Force Control and Its Relation to Timing

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ABSTRACT. Previous work (Keele & Hawkins, 1982; Keele, Pokorny, Corcos, & Ivry, 1985) has suggested two general factors of coordination that differentiate people across a variety of motor movements, factors of timing and maximum rate of successive movements. This study provides comparable evidence for a third general factor of coordination, that of force control. Subjects who exhibit low variability in reproducing a target force with one effector, the finger, tend to show low variability with two other effectors, the foot and forearm. In addition, ability in force control cuts across different force ranges and across situations where force control is either the primary goal or the secondary goal. Force records obtained during a periodic tapping task show that, although force control is largely independent of timing, there are some interactions between the two factors. Force variation appears to distort timing a small amount in part because larger forces speed up implementation of movement, thereby shortening preceding intervals and lengthening following ones, and in part because force variation alters central-timing mechanisms.

DO PEOPLE DIFFER from one another in general factors of coordination? In previous work (Keele & Hawkins, 1982; Keele, Pokorny, Corcos, & Ivry, 1985), we suggested that the maximum rate of repetitive movements and timing control might be two general factors of coordination. In this study, we investigate a similar issue with respect to force control. In addition, the interaction between force control and timing control is examined.

While it appears intuitively clear that some people are more coordinated than others, little research has supported such a view. In an analysis of much literature devoted to the problem, Marteniuk (1974) concluded that success in one skill seems not to predict success in another. Moreover, there is little evidence that specific underlying abilities predict skill. A similar viewpoint emerged from factor analytic work

by Fleishman (1966), which showed that as people become more skilled, task specific factors become more important and general factors decline in importance. The view that coordination is task specific is congenial to conclusions arising from the analysis of many cognitive skills. It has been argued, for example, that chess skill (Chase & Simon, 1973) and memory skill (Ericsson & Chase, 1982) arise largely from extensive learning in which the player acquires a huge repertoire of recognizable patterns. In the motor domain, Allard, Graham, and Paarsalu (1980) found that advanced basketball players have acquired specialized knowledge about particular patterns that allows them to more easily encode positions of the players around them.

Despite the clear evidence that specific knowledge gained from practice is of paramount importance in skill, still it is possible that general coordination factors constrain the degree of skill attainable with high levels of practice. Our previous work suggested that maximum rate of repetitive movement and precision of motor and perceptual timing are such general factors. Keele and Hawkins (1982) reported that the maximum rate at which one can repetitively tap is correlated at .5 or more across such diverse effectors as finger, thumb, wrist, forearm, and foot. Keele, Pokorny, Corcos, and Ivry (1985) showed that motor timing accuracy correlated across finger and foot. Moreover, motor timing in tapping correlates with the ability to judge the durations of intervals between brief perceptual events, suggesting that timing ability is at least partly common to production and perception.

These factors of maximum rate and timing may constrain the ultimate level of performance in highly practiced skills. Book (1924) found that champion typists could tap repetitively considerably faster than control subjects, even when muscle groups minimally involved in typing are used. He also demonstrated a correlation between tapping speed and attained speed in a college typing course, suggesting that sometimes ultimate limits begin to manifest themselves even prior to final skill levels. Importantly, experience in typing did not itself increase tapping speed. In our own work (Keele, Pokorny, Corcos, & Ivry, 1985), professional pianists were significantly faster in finger tapping, less variable in timing of both finger and foot, and more acute in judging the relative durations of perceptual events than were nonpianist control subjects.

Our study investigates a third factor of coordination, that of force control. One question asked is whether the ability to control force is related across different effectors; in this case, index finger, forearm, and foot. Subjects were asked to produce a given force on a force key with one of the effectors. After a few force pulses with feedback, they were asked to produce several more pulses of the same force without feedback. The variability of the peak forces over the pulses without feedback constitutes the measure of force control. We call this task the untimed force task. Thus, the question is reduced to whether or not the variability of force correlates across effectors. Positive evidence would provide support for a general factor of force control.

A major goal in our overall series of studies has been to determine whether different modular systems of the brain control different features of motor production—with one module controlling force, and some other set of factors actions, another module controlling force, and some other set of factors (if not an actual module) setting maximum rates. The problem is compli- cated because, although the systems may be largely independent, still overt manifestations of the processes may interact. Suppose that while attempting to tap at even time intervals there is some random variation in force. If by chance a particular tap was performed with larger than normal force, the effector, say the finger, might travel more rapidly and the tapping key would be pressed early. This random variation in force would tend to shorten the preceding time interval. Assuming that the central timing of the next tap is unaltered, this higher than normal force would also lengthen the following interval. In other words, there should be a negative correlation between force on an individual tap and the length of the interval that precedes it and a positive correlation between force and the length of the following interval. Put another way, force and time could interact at a rather peripheral level.

To study the interaction of force control and timing, the first experiment of this study includes another condition in which the subjects' task is to produce timed taps without having a particular force target. The force of every tap is measured in order to correlate forces of individual taps with preceding and following time intervals. We call the force measurements in this condition timed force to differentiate them from force variability in the untimed condition. Besides correlating force control with time con- trol, correlating force control in the untimed condition with force control in the timed condition allows further exploration of the generality of any force factor across conditions in which its priority is varied.

