DO MOVEMENT DIRECTION AND JOINT IDENTITY AFFECT THE SPEED AND ACCURACY OF SINGLE-JOINT MOVEMENTS?

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INTRODUCTION

Movement speed and accuracy are critical aspects of many sports skills. Throwing, catching, striking, kicking, as well as other manipulatory actions require balancing fast, forceful movements with spatial control of the limb to optimally direct an object. Similar trade-offs between speed and accuracy are necessary during movements that must be timed in relation to an opponent or to external cues. Research has shown that many skilled movement behaviors are characterized by such speed/accuracy trade-offs (SATs); as movement speed increases, spatial accuracy decreases (see Meyer et al., 1990 for a review).

In particular, numerous studies have shown one form of the SAT, Fitts Law or the logarithmic SAT, to be valid across a wide range of effector systems (Meyer et al., 1990). Typically, this is demonstrated by having subjects make repeated movements between two targets and doing a regression analysis which predicts movement time (MT) given Index of Difficulty (ID = log[movement distance / effective target width]). These same studies reveal that the regression parameters change depending on the effector system used. In other words, the slope and strength (as measured by R^2 values) of the linear relationship vary for similar speed/accuracy tests performed by different joints or combinations thereof.

Little research has been directed toward understanding what factors mediate these differences, however. This study is the first in a series which will explore this question by investigating whether such differences can be attributed to kinematic characteristics of the joint motions involved. Here we explore how the identity and direction of single-joint movements affect SATs.

Although clear performance differences have been shown across effector systems, few studies have related them to precise characteristics of the joint motion. The study most often cited in this regard compared SATs for tasks which primarily used finger, wrist or elbow movements (Langolf et al., 1976). The authors neither measured nor restricted the amount of joint motion however. Hence, it is impossible to determine the extent to which the observed performance differences depended upon the joint used.

A recent study by Balakrishnan & MacKenzie (1997) addresses some of these concerns. They compared SAT's for side-to-side movements of the index finger, wrist and elbow, as well as for forward and backward movements of a stylus held in a pincer grip, and side-to-side movements of a hand-held mouse. Splints were used to restrain the non-focal joints when testing finger, wrist and elbow motions. The magnitude of joint motion was estimated however, not measured. Results showed that index finger motion had a significantly larger slope (and hence, was less efficient) than the other motions, whereas the stylus motion was most efficient. Interestingly, the differences reported were nearly an order of magnitude smaller than those implied by Langolf et al. (1976).

Given the lack of data in this area, the present study is designed to more carefully examine the relative efficiency of several single-joint movements during a discrete aiming task.

METHODS

Three right-handed subjects performed a series of single-joint, aimed movements. The movements tested were wrist flexion/extension, elbow flexion/extension and shoulder horizontal abduction/adduction of the right arm. Motion at the other arm joints was restricted by splints, and by instructions to perform all movements within the horizontal plane of the table surface. Subjects began each movement at a designated arm configuration and moved a pointer to a target located so it coincided with a designated angular displacement of the focal joint. The same target position was used for all conditions.

Joint motion was measured using six active infrared markers positioned at the left shoulder, right shoulder, elbow, wrist, and on two parts of a hand-held pointer. Throughout each 3 sec trial, 3D positions of the markers were recorded in real-time using an Optotrak 3020 (Northern Digital) running at 100 Hz. The device had an accuracy of 0.3 mm in the plane where movement occurred.

Data from the plane of movement were used to display a stick figure of the arm, in real-time, via an active-matrix LCD data projector (Proxima 2810). The image was scaled to be the exact size of the actual arm and was about 2 m in front of the subject. The image was refreshed at least 30 times per second and there was no noticeable time lag to its motion. The designated starting arm configuration and target were also shown in the image, were always visible, and were not available on the table. Hence, the subject worked in a true-scale, virtual workspace.

Subjects participated in three sessions, one for each joint. During each session, they were tested in all combinations of the following conditions: 2 movement distances (20, 40 degrees), 3 target widths (0.5, 1.0, 2.0 cm radii), and 2 movement directions (flexion, extension). Subjects performed 20 consecutive trials of each condition, and the order of the conditions was partially counter-balanced across sessions.

Movement time, peak velocity, number of submovements, Cartesian movement distance and spatial errors were measured from each trial. The first three of these measures were determined through an off-line algorithm that monitored tangential velocity of the pointer (Meyer et al., 1988; States, 1994).

RESULTS

The first aim of our analyses was to determine whether logarithmic SATs were influenced by which joint was used or the direction of joint movement. To this end, regression analyses predicting MT given ID, Joint Condition (Wrist, Elbow, Shoulder), and Movement Direction (Flexion, Extension) were run. These were done separately for each subject to insure that results accurately reflected the performance of each individual. Data were mean MT's for each distance/target width combination.

As expected, MT depended significantly on ID for all three subjects. F values for the ID term for subjects 1, 2, and 3 respectively were: $F(1, 16) = 171.0$, $F(1, 16) = 29.0$, and $F(1,24) = 38.7$. All had probability values less than .001. In addition, for all three subjects, Joint Condition contributed significantly to predicting MT [$F(2, 16) = 28.4$, $F(2, 16) = 17.1$, $F(2, 24) = 15.8$; all with $p < .001$]. In contrast, Direction only approached significance for one subject [$F(1, 24) = 3.8$, $p = .06$] and was non-significant for the others. Hence, ID and Joint Condition influenced MT whereas Movement Direction did not.

