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Age-Related Kinematic Differences as Influenced by Task Difficulty, Target Size, and Movement Amplitude

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Fifteen older adults (M = 68 years old) and 15 young adults (M = 23 years old) participated in a speed–accuracy task in which aiming movements were performed on a digitizing tablet to assess movement slowing and variability in older adults. Target-size and movement amplitude influences were analyzed separately to determine if they affected the performance of the young and older adults differently. When target size was increased, older adults did not increase the relative distance traveled in the primary submovement. When movement amplitude was increased, older adults did not scale movement velocities to the same magnitude as young adults did. Both the inability to scale velocity and the inability to increase the relative distance traveled in the primary submovement contribute to slower, more variable movements observed in older adults depending on task parameters. Thus, these data reveal that manipulation of target size and movement amplitude yield two distinct factors that contribute to slowness of movement in older adults.

BIRREN (1974) and Salthouse (1985) hypothesized that all fundamental neural events become slower with advanced age for cognitive and motor functions, resulting in overall movement slowing in older adults. A substantial portion of research has shown older adults to be 30% to 70% slower than young adults on a variety of motor tasks, with pronounced slowing observed as task difficulty increases (Amrhein, Goggin, & Stelmach, 1991; Bellgrove, Phillips, Bradshaw, & Gallucci, 1998; Cooke, Brown, & Cunningham, 1989; Goggin & Meeuwsen, 1992; Pohl, Winstein, & Fisher, 1996; Stelmach, Goggin & Amrhein, 1988; Walker, Philbin, & Fisk, 1997; Welford, 1984). Older adults tend to move more slowly, but do not necessarily make more errors than young adults (Goggin & Meeuwsen, 1992; Salthouse, 1988). Goggin and Meeuwsen (1992) used a speed–accuracy task to assess spatial control in an aiming task by manipulating movement amplitude and target size. They found that older adults emphasized the later portion of the movement to maintain accuracy.

Research has described movement slowing in terms of kinematic parameters and has identified differences between young and older adults on features such as longer deceleration profiles (Bellgrove et al., 1998; Brown, 1996; Cooke et al., 1989; Darling, Cooke, & Brown, 1989; Goggin & Meeuwsen, 1992; Pratt, Chasteen, & Abrams, 1994) and lower peak velocity amplitudes (Bellgrove et al., 1998; Brown, 1996; Cooke et al., 1989; Goggin & Meeuwsen, 1992; Pratt et al., 1994). Cooke and colleagues (1989) studied kinematics of older adults' arm movements in which participants performed tracking movements to varying amplitudes. Both young and older adults increased movement durations and velocity amplitude as movement amplitude was increased. Young adults produced symmetric velocity profiles, whereas older adults showed lengthened deceleration curves. These researchers also reported that maximum velocities were significantly lower in older adults across all amplitudes and were more variable at the short amplitudes. Further, they observed that older adults showed hypometric movements in which they made "discrete submovements" to reach the target.

Velocity profiles can further be parsed using the movement optimization model proposed by Meyer, Abrams, Kornblum, Wright, and Smith (1988) to assess the underlying microstructure of the movement. This method demonstrated that adjustments to the microstructure occur when accuracy constraints are imposed and under heightened task difficulty. Research has also shown that older adults have a reduced ability to propel the limb near the target with the initial ballistic portion of their movement, consequently making more secondary, corrective submovements to reach the target (Bellgrove et al., 1998; Darling et al., 1989; Pratt et al., 1994; Seidler-Dobrin & Stelmach, 1998; Walker et al., 1997). However, a systematic manipulation of target size and movement amplitude in the context of Fitts's law has not been well documented using the movement optimization model.

The present study was designed to assess movement slowing and variability in older adults to provide insight into how movement kinematics and microstructure are adjusted with a systematic manipulation of a speed–accuracy task (Fitts, 1954). We sought to determine whether the impairments observed in the older adults are similar for changes in task difficulty as predicted by Fitts or whether they are related specifically to manipulations in target size or movement amplitude. Further, we sought to determine which kinematic parameter or parameters are most related to movement slowing in older adults and if they are influenced by task difficulty, target size, and movement amplitude. If kinematic and movement-parsing analyses reveal similar changes for target-size and movement-amplitude manipulations, this would suggest that a single deficit may cause movement slowing and increased variability in the older adults. However, if analyses reveal separate changes as target size and movement amplitude are manipulated, it would suggest that movement slowing and variability are not necessarily a result of a unitary deficit but are rather task-feature specific.

Thus, three specific hypotheses were assessed:

1. *Task difficulty comparison:* It was hypothesized that if movement slowing can be attributed to a global-information-processing deficit, then total movement time will increase differentially in older adults compared with young adults as index of difficulty increases. Older adults will produce differentially lower peak velocities and longer deceleration phases with more inflections across all movements regardless of parameters involved.
2. *Influence of target size:* If movement slowing is specifically related to a deficit in accuracy control, we hypothesized that when amplitude is held constant, older adults will show a much greater increase in movement durations relative to young adults when target size is decreased. Older adults will produce movements with longer deceleration phases containing more inflections earlier in the velocity profile compared with young controls.
3. *Influence of movement amplitude:* If movement slowing conversely is specifically related to speed control, we hypothesized that when target size is held constant, older adults will demonstrate a greater increase in movement duration relative to young adults when amplitude is increased. Older adults will produce movements with lower velocities compared with young adults.

The present study furthers the understanding of contributions to movement slowness in older adults by the systematic manipulation of target size and movement amplitude in conjunction with kinematic and movement-parsing analyses techniques.

Methods

Participants

This study involved 30 right-handed participants, 15 young adults (*M* age = 23 years, *SD* = 3) and 15 older adults (*M* age = 68 years, *SD* = 6). All participants filled out the appropriate informed-consent forms in accordance with human participant policies. Young adult participants were recruited from the Arizona State University campus and were given class credit for their participation. Older adult participants were randomly selected from a database of volunteers recruited from the greater metropolitan Phoenix, AZ, community and were paid $10 each for their participation in the study. The experiment took approximately 1 hr, which included participant screening and experimental testing. All particiapnts took a Mini-Mental State Exam (Folstein, Folstein, & McHugh, 1975) to exclude those with other neurological impairments such as dementia. We set the minimum score for inclusion at 28 out of 30. Furthermore, all participants filled out a health-history questionnaire to exclude those who had a history of stroke, arthritis, or other neurological or movement impairments.

To assess functionality of movement, we gave all participants a 20-s tapping task. Older adults produced significantly fewer taps in 20 s (*M* = 27.47, *SD* = 1.92) compared with young adults (*M* = 33.47, *SD* = 5.93). Furthermore, older adults (*M* = 3.60 years, *SD* = 2.69) and young adults (*M* = 3.67 years, *SD* = 0.62) did not differ on years of education past the high school level.