The third experiment examines a second facet of the interaction be- tween force and time. Whereas, in the first study, the influence of ran- dom variations in force and their effect on timing is studied, the third study investigates how deliberate alterations in force of a movement af- fects the timing of movement. Subjects are asked to tap a rhythm in which periodic taps are accented with a heavier force. The question of interest is whether such force alterations also effect timing. Again the issue is to examine the degree to which force and time emanate from different modules.

Experiment 1

Subjects in this study performed three different tasks, each with fore- finger and forearm. One task, which we call untimed force, involved producing target forces in response to an auditory signal by pressing on a button connected to a strain gauge. The second task, called timed force, involved responding on the same apparatus in synchrony with a pace tone that occurred every 400 ms. After synchronization, the pace tone disappeared and the subject attempted to press the response but- ton at the same pace. The onset-to-onset times of the presses were used

to determine the degree of timing variability. In addition, the maximum force of each press was recorded to determine the timed force variability. The third task required the subjects to repetitively press a key as rapidly as possible to determine their maximum rates of movement. Correlating performance on each task between finger and forearm yields an indica- tion of whether force control, timing control, and maximum rate are general factors of coordination. Correlating performance between tasks assesses the interaction of the three factors.

Method

Subjects. Twenty-nine young, right-handed adults were paid to serve in two sessions of the experiment.

Apparatus and procedure. In the untimed force condition, subjects made isometric presses on a button (1.5 cm diameter) that was con- nected to a strain gauge (Grass Model FT100 force transducer). Presses were made with either the right forefinger or the right forearm. For finger presses the tip of the finger rested lightly on the key. When sub- jects heard a tone, they produced a force pulse with a single flexion- extension movement of the extended forefinger. The forearm and palm rested on a surface to restrict movements other than of the finger. For forearm movements the subject curled the fingers into a half-closed fist and rotated the wrist so that the lateral surface of the metacarpophalan- geal joint rested on the key. The subject made pressing movements by a slight extension-flexion pulse of the forearm about the elbow. Although it was possible to also move the wrist, subjects were asked not to. A horizontal line on an oscilloscope screen signified one of five target forces of 3.0, 5.1, 7.0, 9.6, and 10.8 N (corresponding to masses of 310, 525, 720, 980, and 1100 g). At the sound of a tone, subjects made a single force pulse. A threshold force of approximately 0.1 N was used to indicate movement onset. A vertical line with height proportional to the produced force was then shown on the screen. An accurate force would show the vertical line terminating on the horizontal target line. After six such force pulses, the feedback and horizontal target line were re- moved for six remaining pulses for which the subject attempted to pro- duce the target force. During this phase, an interval of either 750, 1000, or 1250 ms transpired between one response and the next tone. Ran- domization of intervals prevented the subject from getting into a rhythm of presses. The standard deviation of force produced when feedback was absent was the primary dependent measure. There were 10 bouts of six pulses of each target force for each effector distributed over the two sessions.

In the timed force task, a pacing tone occurred every 400 ms. Subjects pressed the key in the same manner as for the untimed force task, but in this case they attempted to synchronize the press with the tone. The tone ceased after 12 taps, and the subject continued to tap out the target interval for 30 more taps. The standard deviation of the intertap interval was the primary measure of timing precision. Although subjects were

not instructed to use any particular amount of force other than staying within the bounds of the strain gauge, which accepted a maximum force of 14 N, the force on each tap was also measured. The standard deviation of the force over the 30 taps without the pacing tone is called timed force variability. Over the two sessions each subject produced 30 such trials of 30 taps each with both finger and forearm.

In the third task, subjects tapped as rapidly as possible on a microswitch key with either finger or forearm for bouts of 4 s. In this case, the finger or side of the hand was kept in contact with the key, but the key traveled a short distance of 1.5 mm, and it made a barely audible click and a distinct tactual feel each time it was pressed. Over the two sessions, each subject had 12 bouts of speeded taps for each of finger and forearm (two additional bouts during each session served as warmup).

Each subject performed each task on each day, and the order of the tasks was the same for each subject to ensure that differences in performance of subjects across tasks were not due to differences in test order. Across the two sessions task order was counterbalanced.

Results and Discussion

Force control. Our primary interest in this study is with the correlations among the various dependent variables. However, it is of subsidiary interest to know how force variability depends on target force. Work by Schmidt, Zelaznik, Hawkins, Frank, and Quinn (1979) showed
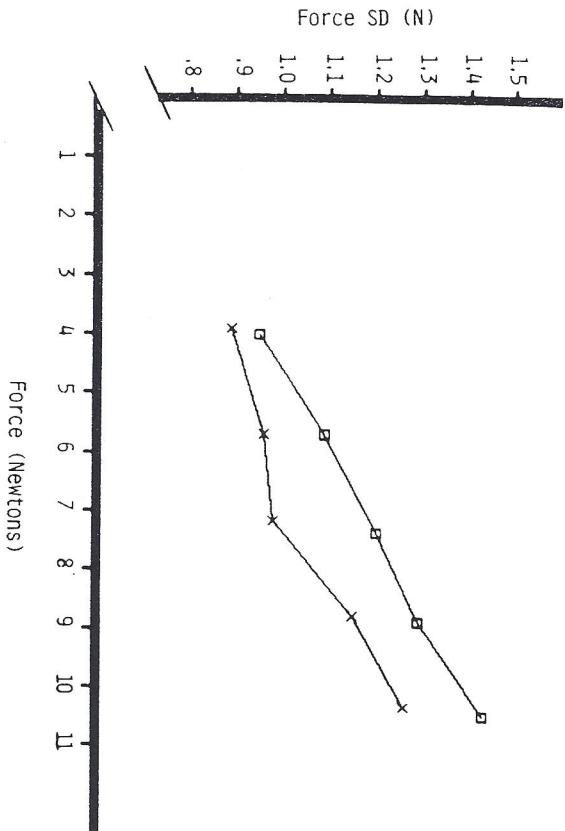

Figure 1. The relation between the standard deviation of produced forces and the mean produced force for five different target values and for finger (Xs) and forearm (boxes).

