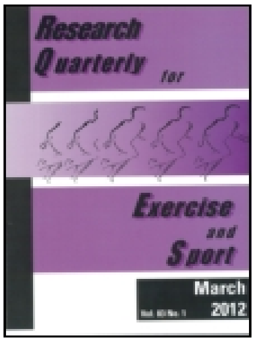

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Part and Whole Practice: Chunking and Online Control in the Acquisition of a Serial Motor Task

Steve Hansen, Luc Tremblay, and Digby Elliott

A four-component aiming movement was used to examine the relative effectiveness of part and whole practice. Following a pretest, participants were assigned to one of three practice groups. Participants in a "Whole" group practiced the four components together as a unit. A "No Overlap" group practiced the first two and last two components of the task, alternating every fifth trial. An "Overlap" group practiced the transition between the second and third components on every trial by alternating practice of the first three and last three components every five trials. Participants in all groups improved significantly from pretest to immediate posttest and maintained their performance over a 24-hr delay. Contrary to the "chunking hypothesis," participants in the No Overlap group improved as much as those in the other two groups. Kinematic data indicated that participants in all three groups learned to use response-produced feedback earlier in the individual movement trajectories. Moreover, participants appeared to acquire a general ability to make transitions between movement components rather than specific transitions. The results suggest that segmented or segmented "overlap" practice regimes may benefit learning movement sequences of short duration.

Key words: motor control, multiple component, practice regime, serial aiming

When two or more discrete movements are strung together to form a movement series, the kinematic characteristics of the individual movement segments will often change as a result of the adjacent elements. For example, the primary component in a two-component movement extension is performed more slowly than the same movement performed in isolation. This phenomenon is termed the "one target advantage." It exists because the secondary movement must be prepared (Chamberlin & Magill, 1989), or at least initiated, during the primary movement (Adam et al, 2000). When the additional movement element is a reversal, there is no temporal cost to the first movement. This may be because the two movement elements are integrated such that the same muscular forces used to decelerate the first movement element also are used to reaccelerate the limb in the direction of the initial starting point (Adam et al., 2000). Thus, although overall performance is maintained, the kinetic and kinematic characteristics of the first movement are somewhat different (Lavrysen, Helsen, Elliott, & Adam, 2002).

Consistent with the apparent codependence of neighboring elements, a traditional assumption of motor programming and skill acquisition has been that, with practice of a serial motor skill, the learner progressively strings together small, programmed units of behavior into a larger package that ultimately forms an entire action (Keele, 1976, unpublished observations as cited in Schmidt & Lee, 1999). The chunking view of skill acquisition suggests an optimal method for practice structure. For example, to combine separate movement units into a single motor program, one must perform the units together so that the transition between movement elements ultimately disappears. The hypothesized sequence of processing events associated with this type of motor learning predicts that either whole practice, or a progressive form of practice in which movement units are systematically added to the practice regime, will be superior to practice regime in which movement units are practiced in

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isolation. When part practice is necessary, perhaps because of the sequence complexity, practicing the transition between movement elements should be of importance.

Although with practice a performer becomes better at integrating adjacent movement elements (Lavrysen et al, 2003) and more efficient at movement planning (Helsen, Tremblay, Van den Berg, & Elliott, 2004), part of skill acquisition involves learning to use response-produced sensory feedback more rapidly and efficiently (Elliott, Binsted, & Heath, 1999; Elliott, Chua, Pollock, & Lyons, 1995; Proteau, Marteniuk, Girouard, & Dugas, 1987). Thus, rather than a movement or movement sequence becoming increasingly structured with practice, variability can actually increase as the system becomes more adept at achieving the desired goal in different ways (Elliott, Helsen, & Chua, 2001). Given this view of learning, it may be that most improvement over practice will be associated with online control of the individual movement elements. In this context, one might predict relatively minor differences between whole and part practice.