Procedures

Participants made point-to-point aiming movements to different targets, which were presented on a computer screen. Target size and movement amplitude were manipulated to yield seven different indices-of-difficulty (ID) conditions (Figure 1). Two IDs of 4 (4a, 4b) and two IDs of 5 (5a, 5b) were used to make comparisons as individual parameters changed (i.e. target size and movement amplitude were manipulated independently). The conditions were IDs 2, 3, 4, 5, and 6 (two each of IDs 4 and 5). Movement amplitudes and target widths were: ID 2 = 9.6 cm, 4.8 cm; ID 3 = 9.6 cm, 2.4 cm; ID 4a = 19.2 cm, 2.4 cm; ID 4b = 14.4 cm, 1.8 cm; ID 5a = 9.6 cm, 0.6 cm; ID 5b = 14.4 cm, 0.9 cm; and ID 6 = 19.2 cm, 0.6 cm. There were 22 blocks of 12 trials. The first contained two of each possible ID to allow the participant to become oriented with the task. Following this were 7 familiarization blocks of 12 trials, which were not analyzed. The last 14 blocks constituted the test phase, in which the first 7 blocks were randomly presented to the participants and the last 7 blocks were counterbalanced. Participants were instructed to move as fast and accurately as possible to the target after a computer-generated go stimulus (tone). The trial ended when participants stopped in the target.

Apparatus

Pen position (x and y) was measured using a Wacom Digitizer UD-1825-R00 (Wacom Technology Corporation, Vancouver, WA) with a sampling frequency of 206 Hz. A program written in OASIS (De Jong, Hulstijn, Kosterman,

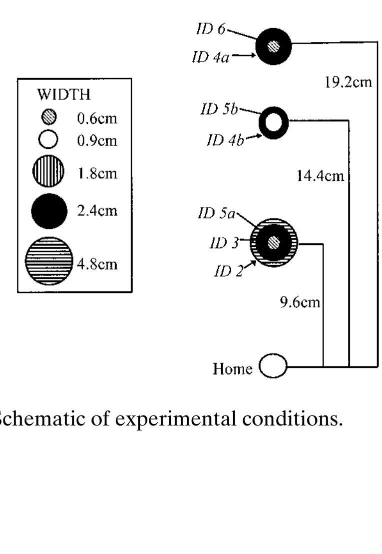

Figure 1. Schematic of experimental conditions.

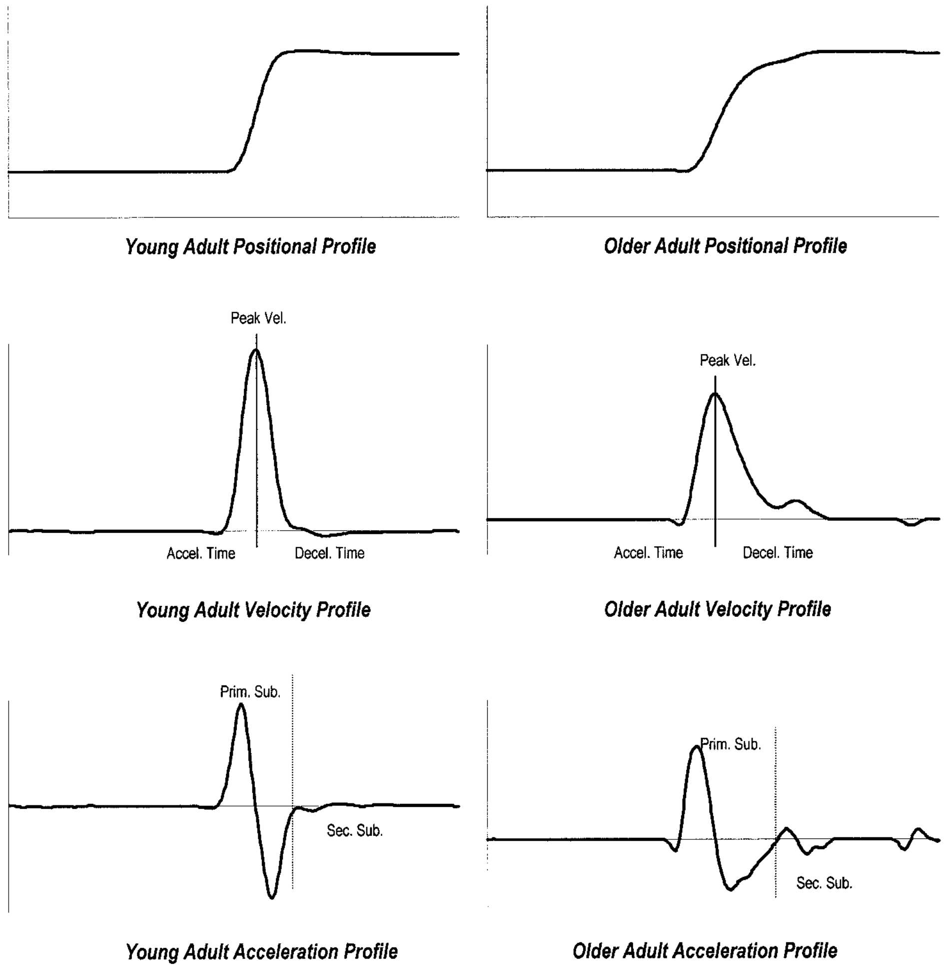

Figure 2. An individual young and older adults' position, velocity, and acceleration profiles. Young adult is on the left, older adult is on the right, position is on the top, velocity is in the middle, and acceleration is on the bottom. Vel = velocity; Accel = acceleration; Decel = deceleration; Prim Sub = primary submovement; Sec Sub = secondary submovement.

Smits-Engelsman, 1996) was used to control the experiment and collect data.

Data Analysis

The pen-tip data were filtered using a second-order dual pass (no phase lag) Butterworth filter (Winter, 1990). A residual analysis was conducted to determine the appropriate cutoff frequency for the data (7 Hz). Velocity and acceleration were computed with a three-point finite difference derivative with endpoint padding to eliminate endpoint problems (Winter, 1990). Normalized jerk score was computed as $\sqrt{(1/2 \int dt\ j^2 (t) \times \text{duration}^5 / \text{length}^2)}$ to evaluate the smoothness of the movement. This variable has no units, because it was normalized for both amplitude and movement duration (Teulings, Contreras-Vidal, Stelmach, & Adler, 1997). The optimal algorithm of Teasdale, Bard, Fleury, Young, and Proteau (1993) was used to determine movement onset from velocity profiles. The algorithm worked by locating the sample at which the velocity time series first exceeded 10% of its maximum value (Vmax). It then worked backward from this point and stopped at the first sample (S) less than or equal to Vmax/10−Vmax/100. The standard deviation of the series between Sample 1 and Sample S (*SD*) was then determined. The onset sample was from S stop, the first sample less than or equal to S-*SD*. The same algorithm in reverse was used for movement offset.

The end of the primary submovement was determined by the second zero crossing of acceleration profile. Each of the subsequent acceleration and deceleration pairs (two zero crossings) were recorded as a secondary submovement (Figure 2).

Labview (Version 3.1, National Instruments Corporation, Austin, TX) was used to analyze data. All data were compiled into a spreadsheet for further statistical analyses. The first two trials of each block were dropped to account for refamiliarization. Dependent variables measured were movement time, peak velocity amplitude, time to peak velocity expressed as a percentage of total time (relative), distance traveled in the primary submovement expressed as a percentage of total distance (relative), the number of secondary corrective submovements, and normalized jerk scores.