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a linear relation between the standard deviation of forces produced and the target force being attempted. Figure 1 shows the relation between standard deviation of force and target force for the untimed force condition of this study. As shown in the Schmidt et al. study there is a reasonably linear relation between the two variables.

Table 1 shows the correlations of primary interest from this study. The variability of timing, variability of timed and untimed force, and the mean intertap interval in the maximum rate task were averaged over data from both sessions for each effector, finger and forearm, and for each subject. Also, the standard deviations for the five force targets were averaged. These mean scores were then correlated across the 29 subjects. For 29 subjects, correlations above .32 are significant by a one-tailed test at the .05 level of confidence; correlations above .38 are significant at the .025 level.

Consider first the correlations among the different conditions of force control. The correlation between untimed force variability of the finger with that of the forearm is .76. An identical value is found for timed force between finger and forearm. Timed and untimed force variability correlate with each other about .4 in the different combinations. Results correlate with each other about .4 in the different combinations. If force variability is averaged over finger and forearm, the timed and untimed force variability correlated .43 (not shown in Table 1). Taken together these correlations suggest considerable commonality in force control across effectors and some commonality across conditions in which force is deliberately controlled or not. As such, force control appears to be a factor of coordination on which people differ.

A potential problem to consider in assessing the correlations among the force variability scores is whether they might be explained by some

Table 1
Correlations Among Speed, Time, and Force

		Timing Variability		Maximum Rate		Untimed Force var.		Timed Force var.
		Finger	Finger, arm	Finger	Finger, arm	Finger	Finger, arm	Finger
Timing var.	Finger	<u>.92</u>						
	Arm	.90	<u>.91</u>					
Maximum rate	Finger	.20	.31	<u>.88</u>				
	Arm	.11	.24	.69	<u>.95</u>			
Untimed Force var.	Finger	.30	.34	.10	.26	<u>.87</u>		
	Arm	.18	.21	.00	.09	.76	<u>.76</u>	
Timed force var.	Finger	.35	.43	.11	.04	.39	.42	<u>.68</u>
	Arm	.37	.42	-.06	-.21	.40	.33	.76	<u>.82</u>

Notes. $r > .32$, $p < .05$. $r > .38$, $p < .025$.
Underlined values are reliabilities based on Session 1 vs. Session 2 correlations.

differential strategy across subjects. One possibility is that some people rise more rapidly from the onset of the force pulse until peak force is achieved than do other people. Perhaps such differences in rise time affect the variability of peak force, the primary measure of interest. For untimed force, the correlations between time to peak force and peak force were very small and nonsignificant, ranging from –.05 to –.20. Thus, for untimed force, the correlation between force variabilities of finger and forearm cannot be explained by different strategies across subjects in time to peak force. For timed force, however, when data of finger and forearm were first averaged and then correlations computed, time to peak force correlated .49 with variability of force. This correlation, while sizeable, is not as large as the .76 correlation between force variabilities of finger and forearm. Thus, in both the timed and untimed tasks, the force variability correlations cannot be accounted for, at least in their entirety, by differences among subjects in time to peak force.

Relation of force control to timing. Consistent with the work of Keele, Pokorny, Corcos, and Ivry (1985), timing control correlates across effectors. In the timing condition of this study, subjects pressed on the response key at regular intervals. The measure of timing variability was the standard deviation, averaged over sessions, of the intertap intervals taken from those periods after cessation of the pace tone. Table 1 shows the correlation between finger and forearm timing to be .90, a figure considerably higher than between finger and foot timing, which was about .45 in the Keele et al. study. Taken together, the two studies suggest considerable commonality among the timing mechanisms of differing effectors.

One factor that could influence the variability of intertap intervals is variation in force. A larger force command from the central nervous system might actuate the muscles more rapidly than a smaller force command, resulting in variation in the time of actual key press. It would be expected, therefore, that people with larger force variation would also show larger time variation. Table 1 shows moderate correlations of about .4 between timing variation and force variation in the timing task, giving support to the prediction. However, variation of force in the untimed condition fails to correlate significantly with timing variation.