This study examined how practice structure influences acquisition of a serial aiming task and the codepen-dence of the individual movement elements. Participants performed an initial pretest (10 trials) on a four-component movement—a two-component reversal followed by a two-component extension. One group then practiced the "Whole" (four-component) criterion movement sequence for 40 trials. Two other groups received only partial practice. Participants in the "No Overlap" group practiced the first two and the last two movement components in isolation. Participants in the "Overlap" group received partial practice that included the transition between Components 2 and 3. All participants then performed both an immediate and a 24-hr retention-transfer test on the whole sequence. As well as measuring reaction time and overall movement time performance, we used three-dimensional optoelectric technology to examine the spatial and temporal characteristics of the aiming trajectories. We expected these kinematic analyses to provide insight into how any improvement with practice was achieved.

Based on the "chunking" hypothesis, one might expect to find the greatest improvement in the "Whole" and "Overlap" practice groups and minimal improvement in the "No Overlap" group. Moreover, at least some of the improvement should be due to a reduction in reaction time and the time needed to transition between movement elements, particularly Elements 2 and 3. Alternatively, if improvement in performing the four-element sequence depends more on the effectiveness of online control processes, one might expect improved efficiency to be associated with the spatial and temporal characteristics of the individual movement trajectories. In this case, no group differences would be anticipated.

Method

Participants

The participants were 36 adult volunteers (17 men and 19 women) ranging in age from 20 to 31 years. All participants were right-handed and had normal or corrected-to-normal vision. All were naïve to the purpose of the experiment. The research was conducted according to the guidelines of the McMaster Research Ethics Board. All research participants provided informed consent.

Apparatus

The participants sat directly in front of a target array, consisting of three buttons, situated on a desk 80 cm in height. The home button was aligned with the participant's midline, and the second and third buttons were 15 cm and 30 cm beyond on the right (see Figure 1). The buttons were 1.5 cm wide and 0.4 cm high. The index of difficulty for any movement was 4.33 bits. The force required to activate the buttons was 410 g. The three-button target array was situated on the top of a box measuring 37 cm x 25 cm x 6 cm (length x width x height).

An infrared emitting diode (IRED) was attached to the dorsal side of the distal phalange of the right index finger. An Optotrak™ 3020 (Northern Digital, Waterloo, Ontario, Canada) sampling at a rate of 200 Hz was used to determine the location of the IRED. A tone generator (100 Hz) connected to a millisecond timer triggered the Optotrak™ sampling. A millisecond timer, a four-bank timer, a pulse counter, a clock counter, and a selector were

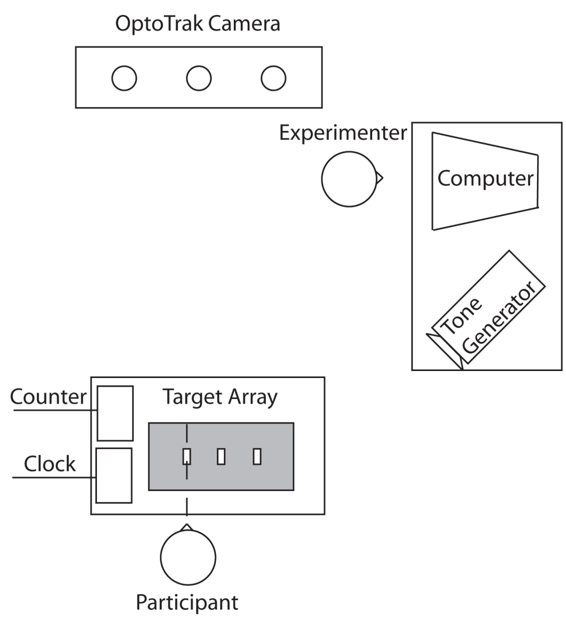

Figure 1. Top-view depiction of the experimental workspace.

connected to provide feedback on movement time and the number of successful components. The Lafayette Instrument Company (Layafette, IN) produced all timers, counters, tone generators, and selectors.