Statistical Analyses

A multivariate analysis of variance with repeated measures was used to analyze the relevant subsets of data. The

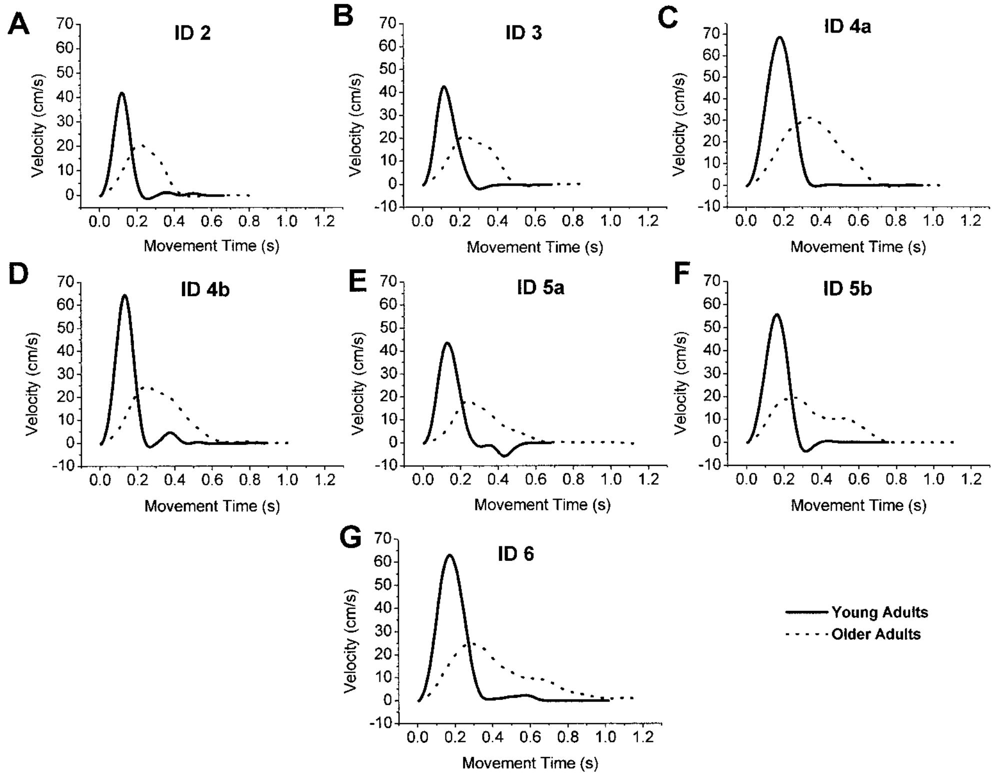

Figure 3. Representative velocity profiles for all indices-of-difficulty (ID) for a single young and older adult participant (movement amplitude, target width). (a) ID 2 (9.6 cm, 4.8 cm), (b) ID 3 (9.6 cm, 2.4 cm), (c) ID 4a (19.2 cm, 2.4 cm), (d) ID 4b (14.4 cm, 1.8 cm), (e) ID 5a (9.6 cm, 0.6 cm), (f) ID 5b (14.4 cm, 0.9 cm), (g) ID 6 (19.2 cm, 0.6 cm).

Geisser-Greenhouse corrected degrees of freedom were used when violations to sphericity occurred. The observed power was reported if it was less than 1.0 for each effect as was the effect size (ω^2 = ES), which is an estimation of the total variance explained by the treatment variation (Keppel, 1991). Values ranged between 0 to 1.0 (.03 is a small effect size, .06 is a medium effect size, .15 is a large effect size; Cohen, 1977). Age main effects as well as ID main effects and Age × ID interactions were reported. For target-size manipulations, ID changes were reported as target-size effects, and for movement-amplitude manipulations, ID effects were reported as movement-amplitude effects. Age main-effect means were pooled across ID, and ID main-effect means were pooled across age groups. For simplicity of data presentation, text and figures refer to a representative comparison for manipulations of target size and movement amplitude, but do not include all pairings. All data pairings are reported in Tables 2 and 3 in their entirety for target-size and movement-amplitude pairings respectively.

Results

Representative movement trajectories for an individual young and older adult participant are shown in Figure 3. Prominent kinematic features that changed as ID increased are longer movement durations, longer deceleration phases, and more submovements. Peak velocity did not systematically increase or decrease as ID increased. The more striking qualitative differences between young and older adults were that older adults produced flattened velocity profiles with a substantial number of inflections. For the first analysis, similar IDs were collapsed (4a–4b, 5a–5b) and are represented by ID 4 and ID 5, respectively. This allowed for examination of kinematic features as a function of difficulty and allowed us to compare the influence of ID on young and older adults. Second, data related to the influence of changing target size were analyzed to assess kinematic features specific to accuracy constraints. Finally, we analyzed data related to the influence of movement amplitude to examine the impact of movement amplitude increases.

Collapsed Task Difficulty Comparison

The multivariate test indicated a significant effect of ID, $F(24,440) = 13.24$, $p < .001$, a significant effect of age, $F(6,23) = 3.314$, $p < .05$, $P = .85$ and a significant Age × ID interaction, $F(24,440) = 2.039$, $p < .005$. Therefore, univariate tests were analyzed for each dependent variable to analyze the effects of age and ID on observed kinematics. Geisser-Greenhouse corrected degrees of freedom rounded to the nearest whole number were used when sphericity violations occurred in these comparisons. Overall movement times lengthened linearly as ID increased for both groups (significant ID main effect), $F(2,56) = 92.4$, $p < .001$, effect size [ES] = .71) which follows Fitts's law. Older adults were significantly slower than young adults at all levels of difficulty (significant age main effect), $F(1,28) = 14.9$, $p < .005$, $P = .96$, ES = .09), and further were differentially af-