The relation between force and timing can also be examined by relating tap-to-tap variations of force with tap-to-tap variations in interval length. Figure 2 shows the correlations between force of a tap and interval lengths that occur before or after a tap by varying amounts. Lag 0 corresponds to the correlation between force of a particular tap and the interval just preceding it. Negative lags concern correlations between force of the tap and earlier intervals, and positive lags concern the relation between the force of a tap and later intervals. The correlations for both negative lags and positive lags beyond 1 are near zero, but there is a small correlation of about –.10 between force and time at Lag 0 and a correlation of .15 at Lag 1. This pattern is as predicted but the correlations are extremely small. Momentary variations in force account for only about 1–2% of the momentary variations in time. Despite their
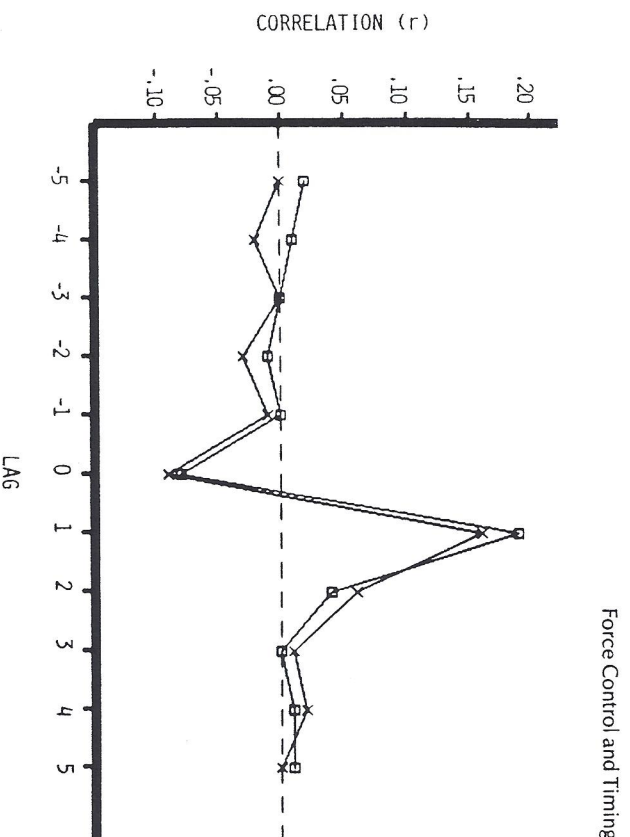

Figure 2. Correlation of individual tap forces with the duration of the preceding and following intertap intervals. Lag 0 corresponds to the correlation between tap force and the duration of the interval terminated by onset of that tap. Lag 1 corresponds to the relation between force and the interval initiated by that force tap. Xs are for the finger and boxes for the forearm.

small size, the correlations are statistically significant because of the fact that they are based on 900 taps per subject for each finger and forearm of 29 subjects.

There is an apparent discrepancy between the magnitude of the correlations in the tap-to-tap analysis and the relation of overall force variation in the timing task to timing variation. The latter is considerably larger than the former. One reason for this is revealed in Figure 3. This figure shows the autocorrelation function of force of taps separated by varying numbers of intervening taps. The Lag 1 autocorrelation refers to the correlation of forces of adjacent taps. The Lag 2 refers to the correlation of the forces of taps separated by one intervening tap; and so on. This figure shows sizeable correlations between successive forces—that is, if one tap involves relatively large force, then following ones tend to be large also. This lack of independence of successive forces would tend to reduce the correlation of force with adjacent time intervals as portrayed in Figure 2. A randomly large force would cause a response to occur early, but if, because of the positive correlations among nearby forces, the preceding force was also large, the tendency to shorten the preceding interval would be weakened, because the preceding response would also have tended to be early.

A final analysis on the relation between force variation and timing variation makes use of a theory of timing developed by Wing (1980) and

Wing and Kristofferson (1973). The theory postulates that variance of intertap intervals comes from the additive influence of two separable sources. One source is variance in a clock, and the other source is variance in the duration of implementing once the timer gives the command to move. The theory implies that while both clock and implementation influence total variance in timing, variance in implementation time also introduces a negative correlation in the duration of successive intertap intervals (cf. Wing, 1980, for details of the model and a summary of data favoring the theory). The magnitude of the covariance of successive intervals serves as an estimator of the implementation time variance. Because implementation variance and clock variance sum to produce total variance of the intertap intervals, clock variance can be estimated by subtracting the implementation variance from the total variance.

Our preceding analysis has suggested that variation in force would induce a tendency for long intervals to be followed by short ones and vice versa. Since the negative correlation of adjacent intervals serves as the estimator of implementation variance in the Wing model of timing, it follows that people more variable in force should also have higher implementation variance. To test this prediction, more stable force and timing variance estimates were derived by first averaging the finger and forearm variances. Contrary to expectation, force variation in the timed task correlates more highly with clock variance ($r = .47$, $p < .01$) than

with implementation variance ($r = -.08$, ns). One reason for not finding a correlation of force variance with implementation variance may be that force variance is small compared to the total force range that muscles are capable of producing. Such small variations may produce negligible differences in muscular activation times, and any such correlation between force variation and timing variation appears to be due only in small part to variation in implementation time. A major part appears to be due to a more central interaction of force and time.

Relation of timing and force control to maximum rate of movements. In earlier studies (Keele & Hawkins, 1982; Keele, Pokorny, Corcos, & Ivry, 1985), it was found that the maximum rate at which people could repetitively move was correlated across different effectors. That observation is confirmed here: Mean intertap interval at maximum rate is correlated across subjects between finger and forearm at .69 (see Table 1). The Keele et al. study also found that timing variation was correlated with maximum rate. People who were more variable in timing tended to be slower in their maximum rate. An explanation of the result is that as one approaches the maximum speed at which the muscles can be contracted, any mistiming of the onsets and offsets of the agonist and antagonist muscle activity will cause the reciprocation rate to be less than what could be achieved with perfect timing. Though the correlations between maximum rate and timing in this study are in the correct direction, they are small and not statistically different from zero. The relation between speed and timing could use further replication to determine whether or not there is a reliable connection between maximum rate and timing variability. Also, in this study there are no significant correlations between maximum rate and force control.