Tasks

The various movement combinations are depicted in Figure 2. The complete four-component task (the whole movement) was a reversal from the primary target to the second and back, immediately followed by an extension to the second target and finishing on the third target. The three-component tasks were as follows: the first three components were labeled “zig,” and the last three were labeled “hook.” The two-component tasks were as follows: the first two of the four-component criterion were labeled “reversal,” and the last two were labeled “extension.”

Procedure

The participants were randomly assigned to one of three groups. All were asked to complete a pretest (10 trials) on the entire four-component movement. The 12 people assigned to the two-component acquisition group practiced 40 reversals and 40 extensions, alternating every five trials (No Overlap group). Participants assigned to the three-component acquisition group practiced 40 hooks and 40 zig movements, alternating every five trials (Overlap group). Finally, the 12 people assigned to the four-component Whole movement group practiced 40 criterion movements. Each group completed 40 criterion movements during acquisition, either in part or in whole. Although the total number of trials was greater for the partial practice groups and the total number of components completed was higher for the Overlap group, the intention was for all participants to complete the criterion 40 times. Following acquisition, the participants completed an immediate posttest (10 trials) on the entire movement sequence. On the following day, they completed a delayed posttest (10 trials) on the entire four-component movement.

For each trial, the participants received a verbal warning (i.e., “ready?”) and a variable fore period of 1.0–2.5 s before they executed the movements. They were to complete their movements in the correct sequence as quickly as possible and without missing targets as soon as the auditory tone sounded. During pre-, post-, and delayed testing, participants received no feedback about their performance. During acquisition, they were required to read their overall movement time from a digital timer as well as report the number of movement elements successfully completed. This was done to ensure participants were aware of all movement errors (i.e., missed buttons).

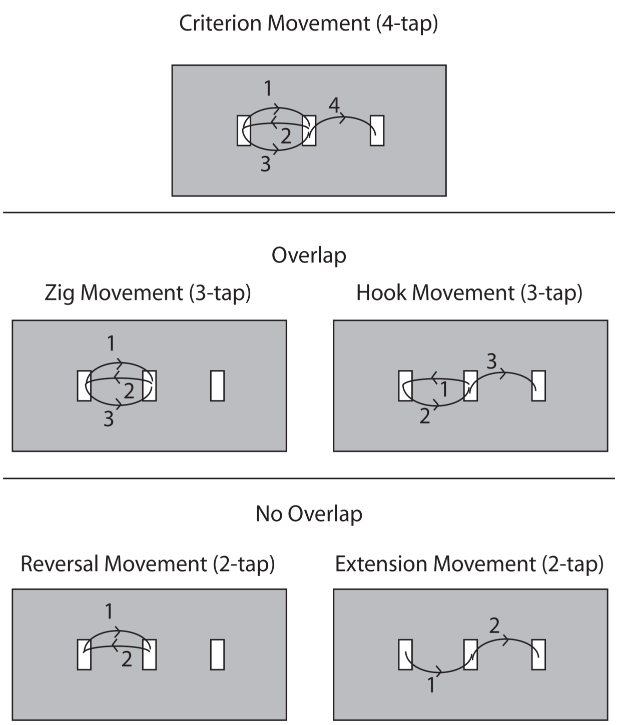

Figure 2. Layout of the movement tasks for the Whole, Overlap, and No Overlap groups.

Dependent Variables

All dependent variables were determined using custom-made software. Displacement data in the primary direction of the movement were differentiated to obtain velocity. Movement start and end were defined from the collection sample where the velocity fell above or below a 30 mm/s velocity criterion. Velocity was differentiated again to obtain acceleration.

Performance Measures. The dependent measures were based on the average of the 10 trials in each of the pre-, post-, and delayed test conditions. Reaction time (RT) was defined as the time between stimulus onset and the moment the finger left the home button. Reaction time was considered an index of planning and movement complexity (Henry & Rogers, 1960). Changes in RT with practice can indicate increased programming efficiency (e.g., Helsen et al., 2004). The other performance measures (movement time-1 (MT1), movement time-2 (MT2), movement time-3 (MT3), movement time-4 (MT4), downtime-1 (DT1), downtime-2 (DT2), downtime-3 (DT3)) provided an index of how quickly participants executed the movement sequence. Total time (TT) was the sum of RT, the four movement times, and the three downtimes. TT provided an overall measure of performance.

