lowest peak velocity. Further, there would be an interaction between target location and effector size, indicating that the performance of reaching toward various locations depends on the hand area of contact with the bell.

Method

Participants

Fifteen right-handed healthy adults (7 men, 8 women) were recruited from two colleges of medicine in Taiwan. Their mean age was 23.6 yr. (*SD* = 3.9 yr.). All participants were naïve to the purpose of the experiments. Participants gave informed consent prior to participation.

Task and Equipment

Participants were instructed to perform the task of ringing the desk bell as soon as possible after the trial began on all experimental trials. A desk bell made of iron was 8.5 cm (3.3 in.) in diameter and 6.5 cm (2.6 in.) in height was used as the target object. Three bell locations were used: a central target position aligned with the starting position, a left (contralateral) target positioned at 45° to the left in relation to the midsagittal axis, and a right (ipsilateral) target positioned at 45° to the right in relation to the midsagittal axis (see Fig. 1). Wherever the bell was placed, it was 38 cm (15 in.) from the starting position.

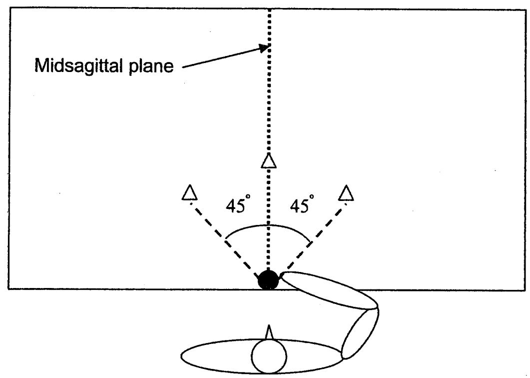

Fig. 1. Schematic illustration of the experimental set-up (Target location △, Hand switch ●)

A 6-camera motion-analysis system (VICON 370 3-D, Oxford Metrics, Inc., Oxford, UK) was used in conjunction with one personal computer (IBM clone) to capture the movement of the passive 3-D marker attached on the styloid process of the ulna during reaching and to collect two channels of analog signals simultaneously. The motion system was used to determine movement trajectory and velocity, whereas the analog signals, connected with a hand switch and a desk bell, indicated the start and the end of the reach. The motion system was calibrated to have averaged residual errors not exceeding 3 mm for each camera before data acquisition. As the participant moved, the instantaneous position of the marker was digitized at a sampling rate of 60 Hz. After data acquisition, the VICON system-analysis software was used to track the kinematic data and to save the markers' 3-D location together with analog data in binary format. Regarding the hand switch and the desk bell, the participant's hand rested on a switch prior to movement initiation. The beginning of movement was recorded when the hand moved off the switch. The end of movement was obtained when the participant pressed the desk bell.

Procedures

Each participant sat on a chair of 40 cm in height in front of a table that was 64 cm in height. Prior to the start of the experiment, the participant was asked to place the hand on the switch located on the edge of the table in line with the participant's midsagittal plane. The experimenter said "ready" to the participants to remind them to rest their hands on the switch and then said "go" to indicate the start of a trial.

A counterbalanced repeated-measures design was used. Each incoming participant received the six conditions, and the sequence of these conditions was randomized. Each participant performed five trials for each condition and one practice trial before executing the task for each condition. The six experimental conditions were formed by the crossing of effector size and target location. The effector size involved two levels, pressing the desk bell with the tip of the right index finger (the high accuracy demand) or with the palmar side of the right hand (the low accuracy demand). Three target locations were identified as mentioned above.

Data Reduction and Data Analysis

After data collection, raw VICON files were converted to three-dimensional coordinates and filtered using a second-order Butterworth filter, with a forward and backward pass at a frequency of 5 Hz. Filtered files were used to compute movement time (sec.), peak velocity (m/sec.), and percentage of time to peak velocity (%). Movement time is the duration between the start and the end of the reach. Velocity is the rate of change of marker position with respect to time. If the change in position or displacement is $\Delta\bar{s}$ over a short period of time Δt, then the velocity is given by $\bar{v} = (\Delta\bar{s}/\Delta t)$.

Mean values for each dependent measure were calculated for the six 5-trial conditions. Two-way 2 (Effector Size) × 3 (Target Position) analyses of variance with repeated measures on both factors were performed. When significant differences were found, multiple comparisons using Fisher's least significant difference (LSD) were carried out. The effect size f associated with the F value and the power level were calculated (Cohen, 1988; Rosenthal & Rosnow, 1991).

Results

Table 1 presents the means and standard deviations of the kinematic variables associated with each testing condition. The effects of effector size and target location and their interactions were addressed below.

Effects of Effector Size

A nonsignificant main effect of effector size for movement time ($F_{1,14} = 4.53$, $p = .05$, effect size $f = .57$, the power level $= .96$) and a significant one for peak velocity ($F_{1,14} = 155.18$, $p < .006$, $f = 3.32$, the power level $> .99$) were found. The condition of a smaller effector elicited lower peak velocity than the condition of a larger effector.