Summary

The ability to control force with finger movement is correlated with the ability to control force with forearm movement. Moreover, force control, when such control is the object of intent, correlates with variations in force when timing control is primary and force control is incidental. These observations suggest that a factor of force control, general to more than one effector, differentiates people.

People also differ from one another in their precision of timing repetitive movements. One minor factor that influences timing precision is force variation. People that are more variable in force during a timing task also tend to be more variable in timing. This relation is largely one between a clock component of timing and force control. However, a microanalysis of tap-to-tap forces and times suggests that there is also a very small relation between force variation and the variation in implementation component of timing such that a randomly large force tends
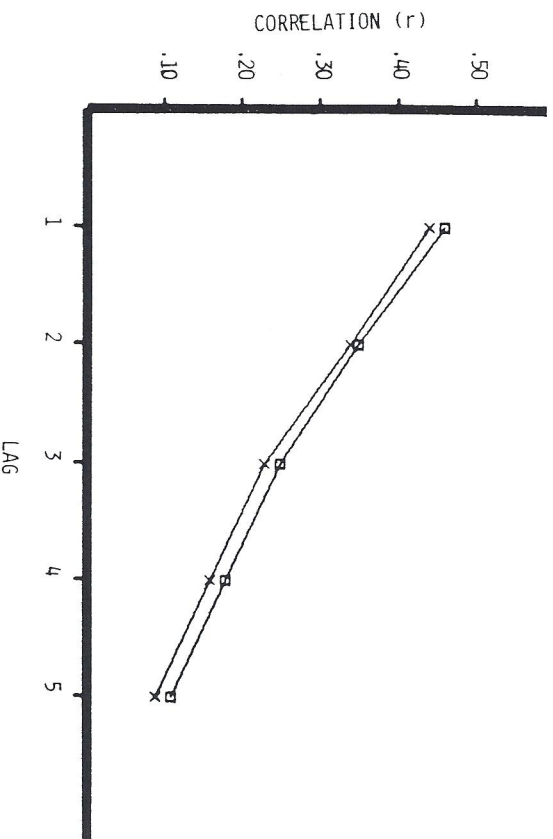

Figure 3. Autocorrelation function of the force of successive taps. The Lag 1 correlation portrays the relation between the magnitude of one force pulse and the magnitude of the next force pulse. The Lag 2 correlation is between forces separated by two intervening intervals. Xs are for the finger and boxes for the forearm.

to shorten the preceding interval and lengthen the following interval. The reverse is true for small forces.

Experiment 2

The first experiment showed that variability of force control was correlated between forefinger and forearm. Regardless of which effector was used, the same force levels were required. The second experiment explores the generality of a force control factor. Subjects in this experiment produced untimed force pulses with either the forefinger or the foot. The force range for the foot was considerably higher than for the finger.

Method

Subjects. Twenty-nine right-handed young adults from the University of Oregon subject pool were paid to participate in the experiment. None had participated in Experiment 1.

Apparatus and procedure. The same apparatus and procedure as used for the force measurement portion of Experiment 1 was used. The force targets for the forefinger were 5.1, 6.1, 7.0, and 7.8 N. For the foot, the target forces were 14.7, 16.9, 19.2, and 21.1 N. For the forefinger the presses were made as before with the tip of the finger always in contact with the isometric force key. For the forefoot, subjects wore socks and rested the balls of their feet on the force key. For each effector subjects made six responses per trial with feedback followed by six responses without feedback. There were five trials for each target force in each of two sessions.

Results and Discussion

The standard deviations of force for the six force pulses without feedback of a given trial were averaged over all force levels and all trials of both days for the finger and the foot. For the finger the force variability averaged over all subjects was 1.5 N; for the foot it was 4.9 N. The correlation of variability of the foot with variability of the finger across subjects was .73, a value near that found between finger and forearm in Experiment 1. The Session 1-Session 2 reliability of force variability for the finger was .91 and for the foot it was .89.

The results of Experiment 2 extend the conclusions of Experiment 1 in suggesting a factor of force control that is rather general. People who are relatively good at producing the same force on repeated occasions with one effector tend quite strongly to be good with another effector. Experiment 1 found such to be the case when comparing finger and forearm, and the second experiment found similar results when comparing finger and foot. Second, such force control appears to be general across a considerable range of force. In Experiment 1, the force ranges for finger and for forearm were equal. The forces were small, requiring rather delicate control for the forearm compared to the finger, given the much greater strength and mass of the forearm. Nonetheless, subjects'

abilities to control force were highly correlated across effector. In the second experiment, the force requirements were different for foot and finger, being considerably higher for the foot, but perhaps more comparable in relation to strength of the two effectors. Again, subjects' abilities correlated highly across the effectors.

