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ABSTRACT. The purpose of the present investigation was to examine whether the ability to adapt to task constraints is influenced by short-term practice in older adults. Young (18–29 years old) and old (65–75 years old) adults produced force output to a constant force target and a 1-Hz sinusoidal force target by way of the index finger flexion. Participants completed each task 5 times per session for 5 concurrent sessions. The amount and structure of force variability was calculated using linear and nonlinear analyses. As expected, there was a decrease in the magnitude of variability (coefficient of variation) in both tasks and task-related change in the structure of force variability (approximate entropy) with training across groups. The authors found older adults to have a greater amount of variability than their younger counterparts in both tasks. Older adults also demonstrated an increase in the structure of force output in the constant task but a decrease in structure in the sinusoidal task. Age differences in the adaptability to task constraints persisted throughout practice. The authors propose that older adults' ability to adapt sensorimotor output to task demands is not a result of lack of familiarity with the task but that it is, instead, characteristic of the aging process.

Keywords: force control, loss of complexity, variability

It is well established that there is a wide range of performance decrements in sensorimotor performance with advanced age. A common finding is that there is an increase in the amount of motor variability across a broad set of tasks (Enoka et al., 2003; Sosnoff & Newell, 2006b; Tracy, Mehoudar, & Ortega, 2007). Although the amount of age-related differences in motor variability is an important marker of neuromuscular health, recent work has demonstrated that the dynamic structure of motor variability provides unique information about the function of the neuromuscular system (Sosnoff, Valantine, & Newell, 2006; Vaillancourt, Slifkin, & Newell, 2001).

The dominant view concerning the influence of the aging process on the dynamic structure of physiological functioning is the loss of complexity hypothesis of aging (Lipsitz & Goldberger, 1992). The loss of complexity hypothesis maintains that with advanced age there is a decrement in *complexity*—that is, aberrations in the time and frequency structure of physiological output (Glass & Mackey, 1988)—and that this decline is linked to functional deficits (Lipsitz, 2002; Lipsitz & Goldberger). The use of nonlinear dynamical methods allows researchers to quantify the time and frequency structure of physiological signals (Stergiou, 2004). Overall, examinations of a broad range of physiological systems have supported the main tenets of the loss of complexity hypothesis (Goldberger et al., 2002).

However, predictions of the loss of complexity hypothesis have not been supported when sensorimotor function has been examined (Vaillancourt & Newell, 2002; Vaillancourt & Newell, 2003; Vaillancourt, Sosnoff, & Newell, 2004). It has been suggested that the loss of complexity hypothesis focuses on the single timescale of the developmental aging process. This critique is based on the theoretical view that the observed motor behavior at a given time results from a dynamic interaction of environmental, organismic, and task constraints (Newell, 1986). Newell and colleagues (Newell, Vaillancourt, & Sosnoff, 2006; Vaillancourt & Newell, 2002) have suggested that the loss of complexity hypothesis does not take into account task constraints on motor action. It is important to note that, in an aging context, the ability to adapt to environmental demands (i.e., task constraints) is essential for independence and maintenance of health (Lipsitz, 2002).

The loss of adaptability hypothesis is based in part on the concept that individual tasks have distinct intrinsic dynamical degrees of freedom (Newell & Vaillancourt, 2001). In this view, successful completion of sensorimotor tasks requires output with various levels of complexity. For example, Newell, Broderick, Deutsch, and Slifkin (2003) demonstrated that tasks that are analogous to fixed point attractors, such as constant force output, require elevated levels of sensorimotor complexity, whereas tasks that are similar to limit cycles, such as rhythmical force output, require lower levels of complexity for successful completion.