Limb Kinematics. Kinematic markers were identified for each of the four components in the movement: peak acceleration (PA1, PA2, PA3, PA4); peak velocity (PV1, PV2, PV3, PV4); and peak deceleration (PD1, PD2, PD3, PD4). The time to and time after peak acceleration, peak velocity, and peak deceleration were also determined.

Over 10 trials for the pretest, immediate test, and posttest, standard deviations of the spatial location of the fingertip in the primary movement axis were determined at PA, PV, PD, and movement termination. The analysis of the standard deviation of the finger's spatial position at these kinematic markers indicated the variability associated with the programming and online control of the movement as it progressed (Khan, Elliott, Coull, Chua, & Lyons, 2002; Khan et al., 2003). Following the rationale of the two-component models of limb control (e.g. Elliott et al., 2001), if offline processes are reflected in the movement trajectory up to peak velocity (Elliott et al, 1999), then online processes should be reflected in the kinematic markers beyond peak velocity. In the absence of online visual processing, errors early in the movement lead to increases in variability later in the movement trajectory (Khan et al., 2002). In the presence of visual information, a reduction in the variability of the finger's location later in the movement reflects more efficient online processing. Specifically, if the variability of the finger's location beyond peak velocity is associated with online processing (Elliott et al, 1999), then a reduction in the variability of the finger at peak deceleration, *with practice*, could reflect an increased efficiency of the online corrective processes.

Results

Performance Measures

A 3 x 3 (Group x Test) mixed analysis of variance (ANOVA) was conducted on mean total time. The analysis yielded only a main effect for test, $F(2, 66) = 60.0$, $p < .0001$. In the absence of a group effect or a group by test interaction, this indicates that participants in all three groups improved from pretest (1,510 ms) to posttest (1,235 ms) and maintained their performance into the delayed test (1,245 ms; Tukey's HSD, $p < .05$). To determine which components of the movement sequences were most sensitive to practice, a 3 x 3 (Group x Test) mixed multivariate analysis of variance was conducted, with the eight temporal sections as dependent variables (RT, MT1, DT1, MT2, DT2, MT3, DT3, MT4). The analysis allowed us to determine if participants achieved overall improvement differently in the three practice groups. As expected, this analysis revealed a main effect of test, $\Lambda(16, 52) = 0.36$, $p < .02$. A main effect of group was also identified, $\Lambda(16, 18) = 0.11$, $p < .0001$, but not a Group x Test interaction ($p > .5$). Follow-up univariate analyses of variance were conducted with Tukey's HSD ($p < .05$) post hoc test, where appropriate.

Reaction Time. The reaction time analysis revealed only a main effect for test $F(2, 66) = 43.04$, $p < .0001$. As is evident in Table 1, there was a significant decrease in RT with practice that was maintained over the 24-hr delay interval. As previously described, the decrease reflects participants' improved ability to prepare the overall movement prior to initiation (e.g., Helsen et al., 2004).

Movement Time. The movement time analysis yielded main effects for test for all four movement time intervals—MT1: $F(2, 66) = 33.79$, $p < .0001$; MT2: $F(2, 66) = 15.14$, $p < .0001$; MT3: $F(2, 66) = 21.16$, $p < .0001$; MT4: $F(2, 66) = 12.03$, $p < .0001$. Participants decreased their movement times with practice and maintained that superior performance over the delay interval (see Table 1).