Experiment 3

Experiment 1 found small to modest correlations between force variation and timing variation in a situation where constant timing was the primary goal. The purpose of the third experiment was to examine the influence of deliberate alterations in force, made to accent periodic taps, on timing variation. Such deliberate force alterations are larger in magnitude than chance variation in force and may, therefore, result in a larger interaction between force control and timing. Subjects were instructed to repetitively tap out a pattern of two short intervals followed by an interval that was twice as long. Subjects were instructed to produce an accent at one of the three tap positions within each cycle of the pattern by making a stronger press on the force key. In a fourth condition, subjects attempted to produce an unaccented pattern by responding with equal force at each position. The question of interest asked how accent position influenced interval duration. If the effect of increased force is to shorten the duration from the central emission of the command to press to the onset of the press, then it would be expected that an accent would decrease the duration of the preceding interval, because the response would occur relatively early, and increase the length of the following interval. However, Experiment 1 found that much of the correlation between force variation and timing variation was due to interactions more central than the implementation stage of movement. As will be seen, a similar conclusion emerges in the current experiment.

This experiment is essentially a replication of an unpublished thesis by Greim (1983), with the only notable difference being that in this study subjects made isometric responses on a force key, rather than moving their fingers, and the forces of the actual pulses were measured.

Method

Subjects. The subjects were 12 young adults drawn from the Cognitive Lab Subject Pool at the University of Oregon and paid for their participation.

Apparatus and procedure. The basic apparatus was the same force transducer as in the first two studies. All responses were made with the right hand. Subjects sat with their forearm and palm resting on a platform and the tip of their index finger on the button atop the force transducer. At the beginning of a condition the subjects were informed which position in the pattern was to be accented. They then listened to a temporal pattern of 50 ms duration clicks. The intervals between onsets of successive clicks in a cycle were 400, 400, and 800 ms, and the accented click was played at a louder volume. The three intervals cycled

repetitively for a total of five times. Subjects synchronized finger presses on the force key with the clicks, making a more forceful press, not to exceed 9.8 N, for the accented position. After the fifth cycle, the clicks disappeared and subjects continued to tap the intervals without reference to the pace signals for another 10 cycles, ending with the long interval (the last interval was excluded from data analysis). Feedback, which was provided at the end of each trial, conveyed the average force produced at each interval and the number of responses, if any, which exceeded the allowable force of 9.8 N. No feedback on timing was provided, since we didn't want subjects to adopt strategies of adjusting times based on feedback.

Altogether there were four accent conditions. Five good trials were obtained for each condition on each of four runs. Trials in which a produced interval differed from the target by plus or minus 50% were rerun. The four bouts of the four conditions were counterbalanced by a four by four latin square design over the course of a session, and the order of conditions was counterbalanced across subjects, also with a latin square design. The experimental session took one to one and a half hours and altogether involved 20 bouts of 10 cycles through the pattern for each condition and each subject.

The four accent conditions required the subject to (a) attempt to make each press the same in force, (b) make the presses at the end of the long intervals more forcefully than the others, (c) make the presses after the first of the short intervals more forcefully, and (d) make the presses that divided the short intervals more forcefully. The only restrictions on force were that the accented press be made more forcefully was that no press could be more than 9.8 N.

Results and Discussion

Before examining the effects of accent position on intertap intervals, it first is useful to present evidence that accents varied by condition. Table 2 shows the mean peak force with which the force key was pressed as a function of accent position. The control condition showed little variation in force with tap position as would be expected given instructions to produce each tap as evenly as possible. The other three conditions showed the accented position to receive a higher force. The unaccented positions showed about the same force as in the control condition. Every one of the 12 subjects showed the pattern exhibited in the means with one exception: One subject failed to produce more force on the accent position that fell between the two 400 ms target intervals.

Although subjects were instructed to make accents with larger force pulses, it also turned out that the accented position received a longer duration force pulse (see Table 2). Again, every subject showed the effect except for the one subject who failed to produce a stronger force in the intended position when the accent was to split the two short intervals. Another measure, which will play a role in subsequent interpretations, is the time from the beginning of the force pulse to reach max-

imum force. The mean results appear in Table 2 where they are seen to mimic the effects of pulse duration: It takes longer to reach peak force the larger the force applied. The last row of Table 2 shows the ratio of the time to reach peak force to the total press time. The ratio is remarkably constant across conditions, being about .42.

The question of primary interest concerns the effects of accent position on the intertap intervals (see Table 3). The expectation based on the idea that force affects implementation time was that an accented tap would lead to a shorter than normal preceding interval and a longer than normal following interval. The data presented in the top two rows of Table 3

Table 2
Peak Forces, Key Press Durations, Time to Peak Force, and Ratio of Time to Peak Force to Key Press Duration (Experiment 3)

	No accent			Accent 1			Accent 2			Accent 3		
Target interval	400	400	800	400	400	800	400	400	800	400	400	800
Force (N)	4.6	4.4	4.8	8.6	4.5	4.3	4.6	8.6	5.3	4.4	4.2	8.8
Press duration (ms)	182	178	187	235	176	178	176	220	193	175	165	245
Time to peak force (ms)	79	75	80	106	74	74	74	95	82	76	71	107
Peak time/duration ratio	.43	.42	.43	.45	.42	.42	.42	.43	.43	.43	.43	.43

Table 3
Mean Onset-to-Onset Intertap Intervals (Unadjusted for Cycle Length), Standardized Intertap Intervals (Adjusted for Cycle Length), Mean Peak Force-to-Peak Force Intertap Intervals (Unadjusted), and Peak-to-Peak Standardized Intervals. All in ms (Experiment 3)