In an empirical examination of the loss of adaptability hypothesis, Vaillancourt and Newell (2003) examined whether the age-related differences in the time and frequency structure (i.e., complexity) of force output are dependent on task demands. Young and old adults produced isometric force output to a constant and a sinusoidal target. In both tasks, older adults were found to have greater motor variability. Aging clearly led to a loss of complexity (i.e., increased structure) when realizing a task demand that required an increase in dynamical degrees of freedom from the intrinsic dynamics (i.e., constant isometric force production), whereas aging was associated with an increase in complexity when the task goal required a reduction in the dynamical degrees of freedom of the motor output (i.e., sinusoidal force production; Vaillancourt et al., 2004). Overall, the findings were

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supportive of the loss of adaptability hypothesis, with older adults demonstrating a loss of adaptability to task constraints with a loss of complexity arising in certain task-dependent instances (Newell et al., 2006).

Quantification of behavioral complexity is central to this investigation. There are several nonlinear dynamical measures capable of quantifying the complexity of a system. Approximate Entropy (ApEn; Pincus, 1991) is a well-established analytical technique sensitive to the signal's time domain complexity. Higher values of ApEn indicate less time-dependent structures and are indicative of increases in complexity. Spectral analysis is another well-established analytical tool sensitive to a signal's frequency domain complexity. A broadband distribution of spectral power is indicative of less structure and greater complexity (Lipsitz, 2002). Researchers have used ApEn and spectral analysis extensively in the aging complexity discussion (Lipsitz & Goldberger, 1992; Newell et al., 2006).

Specific processes relating to sensorimotor processing (Miall, Weir, & Stein, 1985; Slifkin, Vaillancourt, & Newell, 2000; Sosnoff & Newell, 2005) and physiological tremor (Elble & Koller, 1990) occur in different frequency bands observed in isometric force spectral profiles. The lack of adaptability in older adults observed by Vaillancourt and Newell (2003) was associated with increased low frequency power (0–4 Hz bandwidth) in their force spectrum. Recently, it was demonstrated that older adults are less capable of using fast timescales of visual information (4–12 Hz; Sosnoff & Newell, 2008). As low frequency power in isometric force production is associated with sensorimotor processing (Miall et al., 1985; Slifkin et al., 2000), researchers have maintained that older adults are overly reliant on sensorimotor processing. An increase in the reliance on sensorimotor processing with aging is characterized by a less broadband distribution of the force spectrum and is analogous to a decrease in complexity.

It is well established that older adults can improve sensorimotor performance with practice (Bock & Schneider, 2002; Seidler, 2007). Specifically, it has also been shown that practice can improve age-related differences in the magnitude of motor variability (Christou, Poston, Enoka, & Enoka, 2007; Keen, Yue, & Enoka, 1994; Kornatz, Christou, & Enoka, 2005; Ranganathan, Siemionow, Sahgal, Liu, & Yue, 2001), but there is a dearth of evidence that practice influences age-related differences in the time and frequency structure of motor output. Newell et al. (2003) demonstrated that young adults can modify the structure of motor output to task constraints with practice. Consequently, the purpose of this investigation was to examine the influence of practice on the structure of force output as a function of age and task. Specifically, we examined if practice can minimize older adults' loss of adaptability to task constraints. On the basis of the extant data, we predicted that following practice, older adults would still exhibit a loss of adaptability in their sensorimotor output, in comparison with young adults and an increased reliance on sensorimotor processing.

Method

Participants

In all, 72 participants (37 women, 35 men) were recruited for the investigation. They were divided equally into one of two groups on the basis of age. Participants in the old group ($n = 36$) were between the ages of 65 and 79 years ($M = 72.1$ years, $SD = 4.5$ years), and participants in the young group ($n = 36$) were between the ages of 18 and 30 years ($M = 22.9$ years, $SD = 3.4$ years). The old age group comprised 19 women and 17 men, and the young age group comprised 18 men and 18 women. In addition, older participants were screened for dementia with the Mini Mental State Exam (Folstein, Folstein, & McHugh, 1975). Participants met the following criteria: (a) free of any neuromuscular disorders, severe arthritis, or cognitive impairments; (b) able to ambulate without the use of an assistive device (i.e., cane or walker); (c) right handed; and (d) free of tremor disorders. All participants signed informed consent forms that were approved by the University of Illinois Internal Review Board.