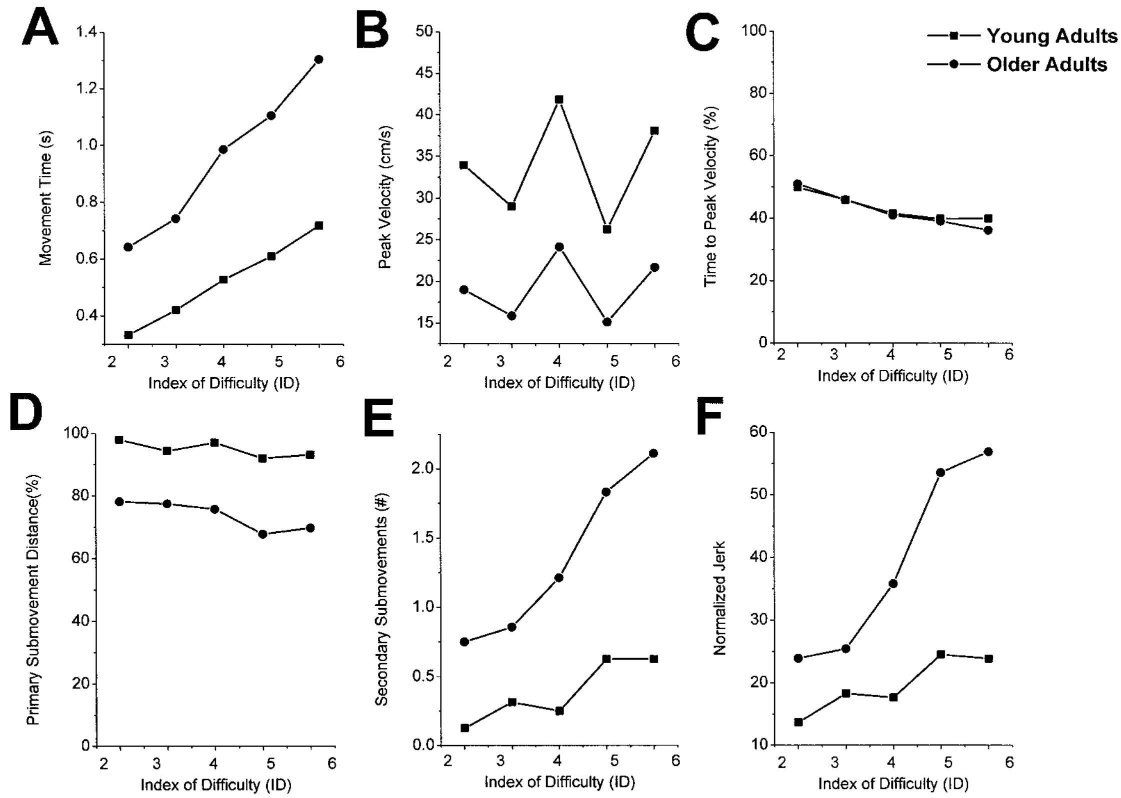

Figure 4. Overall movement kinematic data collapsed across ID 4 (4a-4b) and ID 5 (5a-5b) for young and older adults. (A) Movement time (s), (B) Peak velocity (cm/s), (C) Time to peak velocity (%), (D) Primary submovement distance (%), (E) Secondary submovements (#), (F) Normalized jerk score.

fected at varying levels of ID (Age × ID interaction), $F(2,56) = 7.3$, $p < .05$, $P = .92$, ES = .14) (Figure 4a). There was an ID effect for amplitude of peak velocity, $F(2,65) = 37.2$, $p < .001$, ES = .49. Older adults had significantly lower peak velocities compared with young adults across all IDs (significant age main effect), $F(1,28) = 16.0$, $p < .001$, ES = .70, and were differentially affected at varying levels of ID compared with young adults (significant Age × ID interaction), $F(2,65) = 86.7$, $p < .05$, $P = .68$, ES = .10 (Figure 4b). Furthermore, there was a main effect of ID on relative time to peak velocity, F(2,67) = 88.1, $p < .001$, ES = .70. There was not an age main effect for relative time to peak velocity (ES = 0), however there was a significant Age × ID interaction, $F(2,67) = 4$, $p < .05$, $P = .75$, ES = .07 (Figure 4c).

The microstructure of the movement was further analyzed. There was an effect of ID for relative distance traveled in the primary submovement, with participants covering less distance in the primary submovement with increasing ID (significant ID main effect), $F(4,112) = 10.8$, $p < .001$, ES = .21. Furthermore, there was a significant age main effect with young adults covering greater distances in the primary submovement than older adults did, $F(1,28) = 11.1$, $p < .005$, $P = .90$, ES = .07, but not a significant Age × ID interaction (ES = .02); (Figure 4d). As ID increased the number of secondary corrective submovements also increased for both groups, (significant ID main effect), $F(4,25) = 18.9$, $p < .001$, ES = .34. Older adults produced more secondary corrective submovements compared with young adults across all IDs (significant age main effect), $F(1,28) = 9.7$, $p < .005$, $P = .85$, ES = .05, and were differentially affected as ID increased (significant Age × ID interaction), $F(2,45) = 4.7$, $p < .05$, $P = .75$, ES = .09 (Figure 4e). Normalized jerk scores were higher at increasing IDs for both groups (significant ID main effect), $F(1,39) = 17.6$, $p < .001$, ES = .31. Older adults had significantly less smooth movements than young adults did across all IDs (significant age main effect), $F(1,28) = 10.3$, $p < .005$, $P = .87$, ES = .06, and again were differentially affected as ID increased compared with young adults, (significant Age × ID interaction), $F(1,39) = 5.8$, $p < .05$, $P = .75$, ES = .11) (Figure 4f). Means, standard deviations, and F values are reported in Table 1.

Further analyses of subsets of the data revealed kinematic differences that were influenced by either a change in target size or in movement amplitude. For simplicity of data presentation, text and figures refer to a representative comparison, but do not include all pairings. All data pairings' means, standard deviations, and F values are reported in Tables 2 and 3.

Influence of Target Size (Table 2)

Three combinations of IDs (4a-6, 4b-5b, 2-3-5a) were used to evaluate differences between young and older adults when movement amplitude was held constant and target size was manipulated. Thus, increases in ID were elicited by decreases

Table 1. Overall Collapsed Data, ID 4 (4a-4b), ID 5 (5a-5b)

	Young		*Elderly*				
ID	*M*	*SD*	*M*	*SD*	Effect	*df*	*F*
			Movement Time (ms)				
2	333	90	642	305			
3	420	131	741	347	ID*	2, 56	92.4
4	527	116	986	477	I*	2, 56	7.3
5	609	140	1105	454	Age*	1, 28	14.9
6	717	220	1304	557			
			Peak Velocity (cm/s)				
2	34	12.3	19	9			
3	29	11.1	15.9	7.2	ID*	2, 65	37.2
4	41.8	14.6	24.2	11.2	I*	2, 65	86.7
5	26.3	9.5	15.1	6.6	Age*	1, 28	16
6	38.1	14.7	21.7	9			
			Time to Peak Velocity (%)				
2	49.9	2.5	51	6.3			
3	45.9	3.4	48.1	6.1	ID*	2, 67	88.1
4	41.5	3.2	41	5.1	I*	4, 25	4
5	39.8	3.5	39.1	5.8	Age	1, 28	.1
6	40	4.3	36.2	6.2			
			Distance Traveled in Primary Submovement (%)				
2	98	2.5	78.2	26			
3	94.4	7.1	77.4	26	ID*	4, 112	10.8
4	97	2.1	75.7	25.3	I	4, 112	1.9
5	92	3.7	67.8	25.6	Age*	1, 28	11.1
6	93	7.4	69.7	26.2			
			Secondary Submovement (#)				
2	.13	.15	.75	.67			
3	.32	.14	.86	.83	ID*	2, 45	20.2
4	.25	.19	1.2	1.4	I*	2, 45	4.7
5	.62	.21	1.8	1.5	Age*	1, 28	9.7
6	.63	.28	2.1	1.9			
			Normalized Jerk Score				
2	13.7	5.5	23.9	9.9			
3	18.3	5.4	25.5	12.7	ID*	1, 39	17.6
4	17.7	4.6	35.8	24.5	I*	1, 39	5.8
5	24.5	5.6	53.6	34	Age*	1, 28	10.3
6	23.9	5.4	56.9	44.2			