	No accent			Accent 1			Accent 2			Accent 3		
Target interval	400	400	800	400	400	800	400	400	800	400	400	800
Mean interval	400	398	811	448	398	748	392	427	796	387	389	800
Standardized interval	398	396	806	450	399	751	388	423	789	393	395	812
Peak-to-peak interval	396	403	810	416	398	780	411	414	790	362	425	769
Peak-to-peak standardized interval	394	401	805	418	399	783	407	410	783	388	431	781

Note. For Accent 1 the accented press ends the 800 ms interval and starts the first 400 ms interval. For Accent 2 the accented press divides the two 400 ms intervals. For Accent 3 the accented press ends the second 400 ms interval and starts the 800 ms interval.

show such to be the case in two accent conditions, but only marginally in the third condition in which the accent preceded the long interval. The top row shows the mean intertap intervals averaged over all subjects. If a total tap cycle were veridical in time, it would take 1600 ms. However, on the average some of the conditions took slightly more than 1600 ms and some took slightly less. To facilitate comparison of conditions, the second row shows standardized intertap intervals with each interval adjusted proportionally to achieve a total cycle time of 1600 ms. All statistical tests are based on the standardized intervals.

When the accent falls on the taps that close the long interval and begin the first short interval (Accent 1), the long interval is shortened and the first short interval is lengthened beyond that for the control condition. Eleven of twelve subjects show both effects ($p < .01$ by a two-tailed binomial test). The one subject who does not is the subject mentioned above who did not produce the proper accenting in another condition. This subject produced an accent at the designated point in this condition, but the increase in force was considerably smaller than that of any other subject. The remaining interval shows little change from control to accent as might be expected because it is not bordered by an accent.

When the accent falls on the tap between the two short intervals (Accent 2), the preceding interval again is shortened relative to the no accent condition but in this case for only 8 of 12 subjects ($p > .05$ by a binomial test, but $p < .05$ by a two-tailed t test). The following interval was lengthened for 10 of 12 subjects, $p < .05$. The remaining long interval, which was not bordered by an accent, nonetheless was shortened by 9 of 12 subjects.

The Accent-3 condition in which the accent falls between the second short and the long intervals shows virtually no effect on the short interval and only a small one on the long interval. However, neither interval is significantly different from the control condition.

Overall it appears that accenting decreases the length of the preceding interval and increases the following one, although other effects seem to be operating because the general phenomenon is clearly found in only two of the three accent conditions. A possible reason for at least part of the shortening of the preceding interval and lengthening of the following interval is that when a central command is issued to press, the muscular forces are mobilized more rapidly the stronger the force. This would cause the press to be actuated sooner, shortening the preceding interval. If, however, the timing system is unaltered, then the command for the succeeding response would be given at its normal time, and assuming that the mobilization time for its response was normal, the interval since the onset of the last response would be increased since the last response had occurred early.

Although the onset of a more forceful movement may begin early, it is possible that the peak force is intended to occur at the target time. The data in Table 2 show that it takes longer to reach peak force for the larger accented forces. The intertap intervals can be recalculated to be

based not on the onset times at which the force first crosses threshold but on peak-to-peak times of successive presses. The mean intervals are shown in the third row of Table 3. Again, the mean duration of the total cycle time varies a bit from the target 1600 ms in the various conditions, so the fourth row of the table shows standardized scores with each interval adjusted proportionally so that the total adds to 1600 ms per cycle. For the first two accent conditions, there is some muting of the overall effect of accent when peak-to-peak intervals are compared to onset-to-onset intervals. This lends some credence to the view that part of the effect of increased force is to alter the duration of motor implementation. Still, residual effects of accent on peak-to-peak intervals suggest that not all the effect of accent can be explained by the mobilization time of the response. Furthermore, in the case of the accent at the end of the second short interval and the beginning of the long interval (Accent 3), a completely different result appears. Based on peak-to-peak intervals, the increased force increases the duration of the *preceding* interval and decreases the *following* one, an effect just the opposite of what would be expected by response mobilization speeds. The effects, when compared to the control, are statistically significant, $p < .05$.

The conclusion seems inescapable that accenting does more than just alter the speed of motor implementation. Accent also alters the underlying time structure of the sequence. However, the rules of alteration are not entirely clear to us. Sometimes the accent increases a preceding interval and sometimes it decreases the interval, at least when intervals are measured from peak force to peak force.

The results of Experiment 3 basically confirm the results of Greim (1983). His study did not take actual force measurements and the response rate was somewhat quicker, involving a temporal pattern of 275, 275, and 550 ms. In addition, subjects in the Greim study moved their forefingers up and down on a key rather than isometrically pressing on a strain gauge as in the present experiment. Similar to the present results, he found an accented movement to be followed by a slightly longer than normal interval, but the preceding interval was only slightly if at all shorter than normal. Both the present results and the data of Greim are in contradiction to those of Semjen, Garcia-Colera, and Requin (1984). These authors found that an accent *lengthened* the preceding interval. The procedure of Semjen et al. differs in a couple of respects. Perhaps the most important difference is that their intertap intervals are much quicker than in the present studies, being 180 ms. Experiment 1 of this study and our previous work (Keele & Hawkins, 1982; and Keele, Pokorny, Corcos, & Ivry, 1985) have shown the Semjen et al. intervals to be very close to the maximum rate that people can tap. Weber, Blagowski, and Mankin (1982) have shown that when people speak sequences of letters or numbers as rapidly as possible, they slow down considerably when items must be alternately whispered and spoken aloud. It appears that changing the intensity parameter of a program takes considerable time. In the Semjen et al. study, accenting corresponds to an intensity parameter change, and thus, when one taps

nearly as fast as possible, implementing the change delays the next response. In line with this explanation, Semjen et al. found the same effect, a lengthening of the interval preceding the accent, regardless of whether the accent was an increase or a decrease in force.