Apparatus

Each participant sat in a chair in front of a 17-in. flat-screen computer monitor that was approximately 35 cm in front of them, sitting on a table approximately 100 cm high. The participants placed their right arm and hand palm down on the table, with the distal palmar pad of their index finger on an Eltran EL-500 load cell (1.27-cm diameter) 25 cm in front of their midline. The load cell recorded compressive forces produced by index finger flexion.

The voltage changes from the load cell were amplified by a Coulbourn resistive bridge strain amplifier (V72-25, Coulbourn Instruments, Whitehall, PA), with an excitation voltage of 10 V and an amplifier gain of 100 V. The analog force signal was sampled at 140 Hz with a 16-bit analog-to-digital converter. The smallest increment of change in force that could be detected was 0.0016 N.

Procedures

Estimation of maximal voluntary contraction (MVC). The participant's MVC was determined on the first and last day of testing. Participants were instructed to press down with maximal force on the load cell using index finger flexion without changing the configuration of the hand, wrist, or arm. Trials in which there was visible movement were discarded and redone. Visual feedback of the participant's force output was displayed on the computer monitor. Three 6-s maximal contractions were recorded with 30 s of rest between each contraction. The highest force produced over the three trials determined the participant's MVC.

Experimental design and instructions. Participants produced isometric force output using index finger flexion. They were instructed to adjust their force output to match a target line displayed on the computer screen. The target line corresponded to 15% of the individual participant's MVC.
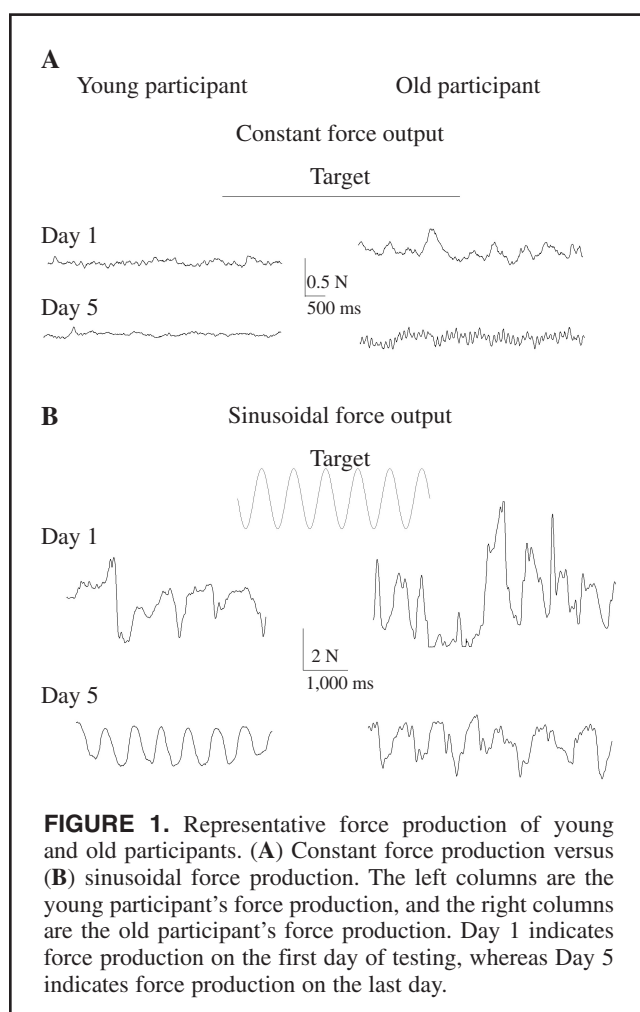
As the participant produced force output, a series of yellow dots corresponding to the force output appeared on the screen. The force trajectory moved from left to right with time across the monitor.