A significant main effect on the percentage of time to peak velocity was

TABLE 1
MEANS AND STANDARD DEVIATIONS OF TARGET LOCATION AND EFFECTOR SIZE BY REACHING KINEMATICS ($N = 15$)

Kinematic Variables	Left Location Effector		Central Location Effector		Right Location Effector		Effector	
	Small	Large	Small	Large	Small	Large	Small	Large
Movement Time, sec.								
M	.49	.48	.45	.44	.45	.40		
SD	.03	.02	.03	.02	.02	.02		
Grand *M*	.49		.45		.43		.47	.44
Grand *SD*	.08		.09		.08		.10	.08
Peak Velocity, m/sec.								
M	1.37	1.62	1.35	1.73	1.56	1.87		
SD	.06	.06	.05	.05	.05	.05		
Grand *M*	1.50		1.55		1.11		1.43	1.74
Grand *SD*	.27		.26		.78		.23	.23
% Time to Peak Velocity								
M	39.73	40.87	35.69	41.46	31.03	36.19		
SD	1.42	1.07	1.81	1.78	.95	1.26		
Grand *M*	40.30		38.58		33.61		35.27	39.51
Grand *SD*	4.82		7.43		4.99		6.43	5.82

also obtained ($F_{1,14} = 15.99$, $p = .001$, $f = 1.07$, the power level $> .99$). When the effector became smaller, the percentage of time to peak velocity tended to decrease.

Effects of Target Location

Significant main effects of target location on movement time ($F_{2,28} = 4.52$, $p = .02$, $f = .57$, the power level $> .99$) and peak velocity ($F_{2,28} = 6.96$, $p = .01$, $f = .71$, the power level $> .99$) were found. *Post hoc LSD* analysis indicated that the left target produced longer movement time than the right one ($p = .01$). The left target engendered lower peak velocity than the right one ($p = .01$), and the central one engendered lower peak velocity than the right one ($p = .004$). The main effects of location on the percentage of time to peak velocity were significant ($F_{2,28} = 14.03$, $p < .006$, $f = 1.00$, the power level $> .99$). The interaction between effector size and target locations was addressed below.

Interaction Effects of Effector Size by Target Location

Contrary to our hypotheses, the interaction effects on movement time and peak velocity were not found ($F_{2,28} = 1.62$, $p = .22$, $f = .34$, the power level $= .69$; $F_{2,28} = 2.06$, $p = .15$, $f = .38$, the power level $= .78$, respectively). There was a significant interaction between the two independent variables in the percentage of time to peak velocity ($F_{2,28} = 11.67$, $p < .021$, $f = .91$, the power level $> .99$). For the conditions of a small effector, the left target location produced a greater percentage of time to peak velocity than the central one ($p=.007$), which, in turn, elicited a greater percentage of time than the right one ($p=.023$). However, for the conditions of a large effector, the left target location showed a greater percentage of time to peak velocity than the right one ($p=.001$) and the central one demonstrated a greater percentage of time to peak velocity than the right one ($p=.001$). The central and the left ones did not show significant differences in this kinematic variable.

Discussion

The findings of this study partially support our hypotheses. Effector size and task location had main effects on movement time, peak velocity, and the percentage of time to peak velocity. A significant interaction effect was found in the percentage of time to peak velocity. The findings support the notions that task constraints may modulate movement performance (Newell, 1986).

Effector size affected peak velocity and the percentage of time to peak velocity significantly but not movement time. The result for movement time is not consistent with the findings of previous studies (Fitts, 1954; Adam, 1992; Berthier, *et al.*, 1996; Bryden, 2000, 2002; Roy, *et al.*, 2000; Saoud, *et al.*, 2000) in which longer movement time was found when the target size was smaller, i.e., higher accuracy demands. One possible reason is that the participant may have used the palmar area rather than the finger tip to press the bell under the conditions of a large effector. If so, the average distance traveled by the hand using the palmar area for pressing the bell would be longer than that involving the finger tip, leading to longer movement time to finish the task for the former situation. The positive effects of using a larger effector were, therefore, washed out, and no significant differences in movement time were found.

The results associated with peak velocity and the percentage of time to peak velocity are consistent with the findings of previous studies (Adam, 1992; Berthier, *et al.*, 1996; Bryden, 2000, 2002; Garry & Franks, 2000; Roy, *et al.*, 2000). The condition of using the palm to press the bell induced lower peak velocity and a shorter deceleration phase, i.e., a greater percentage of time to peak velocity, than that of using the index finger. Peak velocity may reflect the force or impulse at movement initiation (Roy, *et al.*, 2000). Moreover, faster movements increased variability of movement, making the control of accuracy more difficult (Teixeira, 1999). The task using the palm represented an easier task with lower demands of spatial accuracy and may have elicited faster movements to home in the target. Reaching using the palm, thus, appeared to increase the impulse at movement initiation to achieve high peak velocity.