General Discussion

The current studies were concerned with two primary issues, one being the nature of individual differences in force control and the other being the interactions of force and time.

In previous work (Keele, Pokorny, Corcos, & Ivry, 1985), we found subjects to differ from one another on basic timing control. Subjects regular at timing with one effector, such as the finger, tend to be regular with another, such as the foot. This was confirmed in Experiment 1 in which we compared finger and forearm. Moreover, in the prior study, highly skilled pianists are better on the timing measures than are non-pianists. In the current study, one goal was to determine whether a comparable factor of coordination was one of force control. The results suggest that such is the case. Individual differences in force control, measured as variability in producing a target force on several occasions, correlate across effectors of finger, forearm, and foot and across low and high force ranges. In addition, they correlate across situations in which force control is either primary or secondary to timing control. What we have not demonstrated, however, is whether or not this general factor of force control is an important aspect of coordination for various human skills.

The root cause of the correlations of force control across conditions can only be speculated about. They could be due to peripheral factors such as correlated muscle composition across the different motor effectors of individuals, due to central-peripheral factors such as innervation ratios of neurons to muscle fibers that are correlated across different effectors, or due to some central brain mechanism involved in force control. These issues remain for future research.

A second primary issue of this study concerned the relation between timing and force control. Are they completely independent factors? Our evidence suggests that they are separable factors but nonetheless that they interact. The correlations among the various force control situations of Experiments 1 and 2 and the correlations among the timing situations were substantially higher than those between force and timing. Still, when subjects attempt to produce periodic responses, there is modest correlation between variations in force and variations in time. Subjects less variable in force tend to be slightly less variable in timing. A running correlation between the force of individual key presses and the

duration of preceding and following intervals also shows a tiny but systematic effect of force variation on time.

One possible model would be that a clock establishes the duration of movement intervals and then releases a movement implementation stage. Force specification would then be part of the implementation stage. Some aspects of Experiments 1 and 3 do suggest that larger forces are implemented faster than smaller ones. In Experiment 1, the very small correlations between tap force and the durations of the preceding and following intervals are consistent with the view that larger forces are implemented faster than smaller forces. Likewise, there is a tendency in Experiment 3 for accented taps to shorten the preceding interval and lengthen the following one. However, not all the effects of force variation on timing seem relegated to an implementation stage. When the intertap intervals in Experiment 3 were measured from peak force to peak force rather than from onset-to-onset of the forces, differing force accent positions still interacted with the magnitude of the intervals produced. Moreover, accent did not always shorten the preceding interval and lengthen the following one. These observations suggest that force is altering the basic temporal structure that occurs prior to implementation. Such results are consistent with another observation from Experiment 1. Recall that by a model of Wing (1980), the total variance of intertap intervals can be decomposed into clock variance and variance in motor implementation time. In Experiment 1, it was found that individual differences in force control correlated more highly with clock variance than with motor variance.

These results are in agreement with the results of a study of a Parkinson patient with slow, weak movements (Wing, Keele, & Margolin, 1984). That patient, who presumably has difficulty providing sufficient force for normal movement, also exhibited a large increase in clock variance by the Wing model. In a preliminary report of a cerebellar patient (Keele, Manchester, & Rafal, 1985), we speculated that in preparing a movement both time and force must be specified before the response is released and before another timing cycle begins. Thus, variances in both a timekeeper per se and in force preparation time may manifest themselves in a timing loop prior to actual movement implementation. It appears, therefore, that factors of force control and timing control are largely, but not entirely, independent. Force and time appear to have a modest interaction in both peripheral and central stages of motor production.

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Using Relative Motion Plots to Measure Changes in Intra-Limb and Inter-Limb Coordination

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ABSTRACT. Methods for determining the degree of similarity between relative motion plots are examined and computational methods outlined. Hypothetical examples are provided to simply illustrate the function of selected indices of pattern shape, size, and orientation. Methods of using a composite of these measures to assess asymmetry, abnormality, or refinements in motor function are discussed. Statistical procedures for determining the reliability of assessments of change in relative motions are presented. A modification to Freeman's (1961) pattern-recognition method is suggested as a more parsimonious application to angle-angle data derived in human movement research.

RESEARCHERS IN MANY human movement domains share a common need; that is, to describe accurately changes in the movement pattern of one limb segment in relation to another or to compare the motion of different limbs. Inter-limb and intra-limb coordination can be operationalized using the relative pattern of angular displacement over time of limb segments. The method of angle-angle graphical representation was devised by Grieve (1968) for use as a method to analyze walking patterns. Movement patterns described in this way are called relative motion plots or angle-angle plots because the diagrams obtained show change in segment angles over the course of one movement cycle. Our aim is to suggest some improvements over previous attempts made to quantify the difference in coordination patterns as reflected in rela-