To manipulate task constraints, participants produced force output to a constant target (15% MVC) and a sinusoidal target (see Figure 1). The sinusoidal target was centered at 15% MVC and fluctuated between 10% and 20% MVC at 1 Hz. Half of the participants produced force output to the constant target first, followed by sinusoidal force output.

Each testing session included five trials of each target performed over 5 continuous days (5 Trials × 2 Conditions × 5 Days = 50 trials total). Each trial was 20 s in length, with a 30-s rest interval to prevent fatigue. After the completion of each condition, participants were given a 1-min rest period.

Participants were instructed to minimize the deviation between the yellow force trajectory and the red target line. Each participant received a feedback score at the end of each trial to encourage performance. We used root mean square error for the feedback score, and we calculated it using the following equation:

$$[\Sigma(s - f_i)^2 / n - 1]^{1/2},$$

FIGURE 1. Representative force production of young and old participants. (**A**) Constant force production versus (**B**) sinusoidal force production. The left columns are the young participant's force production, and the right columns are the old participant's force production. Day 1 indicates force production on the first day of testing, whereas Day 5 indicates force production on the last day.

where s is the value of the target, f_i is the ith force sample, and n is the number of data samples.

Data analysis. The initial 7 s and the final 1 s were removed from the data to avoid the effects of the initial stabilization period and any premature cessation of force production. Overall, the middle 12 s were analyzed. All data processing was performed using software written in MATLAB (Version 7.0; Mathworks, Natick, MA).

Task performance. To access task performance as a function of age and task, we calculated the within-trial mean and coefficient of variation (*SD*/*M*) of the force data.

Structure of force output. We examined the influence of age and task on the structure of force output in the time and frequency domain. The time domain structure of force output was assessed with ApEn (Pincus, 1991). ApEn yields a single value that quantifies the regularity (structure) of a time series. A regular (i.e., structured) signal such as an ideal sinewave would have an ApEn value approaching 0, whereas a random time series (white noise) would have a value close to 2. Increases in ApEn have been interpreted as a decrease in the signal's time sequential structure (Pincus). The appendix in Slifkin and Newell (1999) provides a brief explanation of how ApEn is calculated.

We used spectral analysis to access how the frequency domain structure of force output was accessed. We computed the power spectrum with the SPECTRUM command in MATLAB (Version 7.0) that uses Welch's averaged periodogram method. We used a 256-point nonoverlapping Hanning window with a sampling frequency of 140 Hz, resulting in a 0.39-Hz bin width. The power in each bin represented the amplitude of force oscillations that occur at the frequency specified by the bin. Changes in power as a function of age and task were calculated. Specifically, we determined the amount of power in 4-Hz bandwidths from 0 to 4 Hz, 4 to 8 Hz, and 8 to 12 Hz (Vaillancourt & Newell, 2003). This frequency range accounted for approximately 99% of the power in the spectrum.

Statistical analysis. The average of the five trials of the dependent variables previously discussed was placed independently in a three-way mixed model (2 × 5 × 2) analysis of variance (ANOVA), with age as a between-subjects factor and day and task as within-subject factors. When relevant, we used Tukey's Honestly Significant Difference Test to determine the specific effects contributing to the general ANOVA. All statistics were evaluated as significant when there was less than a 5% chance of making a Type I error ($p < .05$), and only significant effects are reported. All statistical analyses were completed using SPSS statistical package (SPSS, Chicago, IL).

Results

MVC

MVC ranged from 6.47 N to 32.41 N, with an average of 16.52 N (*SD* = 5.02 N). There was no change in MVC from the first (16.34 N) experimental session to the last (16.64 N)