The percentage of time to peak velocity is related to the motor preprogramming and visual feedback utilization (Jeannerod, 1988). The task using the palm without emphasis on precise control is a skillful and well practiced movement for healthy adults. They may retrieve sufficient information about the location and orientation of the hand from the memory and previous experience to accomplish the task (Berthier, *et al.*, 1996), indicating such movements be executed largely in a preprogrammed or feedforward manner. In contrast, using the index finger to press the bell increased the demands of spatial accuracy. Participants employed sensory feedback control that primarily occurred in the deceleration phase to guide the hand to press the bell. Participants prolonged the deceleration phase to allow for updating the estimation of the object's position and location to correct movement errors (Adam, 1992; Berthier, *et al.*, 1996; Roy, *et al.*, 2000). Taken together, the movement with lower demands of spatial accuracy tended to be more preprogrammed and required a shorter deceleration phase. The movement with higher demands of spatial accuracy utilized visual feedback control, and a longer deceleration phase was needed.

These results are generally reminiscent of classical studies (Fitts, 1954; Adam, 1992; Berthier, *et al.*, 1996; Garry & Franks, 2000; Roy, *et al.*, 2000) but are of interest because the effects of spatial accuracy operationalized by increasing effector size in the present study are similar to those by increasing target size. This finding suggests that the effects of spatial accuracy might be generalized to a broader situation in daily life. For example, one might not magnify the size of the light switch but touch the switch with the palm instead of the finger tip to decrease the spatial accuracy requirement and attentional load.

In addition, there were main effects of target location on the three dependent variables. Movements using the right limb to the right target were completed more quickly and achieved higher peak velocity than those to the left target. These results are consistent with the findings of previous studies (Fisk & Goodale, 1984, 1985; Gordon, *et al.*, 1994; Carey, *et al.*, 1996; Roy, *et al.*, 2000; Carey & Otto-de Haart, 2001). Peak velocity might be more sensitive to the location effects than movement time because a gradient of the target location effect is more clearly seen in peak velocity than in movement time. The advantage of movements into the right side might result from the visuomotor transmission within one hemisphere. The information on the right target and the movement control of the right limb were processed primarily within the left hemisphere whereas the visual information about the left target has to cross the corpus callosum to reach the left hemisphere to generate and control the movement of the right limb (Jakobson, *et al.*, 1994; Velay, *et al.*, 2001). Nevertheless, the "within- vs between-hemisphere processing" hypothesis is not sufficient to explain the results. First, the proximal muscles of the upper extremity may be partly controlled by the ipsilateral hemisphere (Carey, *et al.*, 1996). Second, the right hemisphere is dominant for processing visuospatial information (Farne, Roy, Paulignan, Rode, Rossetti, Boisson, & Jeannerod, 2003; Haaland, *et al.*, 2004), especially in the coding of movement direction (Barthelemy & Boulingues, 2002). The reaching movements using the right limb onto the right target may not only involve the left hemispheric process but also, to less extent, the right hemispheric control including spatial information process and proximal muscle control. Third, the longer deceleration phase during the movements onto the right side than onto the left side could be better accounted for by the biomechanical characteristics of the movement. With the hand on a central starting position close to the body, the movements onto the right side, i.e., abductive movements, were much more parallel to the upper arm axis than those onto the left side, i.e., adductive movements. Movements in which the hand-path direction was parallel to the long axis of the upper arm have lower inertial loads than a more perpendicular hand path, which may require less time to achieve peak velocity, i.e., a longer deceleration phase, and engender shorter movement time and higher peak velocity for the former one (Gordon, *et al.*, 1994; Carey, *et al.*, 1996; Carey & Otto-de Haart, 2001). Our rightward and leftward movements provided a good approximation of "parallel" and "perpendicular" movement categories, respectively.

The interaction effect of effector size and target location was found in the deceleration phase, suggesting that sensorimotor process (feedback and feedforward control) and biomechanical factors confluence the movement execution under task constraints. There is a clear trend in the conditions of using the index finger to press the bell in that movements onto the left target produced a shorter deceleration phase than that onto the central one, which, in turn, elicited a shorter deceleration phase than that onto the right one. A similar trend was observed in the conditions of using the palm except that the leftward movement did not produce a shorter deceleration phase than the central one. One possible reason is that the tasks using the index finger required higher accuracy demands than those using the palm, leading to a longer deceleration phase for sensory feedback control in the former situation. In comparison with the tasks using the palm, there may be more room for shortening of the deceleration phase when the index finger movement is directed onto the left side.

In summary, this experiment was devised to examine whether constraints of effector size and target location affect movement performance and whether there is any interaction between these two constraints. One of the unique contributions of this study is to demonstrate that accuracy demands may be imposed not only by target size but also by the performer's effectors. Effects of effector size in the pressing a bell task might be a consequence of preprogramming the movement and processing the visual input within hemispheres. Location effects might be the consequences of both biomechanical and neurological factors. Further research on clinical populations such as patients with cerebral vascular accidents may improve the understanding of how task parameters constrain visually guided movements. Moreover, target location might not be restricted to the horizontal plane, as in the present study, and may be investigated in the vertical and radial dimensions. Continued research may study the kinematic profile of reaching for targets of various properties, e.g., size and orientation, as positioned at different planes with differential accuracy demands in neurologically intact and neurologically impaired populations.

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