Downtime. The downtime analysis revealed main effects for test—DT1: $F(2, 66) = 31.04$, $p < .0001$; DT2:

Table 1. Temporal sections as a function of group and test

Group/test	Temporal section (ms) RT	MT1	DT1	MT2	DT2	MT3	DT3	MT4	TT
No overlap									
Pretest	336	204	171	206	133	210	161	208	1,630
Immediate posttest	250	183	111	186	93	189	110	189	1,311
Delayed posttest	240	181	121	180	88	192	116	183	1,301
Overlap									
Pretest	343	212	139	200	90	213	105	194	1,496
Immediate posttest	278	187	75	188	51	190	71	179	1,220
Delayed posttest	251	194	100	196	56	195	78	181	1,251
Whole									
Pretest	313	198	144	192	92	211	117	191	1,458
Immediate posttest	277	184	78	178	45	194	64	177	1,198
Delayed posttest	257	185	90	181	46	198	71	182	1,210

Note. All times are in ms; RT = reaction time, MT = movement time, DT = downtime, TT = total time.

$F(2, 66) = 17.02$, $p < .0001$; DT3: $F(2, 66) = 31.27$, $p < .0001$. Post hoc analysis indicated reliable differences between the pretest and both retention tests for all three downtimes. The DT2 and DT3 analyses also yielded main effects for group—DT2: $F(2, 33) = 3.56$, $p < .05$; DT3: $F(2, 33) = 5.74$, $p < .01$. In both cases, this was the result of the No Overlap group spending more time on the target than the other two groups. This difference was apparent during the pretest before the different practice regimes were introduced (see Table 1). Subsequently, two 3 x 2 (Group x Test) analyses of covariance on the DT2 and DT3 retention scores, with the prescores used as a covariate, were conducted. The analysis failed to yield significant effect for either group or test ($p > .10$). This indicates that the pattern of improvement was similar for the three groups.

Kinematic Measures

To examine the contribution of prior planning and online processes to skill acquisition, the peak velocity of the four components was examined. A 3 x 3 x 4 (Group x Test x Component) mixed analysis of variance was used. Peak velocity is often taken as a kinematic index of the muscular impulses used to propel the limb toward the target and is usually thought to depend more on prior planning than online processes. The peak velocity analysis revealed only main effects for test, $F(2, 66) = 7.1$, $p < .01$, and component, $F(3, 99) = 7.8$, $p < .001$. Participants in all three groups increased their peak velocities from pretest (1.39 m/s) to the immediate test (1.49 m/s) and maintained those velocities into the delayed test (1.48 m/s; Tukey's HSD, $p < .05$). Moreover, PV2 was greater than PV1, and both PV1 and PV2 were greater than PV3 and PV4 in the immediate test (see Table 2). In terms of practice, it would seem that some improvement could be attributed to preparing overall faster movements either during the RT interval or the preceding movement or downtime.

Table 2. Peak velocity as a function of group and test

Group/test	PV1	PV2	PV3	PV4
No overlap				
Pretest	1.41	1.39	1.36	1.30
Immediate posttest	1.53	1.54	1.49	1.44
Delayed posttest	1.63	1.53	1.50	1.48
Overlap				
Pretest	1.31	1.61	1.31	1.39
Immediate posttest	1.44	1.51	1.47	1.48
Delayed posttest	1.42	1.47	1.41	1.42
Whole				
Pretest	1.44	1.48	1.37	1.36
Immediate posttest	1.50	1.63	1.45	1.45
Delayed posttest	1.51	1.53	1.44	1.46

Note. PV = peak velocity; PV is measured in m/s.