experimental session ($p = .33$). There was a trend toward greater MVC in the young adults (17.47 N) than in the older adults (15.52 N), but participants did not show traditional levels of significance ($p = .07$).
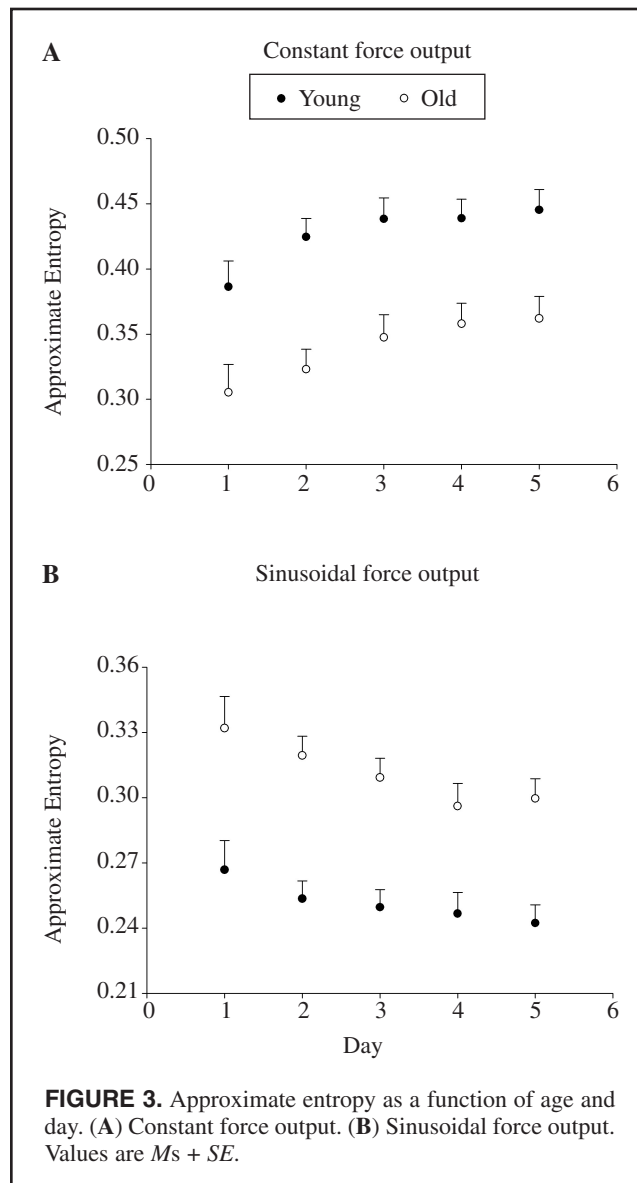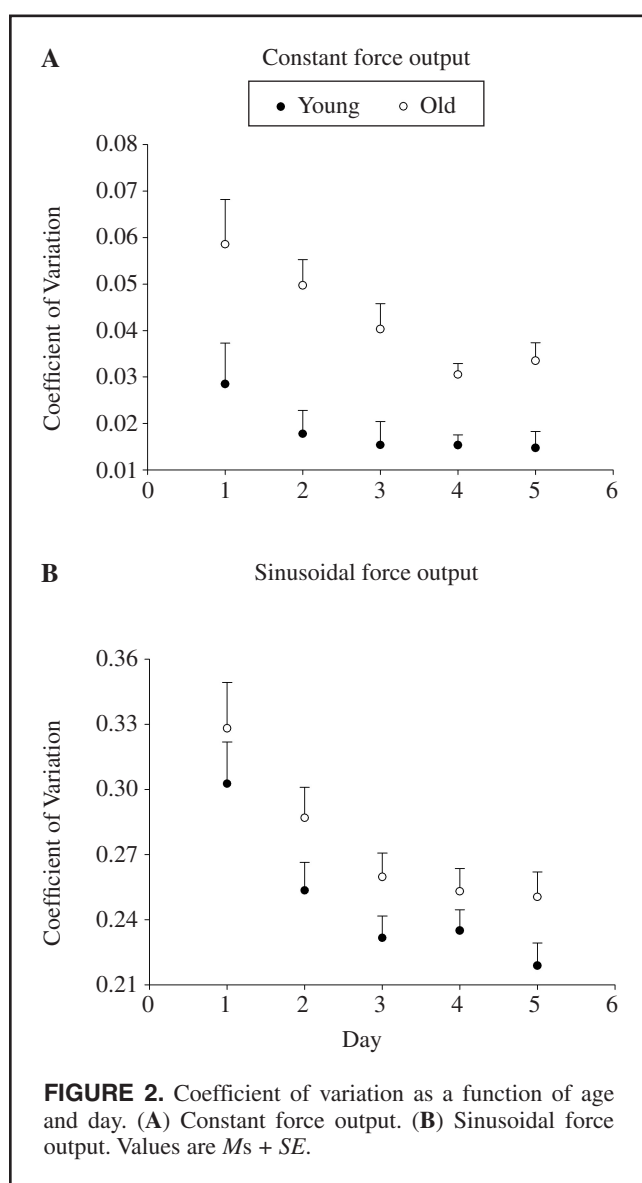
Magnitude of Force Variability