Note: ID = index-of-difficulty; I = interaction.
*$p < .05$.

in target size. The comparison between 2, 3, and 5a is highlighted (Figure 3a, 3b, 3e). Movement amplitude was fixed at 9.6 cm, and target sizes were 4.8, 2.4, and 0.6 cm respectively. The multivariate test indicated a significant effect of target size, $F(12,17) = 30.23$, $p < .001$, a significant effect of age, $F(6,23) = 3.94$, $p < .01$, $P = .91$, and a significant Age × Target Size interaction, $F(12,17) = 2.97$, $p < .05$, $P = .89$. Therefore, we analyzed univariate tests for each dependent variable to analyze the effects of age and decreases in target size on observed kinematics. Geisser-Greenhouse corrected degrees of freedom rounded to the nearest whole number were used when sphericity violations occurred in these comparisons. Both young and older adults produced slower movement times as target size decreased, (significant target size main effect), $F(2,56) = 98.4$, $p < .001$, ES = .68. Older adults were significantly slower than young adults at all target sizes (significant age main effect), $F(1,28) = 15.1$, $p < .005$, $P = .96$, ES = .14, and were differentially slower as target size decreased (significant Age × Target Size interaction), $F(2,56) = 7.2$, $p < .005$, $P = .92$, ES = .12 (Figure 5a). Furthermore, as target size decreased, amplitude of peak velocity decreased for both groups, (significant target size effect), $F(2,56) = 37.8$, $p < .001$, ES = .45). Older adults had significantly lower peak velocities across all target sizes (significant age main effect), $F(1,28) = 15.8$, $p < .001$, ES = .14, and were differentially affected at the larger target size (significant Age × Target Size interaction, $F(2,56) = 3.3$, $p < .05$, $P = .61$, ES = .05 (Figure 5b). Relative time to peak velocity decreased as target size decreased for both groups, (significant target size effect), $F(2,56) = 128$, $p < .001$, ES = .74). There was neither a significant age main effect (ES = 0) nor an Age × Target Size interaction (ES = 0) suggesting that the change in relative time to peak velocity was a function of change in target size solely (Figure 5c).

Relative distance traveled in the primary submovement decreased with decreasing target size for both age groups (significant target size effect), $F(2,56) = 17.7$, $p < .001$, ES = .27. Older adults also had significantly shorter relative primary submovement distances compared with young adults, (significant age main effect), $F(1,28) = 11$, $p < .005$, $P = .89$, ES = .10, and produced differentially shorter relative primary submovement distances as target size decreased (significant Age × Target Size interaction), $F(2,56) = 3.6$, $p < .05$, $P = .65$, ES = .05 (Figure 5d). The number of secondary, corrective submovements were significantly higher as target size decreased across groups, (significant target size main effect), $F(2,56) = 44.3$, $p < .001$, ES = .48. Older adults produced more secondary, corrective submovements across all target sizes compared with young adults (significant age main effect), $F(1,28) = 11.1$, $p < .005$, $P = .90$, ES = .10, and were differentially affected as target size decreased (significant Age × Target Size interaction), $F(2,56) = 5.1$, $p < .01$, $P = .80$, ES = .08 (Figure 5e). Normalized jerk scores increased as target size decreased for both groups (significant target size main effect), $F(1,35) = 34.1$, $p < .001$, ES = .42. Older adults produced consistently less smooth movements than young adults did across all target sizes (significant age main effect), $F(1,28) = 13.3$, $p < .005$, $P = .94$, ES = .12, and were differentially affected as target size decreased (significant Age × Target Size interaction), $F(1,35) = 8.6$, $p < .01$, $P = .87$, ES = .14 (Figure 5f).

Influence of Movement Amplitude

Two combinations of IDs (3-4a, 5a-6) were designed to evaluate differences between young and older adults when target size was held constant and movement amplitude was changed. Thus, ID increases were elicited by increases in movement amplitude. The comparison between 3 and 4a is highlighted (Figure 3b, 3c). Target size was held constant at 2.4 cm, and amplitude was increased from 9.6 to 19.2 cm. The multivariate test indicated a significant effect of movement amplitude, $F(6,23) = 196.7$, $p < .001$, a significant effect of age, $F(6,23) = 3.9$, $p < .05$, $P = .76$, and a significant Age × Movement Amplitude interaction, $F(6,23) = 3$, $p < .05$, $P = .89$. Therefore, we analyzed univariate tests for each dependent variable to analyze the effects of age and increases in movement amplitude on observed kinematics. Geisser-Greenhouse corrected degrees of freedom rounded to the nearest whole number were used when sphericity violations occurred in these comparisons. Both young and

Table 2. Influence of Target Size (TS)

ID	Young M	Young SD	Elderly M	Elderly SD	Effect	F
Movement Time (ms)						
2	333	90	642	305	TS*	98.4
3	420	131	741	347	I*	7.2
5a	609	140	1105	454	Age*	15.1
Peak Velocity (cm/s)						
2	34	12.3	19	9	TS*	37.8
3	29	11.1	15.9	9.2	I*	3.3
5a	21.2	9.1	12	5.1	Age*	15.8
Time to Peak Velocity (%)						
2	50	2.5	51	6.3	TS*	128
3	46	3.4	48	6	I	1.1
5a	38	3.9	37	5.7	Age	.5
Distance Traveled in Primary Submovement (%)						
2	98	2.5	78.2	22.9	TS*	17.7
3	94.4	7.1	77.4	26	I*	3.6
5a	91.2	4.4	64.8	27	Age*	11
Secondary Submovements (#)						
2	.13	.15	.75	.67	TS*	44.3
3	.32	.14	.86	.84	I*	5.1
5a	.8	.32	2.0	1.4	Age*	11.1
Normalized Jerk Score						
2	13.6	5.5	23.9	9.9	TS*	34.1
3	18.3	5.4	25.5	12.7	I*	8.6
5a	27.7	8.2	60.2	34.8	Age*	13.3
Movement Time (ms)						
4a	528	125	1034	524	TS*	49.4
6	717	220	1304	557	I	1.5
					Age	14.5
Peak Velocity (cm/s)						
4a	48	16.7	27.6	12.9	TS*	43.8
6	38.1	14.7	21.7	8.9	I	2.8
					Age*	14.5
Time to Peak Velocity (%)						
4a	37.7	3.9	36.5	5.7	TS	1.1
6	39.9	4.3	36.2	6.2	I	1.8
					Age	2.2
Distance Traveled in Primary Submovement (%)						
4a	98.5	1.6	76.1	28	TS*	14.9
6	93.1	7.4	68	26.2	I	.1
					Age*	10.9
Secondary Submovements (#)						
4a	.16	.18	1.2	1.5	TS*	24.7
6	.63	.28	2.1	1.9	I	2.3
					Age*	8.7
Normalized Jerk Score						
4a	16	3.9	38.6	29.4	TS*	12.4
6	23.9	5.4	56.9	44.2	I	2
					Age*	9.5
Movement Time (ms)						
4b	257	113	937	452	TS*	44.2
5b	603	153	1118	521	I*	7.41
					Age*	12.8
Peak Velocity (cm/s)						
4b	35.6	12.9	20.7	9.5	TS*	25.5
5b	31.3	10.1	18.2	8.4	I	1.8
					Age*	14.3
Time to Peak Velocity (%)						
4b	45.4	3.7	45.4	6.5	TS*	34.9
5b	42.6	4.1	45.4	5.2	I	.9
					Age	.1
Distance Traveled in Primary Submovement (%)						
4b	95.5	3.6	75.4	25.3	TS*	8
5b	92.9	6.6	70.7	24.6	I	.6
					Age*	10.7

continued

Table 2. Influence of Target Size (*Continued*)