While increases in peak velocity often accompany more ballistic or preprogrammed movements, participants may also develop a strategy of getting to the target area quickly so they have more time to engage in closed-loop control. Presumably, variability in the finger path would demonstrate how stereotyped or planned the movement was from trial to trial (Khan et al, 2002; Khan et al, 2003). To examine the variability of the finger's trajectory, a 3 x 3 x 4 x 4 (Group x Test x Component x Kinematic Marker) ANOVA of the standard deviation of the finger location at peak acceleration, peak velocity, peak deceleration, and movement endpoint was conducted. Analysis of the spatial variability at the different trajectory points revealed a main effect of test, $F(2, 66) = 4.5$, $p < .015$, component, $F(3, 99) = 14.21$, $p < .001$, and location, $F(3, 99) = 85.1$, $p < .001$, in addition to a Test x Location interaction, $F(6, 198) = 8.4$, $p < .001$, and a Component x Location interaction, $F(9, 297) = 6.2$, $p < .0001$. The overall variability decreased from the pretest (8.5 mm) to the immediate test (7.7 mm) and returned to its original level in the delayed test (8.33 mm). The component variability significantly increased from the first (6.99 mm) to the second (8.33 mm) component and stayed at that level for the remaining components (8.33 mm, 9.04 mm, respectively). Unexpectedly, the standard deviation of the finger location at peak velocity did not change significantly following practice. However, the standard deviation of the location at peak deceleration decreased significantly between the pretest and immediate test and maintained that level in the delayed test (see Figure 3). The decrease at peak deceleration, combined with the fact that spatial variability at movement termination was unchanged by practice, suggests participants learned to engage in effective online control earlier in the movement trajectory. Analysis in which we examined the *z* transform of within-trial correlation between peak acceleration and peak deceleration supported the interpretation of the spatial variability data. Specifically, in a Group x Test repeated measures analysis, we found a main effect of test $F(2, 66) = 4.36$, $p < .017$. The correlation between peak acceleration and peak deceleration significantly decreased from the pre- (0.24) to the immediate posttest (-0.03). It returned to an intermediate level in the delayed test (0.11).

Discussion

The purpose of our experiment was to examine how practice structure influenced a serial aiming task and the codependence of the movement segments. It was hypothesized that individuals who practiced movements containing a transition between adjacent movement components, as well as those who practiced the criterion movement only, would perform better than those who did not. The results did not support this hypothesis. Specifically, participants who practiced the transition between Components 2 and 3 exhibited similar results to those who had no practice with the transition. That is, participants in all three groups learned to plan and execute their movements more rapidly and efficiently.

Although practice with specific movement transitions did not have the impact on performance that we expected, participants did get better at integrating movement elements. This improvement is reflected in the reduced transition times (i.e., downtimes) between movement elements. Perhaps what participants acquired was a more general ability to control one movement online while preparing the next movement in the sequence.

With practice, participants exhibited a significant decrease in the spatial variability at peak deceleration, not at peak velocity or the termination of individual components. This indicates that participants used concurrent feedback rapidly and efficiently earlier in each movement component. This heightened efficiency of each component transfers to improved performance of the criterion movement. Perhaps this increased efficiency allows the participant to reallocate attentional resources to subsequent movements, thereby increasing the potential length of the series, as with segmented (progressive part) practice. In this context, performance and kinematic data can provide an indication of when individuals may be ready to add a subsequent segment onto their sequence.

The pattern of spatial variability at the four kinematic markers in our pretest was similar to the variability observed by Khan et al. (2002), when participants had full visual information available over the course of the movement and when vision was eliminated on movement initiation. Specifically, spatial variability in the primary movement direction increased from peak acceleration to peak velocity and again at peak deceleration. Although the decrease in variability between peak deceleration and the movement end was less dramatic when vision was eliminated, it was nonetheless apparent. Results from the Khan et al. (2002) study indicated that participants in our experiment might have become better at using visual or kinesthetic feedback earlier in the limb's trajectory. The increased online flexibility with practice was also evident in the reduction of trajectory symmetry that occurred over practice. Once again, this indicates that part of skill acquisition involves learning to use response-produced feedback during the deceleration phase of the primary movement. The processes involved in executing each segment following practice seem to be similar under both practice regimes.