Figure 1 shows an example of these effects for Subject 1. The circles, triangles and plus signs represent the wrist, elbow and shoulder data respectively. Regression lines for each joint are given by the solid, dashed, and dashed/dotted lines. For all three subjects and as illustrated here, the intercept was greatest for the shoulder and least for the wrist. No systematic pattern in the slopes was evident across subjects.

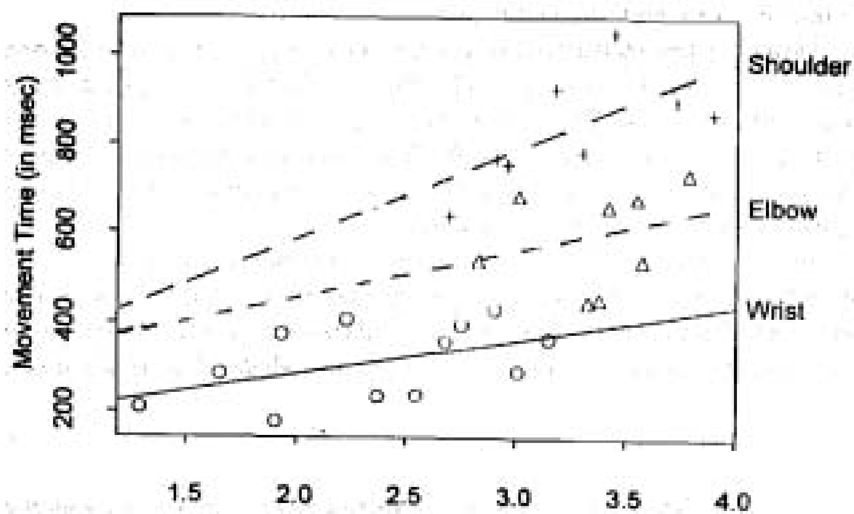

Figure 1 - Logarithmic Speed/Accuracy Trade-offs at Each Joint.

DISCUSSION

Results demonstrate that SATs vary for single-joint wrist, elbow and shoulder movements, and that joint identity contributes significantly to predicting MT, even when ID is accounted for. These findings extend previous work which demonstrates that SAT's vary depending on which effector system is used to perform the task. Our results suggest that those effects are due, at least in part, to which joint(s) are involved in the movement. They offer the possibility that more precise estimates of MT may be possible if a factor giving the identity and magnitude of joint motion is included along with ID in a SAT regression equation.

Our results show some agreement and some differences with previous work. As in Langolf et al.'s study (1976), differences were evident between effector systems, with the larger effector systems (shoulder vs. wrist in this study; arm vs. fingers in Langolf's study) generating slower MTs. Both of these findings can be explained by a common argument about the role of inertia in movement control (Rosenbaum et al., 1991; Gordon et al., 1995). It suggests that movements which cause more massive body segments to move will be performed most easily at a slower pace than movements which cause only lightweight segments to move. Extending this argument to SAT's, if movements that must overcome large inertial forces are difficult to control, then that effector system may also be difficult to move quickly and accurately. Slower MT's for the shoulder than for the elbow, and for the elbow than for the wrist, as found here, support this argument.

Our results and those of Langolf et al. (1976) also differ from the one study that specifically compared SATs for single-joint movements (Balakrishnan & MacKenzie, 1997). The only significant difference those authors found was that abladduction of the index finger yielded slower MT's than did wrist abladduction or side-to-side movements of the forearm (which were presumably generated by rotation about the long axis of the humerus). This is especially interesting since the slowest effector system was the one moving against the least inertial resistance, and it suggests a problem with the inertial control argument. Clearly the strength and structural suitability (insertion point, angle of pull, joint range of motion, etc.) of the involved muscles will also influence how easily a particular joint can be controlled. The limited number & size of muscles around the index finger, their less than ideal insertion points for abladduction, and the joint's limited range of motion in that direction may make index finger ab/adduction especially difficult to control. Whether this is an unusual exception that "proves the rule," or a typical finding awaits further investigations. These must be designed to compare SAT's while clearly controlling and measuring joint motion. In lieu of additional contradictory evidence, our results support the inertial control argument.

One other aspect of our results may differ from those of Langolf et al. (1976) and Balakrishnan et al. (1997). We found no clear differences in the slopes for the different joint movements. One reason the other two studies may have seen these where we did not, is that they did their analyses on data averaged across three subjects. By using within-subject analyses, we require the same significant differences to show up in each individual's data in order to identify a pattern, a more rigorous test. One argument in favor of this interpretation is that we saw some tendencies toward differences in slope, especially between the wrist and shoulder. To address this issue, we plan to continue these investigations by looking at additional subjects, and perhaps additional distance/target width conditions.

CONCLUSIONS

We have demonstrated that for discrete, single-joint, aimed movements the joint used will influence the speed/accuracy trade-off obtained. We found no evidence to suggest that direction of joint motion had an effect. These results support work of Langolf et al. (1976) and Rosenbaum et al. (1991) which implies that joints which move against the least inertial resistance will be able to move more quickly than joints feeling a large inertial resistance.

Our findings suggest that the differing efficiencies of various multi-joint movements may depend, at least in part, on the identity and magnitude of the joint motions which contribute to the movement. This offers the possibility of predicting which patterns of joint coordination will lead to the best SAT's, and hence, of optimizing a wide variety of skilled motor activities.

Additional work is needed to investigate whether slopes differ reliably for different joints, whether the observed effects are common to joint motions other than those tested here, and the extent to which the observed effects are evident within the context of multi-joint movement. A related series of studies is planned to address these questions.

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