ID	Young M	Young SD	Elderly M	Elderly SD	Effect	F
Secondary Submovements (#)						
4b	.34	.24	1.2	1.4	TS*	20.2
5b	.45	.2	1.7	1.7	I*	8.1
					Age*	7.1
Normalized Jerk Score						
4b	19.3	6.5	33.1	23	TS*	13.3
5b	21.4	5.5	46.9	35.2	I*	7.4
					Age*	6.8

Notes: I = interaction. Degrees of freedom for comparisons with 3 items (2, 56), and for comparisons with 2 items (1, 28).

*$p < .05$.

older adults were significantly slower as amplitude increased (significant movement amplitude main effect), $F(1,28) = 34.5$, $p < .001$, ES = .36. Older adults were significantly slower than young adults at both movement amplitude (significant age main effect), $F(1,28) = 13.1$, $p < .005$, $P = .94$, ES = .17), and were differentially slower as movement amplitude increased (significant Age × Movement Amplitude interaction), $F(1,28) = 7.3$, $p < .05$, $P = .74$, ES = .09 (Figure 6a). Amplitude of peak velocity increased as movement amplitude increased for both groups (significant movement amplitude main effect), $F(1,28) = 139.8$, $p < .001$, ES = .70. Older adults produced significantly lower peak velocities across movement amplitude compared with young adults (significant age main effect), $F(1,28) = 14.8$, $p < .005$, $P = .96$, ES = .19, and did not increase amplitude of peak velocity at the same rate as young adults as movement amplitude increased (significant Age × Movement Amplitude interaction), $F(1,28) = 7.9$, $p < .01$, $P = .77$, ES = .10 (Figure 6b). Furthermore, relative time to peak velocity decreased as movement amplitude increased for both groups (significant movement amplitude main effect), $F(1,28) = 213.7$, $p < .001$, ES = .78. There was not a significant age effect (ES = 0), however there was a significant Age × Movement Amplitude, $F(1,28) = 6.2$, $p < .05$, $P = .67$, ES = .08 (Figure 6c).

Relative distance traveled in the primary submovement was significantly different only between groups (significant age main effect), $F(1,28) = 8.6$, $p < .01$, $P = .81$, ES = .11, with older adults covering less relative distance in the primary submovement at both amplitudes (Figure 6d). Older adults made more secondary, corrective submovements compared with young adults independent of amplitude (significant age main effect), $F(1,28) = 8.1$, $p < .01$, $P = .78$, ES = .11 (Figure 6e). Furthermore, older adults had significantly less smooth movements than young adults across all movement amplitudes (significant age main effect), $F(1,28) = 8.5$, $p < .01$, $P = .81$, ES = .11, and were differentially affected as movement amplitude was increased (significant Age × Movement Amplitude interaction), $F(1,28) = 6.1$, $p < .05$, $P = .66$, ES = .08 (Figure 6f).

Discussion

Collapsed Task Difficulty Comparison

To determine the systematic influence of task difficulty, IDs 4a and 4b, as well as 5a and 5b, were collapsed to create

Table 3. Influence of Movement Amplitude (MA)

	Young		Elderly			
ID	*M*	*SD*	*M*	*SD*	Effect	*F*
			Movement Time (ms)			
3	420	131	741	347	MA*	34.5
4a	528	125	1034	524	I*	7.3
					Age*	13.1
			Peak Velocity (cm/s)			
3	29	11.1	15.9	7.2	MA*	139.8
4a	48	16.7	27.6	12.9	I*	7.9
					Age*	14.8
			Time to Peak Velocity (%)			
3	45.9	3.4	48.1	6	MA*	213.7
4a	37.7	3.9	36.5	5.7	I*	6.2
					Age	.1
			Distance Traveled in Primary Submovement (%)			
3	94.4	7.1	77.4	26	MA	.4
4a	98.6	1.6	76.1	28	I	1.5
					Age*	8.6
			Secondary Submovements (#)			
3	.31	.14	.86	.84	MA	.5
4a	.16	.18	1.2	1.5	I	3.2
					Age*	8.1
			Normalized Jerk Score			
3	18.3	5.4	25.5	12.7	MA	2.9
4a	16	3.9	38.6	12.7	I*	6.1
					Age*	8.5
			Movement Time (ms)			
5a	609	140	1105	454	MA*	30.1
6	717	220	1304	557	I	2.6
					Age*	15.7
			Peak Velocity (cm/s)			
5a	21.2	9.1	12	5.1	MA*	156.9
6	38.1	14.7	21.7	8.9	I*	11.6
					Age*	13.2
			Time to Peak Velocity (%)			
5a	37.7	3.9	37.5	6	MA	.41
6	39.9	4.3	36.2	6.2	I*	5.0
					Age	1.3
			Distance Traveled in Primary Submovement (%)			
5a	91.2	4.4	64.8	27	MA*	4.3
6	93.1	7.4	69.7	26.2	I	.8
					Age*	13.2
			Secondary Submovements (#)			
5a	.79	.32	2	1.4	MA	0
6	.63	.28	2.1	1.9	I	1.8
					Age*	9.8
			Normalized Jerk Score			
5a	27.7	8.2	60.2	34.8	MA	1.9
6	23.9	5.4	56.9	44.2	I	0
					Age*	10.5

Notes: I = interaction. All degrees of freedom (1, 28).
$^*p < .05$.

IDs 4 and 5 respectively (Figure 4). This made it possible to evaluate IDs 2 to 6 in an ordinal manner. Overall comparisons revealed that as ID increased, movement durations lengthened as Fitts's law states, for both young and older adults (Figure 4a). Older adults' movement durations, however, increased at a greater rate than those of young adults did (Amrhein et al., 1991; Cooke et al., 1989; Goggin & Meeuwsen, 1992; Pohl et al., 1996; Stelmach et al., 1988; Walker et al., 1997; Welford, 1984).

Movement characteristics that differentiated older adults from young adults were peak velocity, relative time to peak velocity, number of secondary submovements, and normalized jerk scores. Peak velocity did not change systematically for either group, suggesting that it was not a major contributor to lengthened movement durations; however, relative time to peak velocity did change systematically for young and older adults. Although there were no age group differences, as ID increased, time to peak velocity decreased such that the majority of the time was spent in the deceleration phase as task difficulty increased (Billon, Bootsma, & Mottet, 2000). Distance traveled in the primary submovement was shortened as a function of ID, but it did not interact with age. The number of secondary submovements and normalized jerk scores increased differentially between young and older adults as a function of ID. However, both these variables are a function of distance traveled in the primary submovement, which did not systematically differentiate young and older adults. For the collapsed data comparison, combining target-size and movement-amplitude manipulations created ID changes. Kinematic changes were not systematic in relation to task difficulty alone as would be expected if there is a global affect of information-processing slowing (Fitts, 1954; Haaland, Harrington, & Grice, 1993; Welford, 1984). To get a better understanding of how each of these variables influenced performance, we partitioned data into subsets in which increases in ID were achieved by systematically decreasing target size or increasing movement amplitude.