It is clear in Figures 2A and 2B that (a) all age groups improved their performance as a function of practice, (b) the constant force output is less variable than the sinusoidal force output, and (c) the older adults have greater force variability. Statistical analysis supported these observations, demonstrating a main effect for day, $F(4, 308) = 27.4$, $p < .001$, $\eta^2 = .26$; for task, $F(1, 77) = 1200$, $p < .001$, $\eta^2 = .94$; and for age, $F(1, 77) = 7.4$, $p < .001$, $\eta^2 = .09$. Post hoc analysis revealed that there was a decrease in coefficient of variation (CV) as a function of training, with the greatest CV (0.179) occurring on the first day and the lowest CV occurring on the last day (0.129). There was no significant improvement in force variability from the 3rd day to the 5th day. Overall, the CV was lower in the constant force task (0.030) than in the sinusoidal task (0.262). Across both tasks, the young age group (0.133) had lower CV than did the older age group (0.159). Statistical analysis focusing on the separate tasks revealed that the older adults were more variable in both constant (0.042 vs. 0.018) and sinusoidal tasks (0.275 vs. 0.248; $ps < .05$).

Structure of Force Variability

Figures 3A and 3B illustrate the effect of day, task, and age on ApEn. It is clear in the figure that there is a significant effect of task, with the ApEn being greater in the constant force task than in the sinusoidal task (0.380 vs. 0.222, respectively), $F(1, 72) = 209.8$, $p < .001$, $\eta^2 = .75$. It is also noticeable that the effect of day and age on the structure of force variability is dependent on task. In line with this observation,


FIGURE 2. Coefficient of variation as a function of age and day. (**A**) Constant force output. (**B**) Sinusoidal force output. Values are Ms + SE.

FIGURE 3. Approximate entropy as a function of age and day. (**A**) Constant force output. (**B**) Sinusoidal force output. Values are Ms + SE.

we found a Task × Age interaction, $F(1, 72) = 43.5$, $p < .001$, $\eta^2 = .38$, and a Task × Day interaction, $F(4, 288) = 32.9$, $p < .001$, $\eta^2 = .31$. Post hoc analysis revealed that the Task × Age interaction resulted from the young age group's having greater ApEn than older adults in constant force output (0.427 vs. 0.339) but lower ApEn in sinusoidal force output (0.192 vs. 0.251). Similarly, the Day × Task interaction resulted in an increase in ApEn with practice in constant force output, but a decrease in ApEn with training in sinusoidal force output.