The significant increase in the standard deviation of the finger locations at the kinematic markers between the first and ensuing components may depend on the events of the primary segment. Specifically, control of the subsequent movement is changed a priori based on the error detection and correction processes that occur in the previous segment. For example, if the participant determines that the finger will overshoot the primary target, he or she will adjust the next movement to be shorter, in the case of an extension, or longer, in the case of a reversal. In other words, participants can begin with their finger consistently in the middle of the first button. However, following their initial movement, the finger location at peak acceleration will depend on the termination point of the previous movement. By necessity, the codependence of the move-

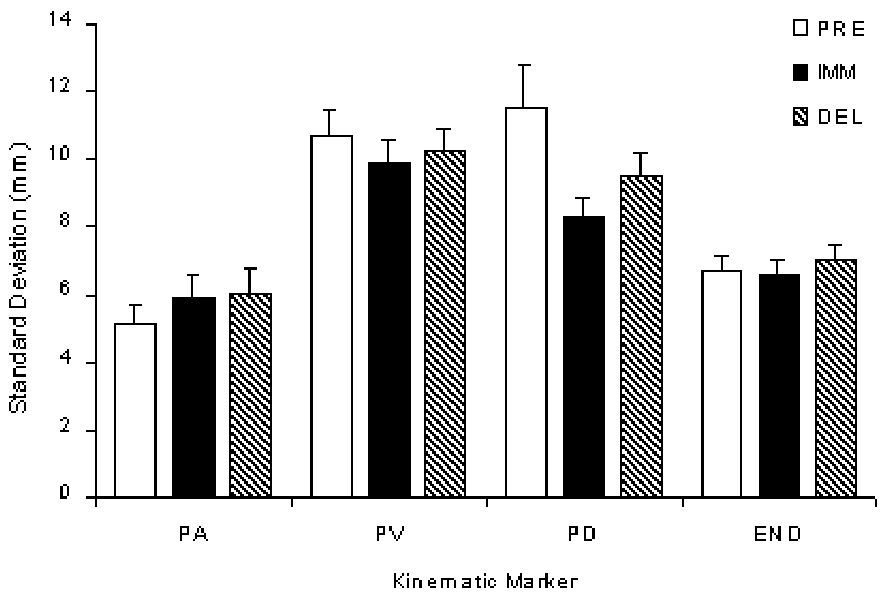

Figure 3. Standard deviation (mm) of the finger's position at peak acceleration (PA), peak velocity (PV), peak deceleration (PD), and end of the movement (END) for the pretest (PRE), immediate posttest (IMM), and delayed posttest (DEL).

ment components unfolds from the production and correction of between-component movement errors.

The results of this study have practical implications for learning or relearning the use of telephone keypads, automatic teller machines, and security keypads. In this context, our kinematic results are instructive toward creating practice regimes. In comparing various practice strategies, the advantage of a segmented practice regime is that the criterion task becomes less complicated. The participant can, therefore, concentrate on performing the individual parts leading to overall criterion improvement. The advantage of a whole practice regime is that the participant is exposed to the spatial and temporal coordination of the criterion movement in the performance context. In this experiment, the Overlap group completed a form of segmented practice with a component movement common to each movement segment. The Overlap group could take advantage of the reduced movement complexity, but it had the added benefit of learning the spatial and temporal constraints involved with the transition between segments. In other movement contexts, learning the newly introduced segment and transition between segments may impede the effectiveness of the traditional progressive part method. In contrast, only the spatial and temporal components of the subsequent segment impede the participant's performance using the Overlap method. In serial aiming movements, this study has demonstrated that this hybrid of segmented practice is as efficient as whole practice and the traditional segmented practice regimes. The exploration of this type of segmented practice in longer movement sequences and other task contexts is required.

In summary, we were interested in how practice structure could influence the performance and programming, or codependence, of the movement components of a serial aiming task. Our results did not support the hypothesis that motor learning involves "chunking" of movement components. However, it is evident the participants became more proficient at reducing movement error that sometimes carries over from one element to another. From a practical point of view, practice involving component elements of a movement sequence should transfer to the larger sequence as long as the information processing procedures inherent in the whole task do not differ (Elliott, Ricker, & Lyons, 1998). Thus, segmented and segmented Overlap practice may be a viable option for some short duration movement sequences, when the component elements are similar.

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