Influence of Target Size

To determine the influence of target size, we held movement amplitude constant while target-size was manipulated. Older adults showed greater increases in movement time compared with young adults as target size decreased (Figure 5a). Peak velocity, relative distance traveled in the primary submovement, number of secondary submovements, and normalized jerk scores all exhibited significant Age × Target Size interactions, suggesting that older adults behave differently than young adults for decreasing target sizes (Figure 5). The movement durations of older adults were differentially slower at the smallest target size (highest ID) at which the lowest peak velocities were observed for both young and older adults. Pearson *r* correlations of the differences across changes in target size between movement time and particular kinematic variables were squared to interpret as variance accounted for in slower movement times of older adults. Peak velocity accounted for 22% ($r = -.47$) of variance in movement time of young adults but only 1% ($r = .10$) of variance in older adults.

Relative distance traveled in the primary submovement showed differential effects between groups as target size was decreased such that older adults covered substantially less distance in the primary submovement across the three target sizes, specifically between IDs 3 and 5a, the older adults shortened the relative primary submovement distance to a greater extent than the young adults. Relative distance traveled in primary submovement accounted for 23% ($r = -.48$) of variance in movement time for older adults, but

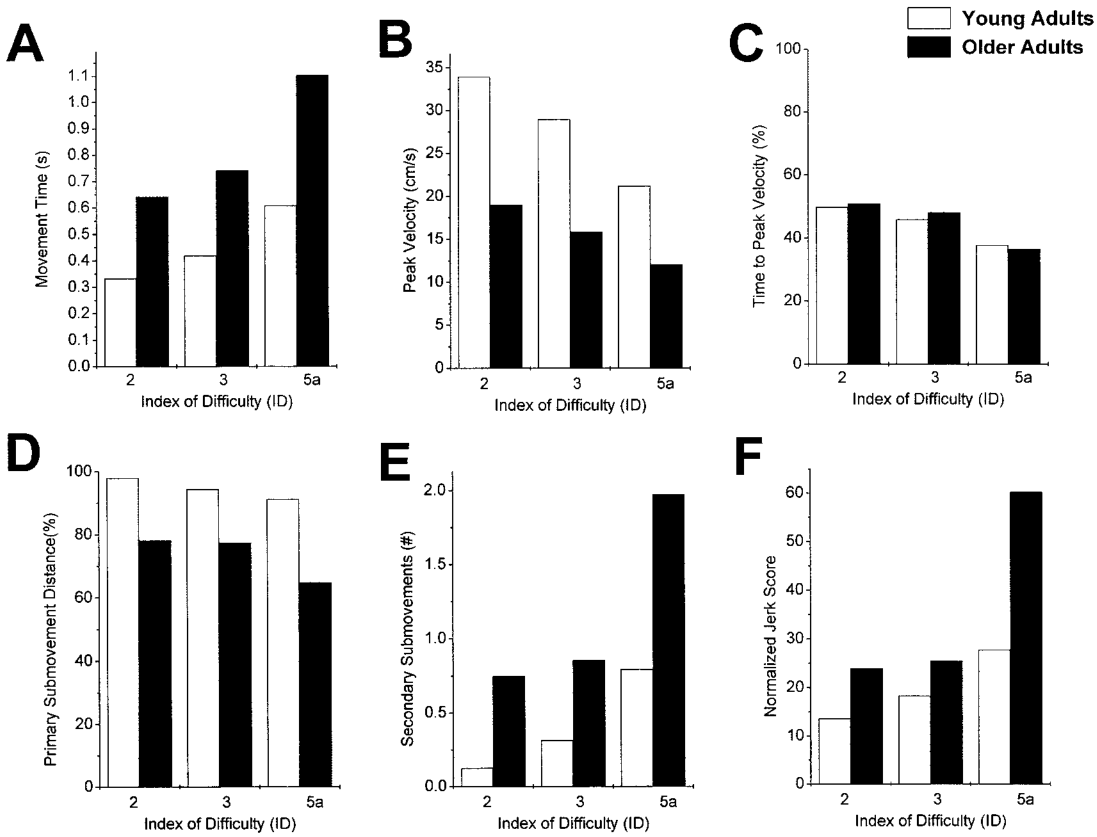

Figure 5. Influence of target size on movement kinematics for young and older adults. (A) Movement time (s), (B) Peak velocity (cm/s), (C) Time to peak velocity (%), (D) Primary submovement distance (%), (E) Secondary submovements (#), (F) Normalized jerk score.

only 2% ($r = -.13$) for young adults. Thus, relative distance traveled in primary submovement determined a large portion of slower movement times in older adults when target size was decreased.

Furthermore, increasing accuracy constraints caused the older adults to alter the microstructure of their movements such that more secondary, corrective movements were needed to achieve a target, thus contributing to differentially slower movement times observed as target size was decreased (Bellgrove et al., 1998; Darling et al., 1989; Pratt et al., 1994; Seidler-Dobrin & Stelmach, 1998; Walker et al., 1997). In the present study, secondary submovements accounted for 76% ($r = .87$) of the variance in movement times for older adults, whereas for young adults they only accounted for 23% ($r = .48$) of the variance. These results indicate that accuracy constraints influence movement substructure in older adults and lead to increased variability in older adults. Pratt and colleagues (1994) observed shortened primary submovements in older adults compared with young adults. They reported that older adults were unable to lengthen the distance traveled in the primary submovement with extensive practice. The present data furthers these findings and establishes that shortened primary submovements were a substantial contributor to movement slowing in older adults when target size was decreased, placing an emphasis on accuracy.

Influence of Movement Amplitude

To determine the influence of movement amplitude, target size was held constant while movement amplitude was manipulated. Although in both groups movement time was increased by movement amplitude increases, older adults again were differentially slower than young adults at the longer movement amplitudes (Figure 6a). Several characteristics exhibited Age × Movement Amplitude interactions including peak velocity, relative time to peak velocity, secondary submovements, and normalized jerk scores (Figure 6). Peak velocity increased for both groups as movement amplitude increased, however older adults did not increase their peak velocity similarly to young controls. Pearson r correlations of the differences across changes in movement amplitude between movement time and particular kinematic variables were squared to interpret as variance accounted for in slower movement times of older adults. Peak velocity accounted for 20% ($r = -.45$) of variance in movement time for young adults, but only 1% ($r = -.10$) for older adults. This suggests that older adults did not scale their velocity as movement amplitude was increased in the same manner as young adults did. However, differential increases in peak-velocity amplitude as a function of movement amplitude increases led to differentially slower movement times, and thus the slower movement times observed in older adults in this comparison.

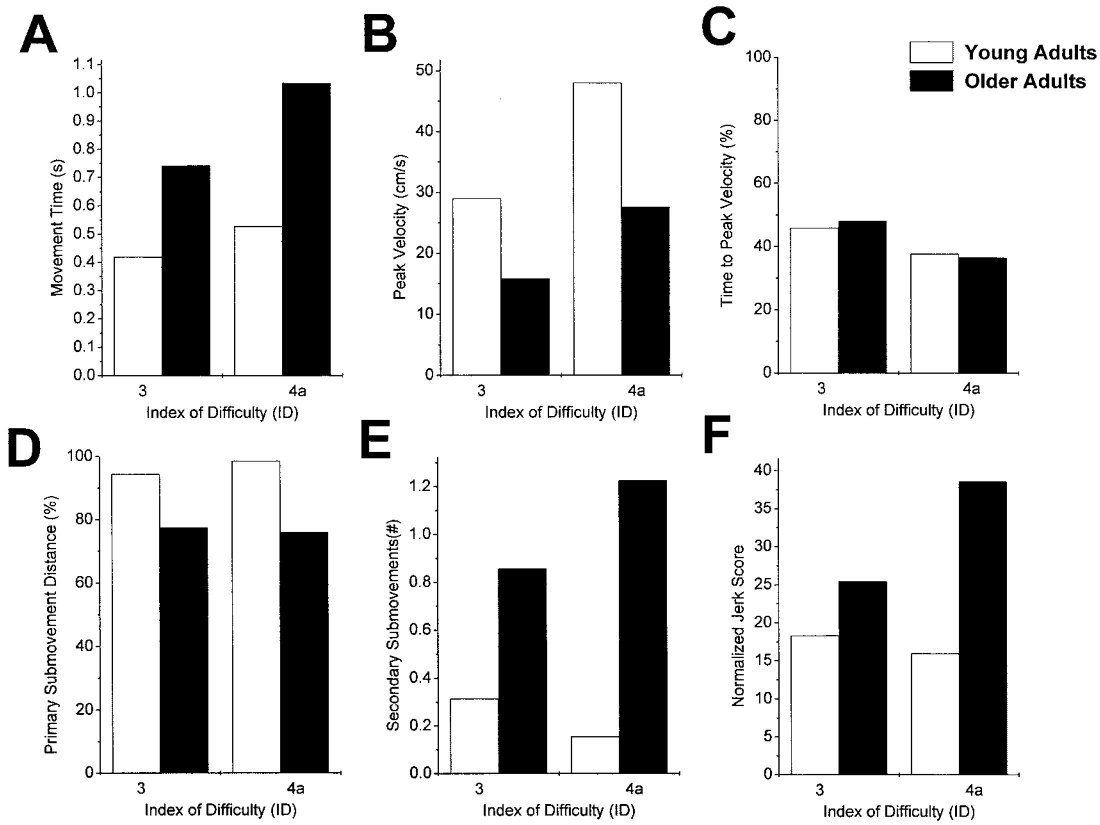

Figure 6. Influence of movement amplitude on movement kinematics for young and older adults. (A) Movement time (s), (B) Peak velocity (cm/s), (C) Time to peak velocity (%), (D) Primary submovement distance (%), (E) Secondary submovements (#), (F) Normalized jerk score.

There was an overall slowing of older adults compared with young adults that may be explained by the shorter relative distance traveled in the primary submovement (Pratt et al., 1994; Seidler-Dobrin & Stelmach, 1998). However, of interest in this experiment was the specific contribution to the increased rate of slowing observed at the longer movement amplitudes. This difference was explained by the inability to ramp force as observed by differentially lower peak velocities across movement amplitudes. The number of secondary submovements and normalized jerk scores showed significant interactions and may be a consequence of lower peak velocities resulting in slow movements with multiple inflections and less smooth movements. From this comparison it was determined that the inability of older adults to increase peak velocity at the same rate as young adults primarily contributed to slower movement times observed in older adults as movement amplitude increased and higher movement variability appeared. The inability to ramp velocity may be a consequence of neuromuscular changes (Galganski, Fuglevand, & Enoka, 1993; Welford, 1984).

Summary

Older adults respond to changes in task difficulty by making different adjustments in response to accuracy and amplitude constraints. When the data were separated into influences of target size and of movement amplitude, the kinematic characteristics that differentiated young and older adults were dependent on the task constraints imposed. Although other parameters changed, relative distance traveled in the primary submovement was the primary source of movement slowing when target size was decreased, whereas differential scaling of peak velocity was the primary contributor when movement amplitude was increased.

These findings suggest that older adults are unable to effectively propel their limb to the target in a single step, which results in multiple secondary, corrective submovements, causing their limb movement to be less smooth and slower. The exact cause for having a reduced ability to propel the limb to a target in a single step is not understood. Some have thought it may be related to a central planning deficit but this seems unlikely (Amrhein et al., 1991; Goggin & Meeuwsen, 1992; Haaland, Harrington, & Grice, 1993; Seidler-Dobrin & Stelmach, 1998; Stelmach et al., 1988; Welford, 1984). If differential effects were a result of central mechanisms it might be expected that all task conditions would show similar impairments, which was not the case in this study.

Another possibility may be that older adults could not produce the necessary forces to complete the desired movement resulting in lower peak velocities and shorter relative submovement distances. Galganski and colleagues (1993) reported that age affected force variability at low target forces. This consequently led to the inability to ramp forces accurately and/or efficiently. The present data for manipulations in movement amplitude could be explained by this interpretation. However, Walker and colleagues (1997) have previously shown that when accuracy was not a factor in an aiming movement, older adults produced movement velocities that were very similar to those of the young adults. The combination of the findings from Galganski and colleagues and Walker and colleagues suggests that older adults are able to produce forces needed to propel the limb to the target, however the ability to modulate forces is constrained by the presence of terminal accuracy requirements. This decrement in force modulation may result from observed problems in the timing and phasing of muscle activation (Darling et al., 1989). A force modulation deficit may lead to the inability to propel the limb to the target effectively; however, similar kinematic outcomes would be expected in the task manipulations if this were the only mechanism.

Older adults have been shown to produce normal agonist muscle bursts, but abnormal phasic antagonist muscle bursts during the deceleration phase of the movement resulting in increased cocontraction (Darling et al., 1989). Seidler-Dobrin, He, & Stelmach (1998) have shown that older adults have considerably more cocontraction during point-to-point movements compared with young adults. Cocontraction may help reduce the variability and speed of the movement allowing participants to have more control of the terminal phase of the movement, thus leading to lower velocities and shorter distances traveled in the initial phase of their movement. Furthermore, opposing muscles may act to reduce the torque about the joints, thus restricting the ability to propel the limb accurately towards the target. Again, this may lead to the outcomes observed in this study, but further research is necessary to confirm.

The present study has established that older adults are affected differently than young adults during a Fitts's law task, suggesting slowing in older adults' aiming movements is not necessarily a consequence of a unitary factor. Components of movement, measured by kinematic analyses, contributed differently to movement slowing when target size and movement amplitude were manipulated separately.

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