Adaptability

To further examine the interaction between age and task on the structure of force variability, we calculated difference scores. On the basis of previous work (Newell et al., 2003; Vaillancourt & Newell, 2003), it is known that greater adaptation to task demand will result in greater difference between ApEn values across tasks. We calculated a difference score indicative of adaptability by subtracting individual trial ApEn values for the sinusoidal task from those of individual trails of the constant task. As such, a greater difference score is indicative of greater adaptability of motor output across tasks. Figure 4 illustrates the effect of age and day on difference scores. It is clear in the figure that although both age groups increase their adaptability with practice, age differences persist across practice.
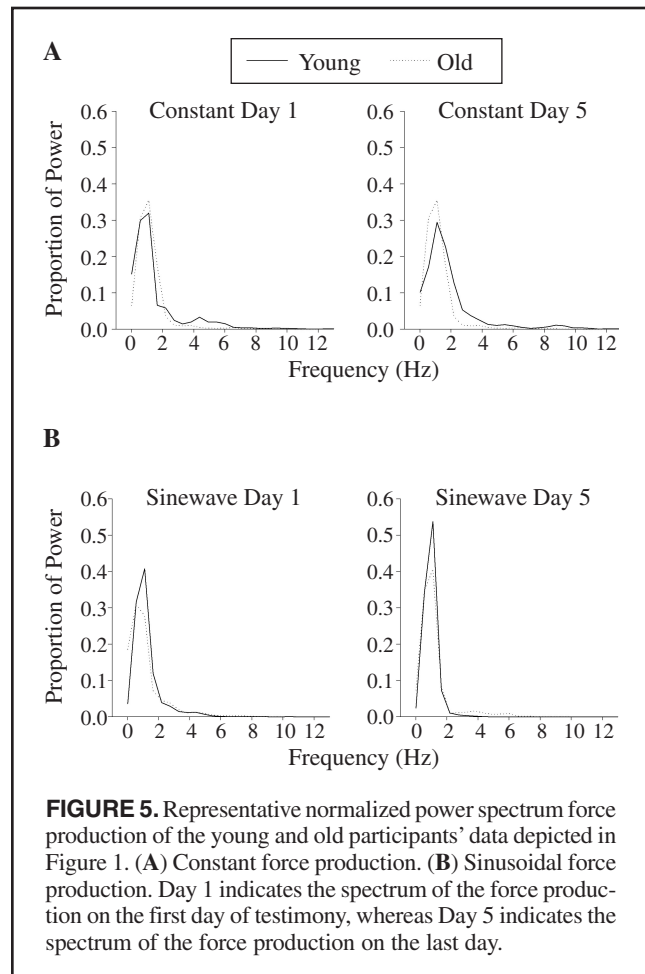
Statistical analysis of the difference scores included a mixed model two-way (5 × 2) ANOVA with day as a within-subject factor and age as a between-subjects factor. This analysis confirmed main effects for day, $F(4, 288) = 32.92$, $p < .001$, $\eta^2 = .31$, and for age, $F(1, 72) = 43.51$, $p < .001$, $\eta^2 = .38$. Post hoc analysis revealed that adaptability increased with practice from 0.106 on Day 1 to 0.193 on Day 5. Overall, young adults had greater adaptability (0.235) than did
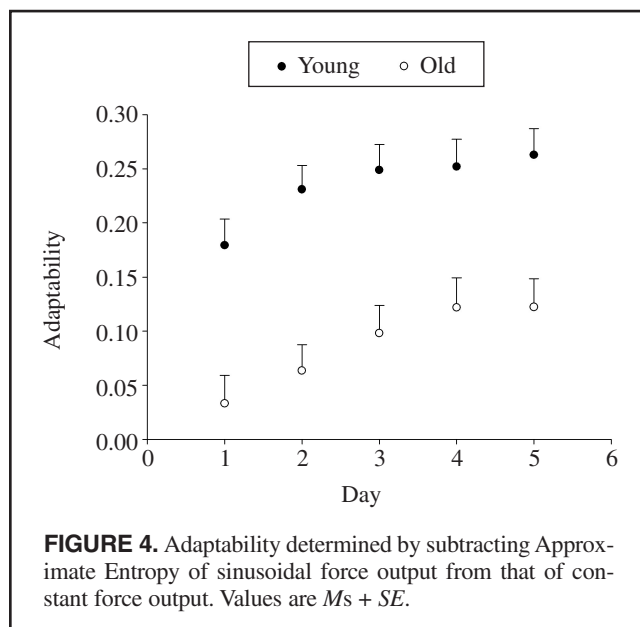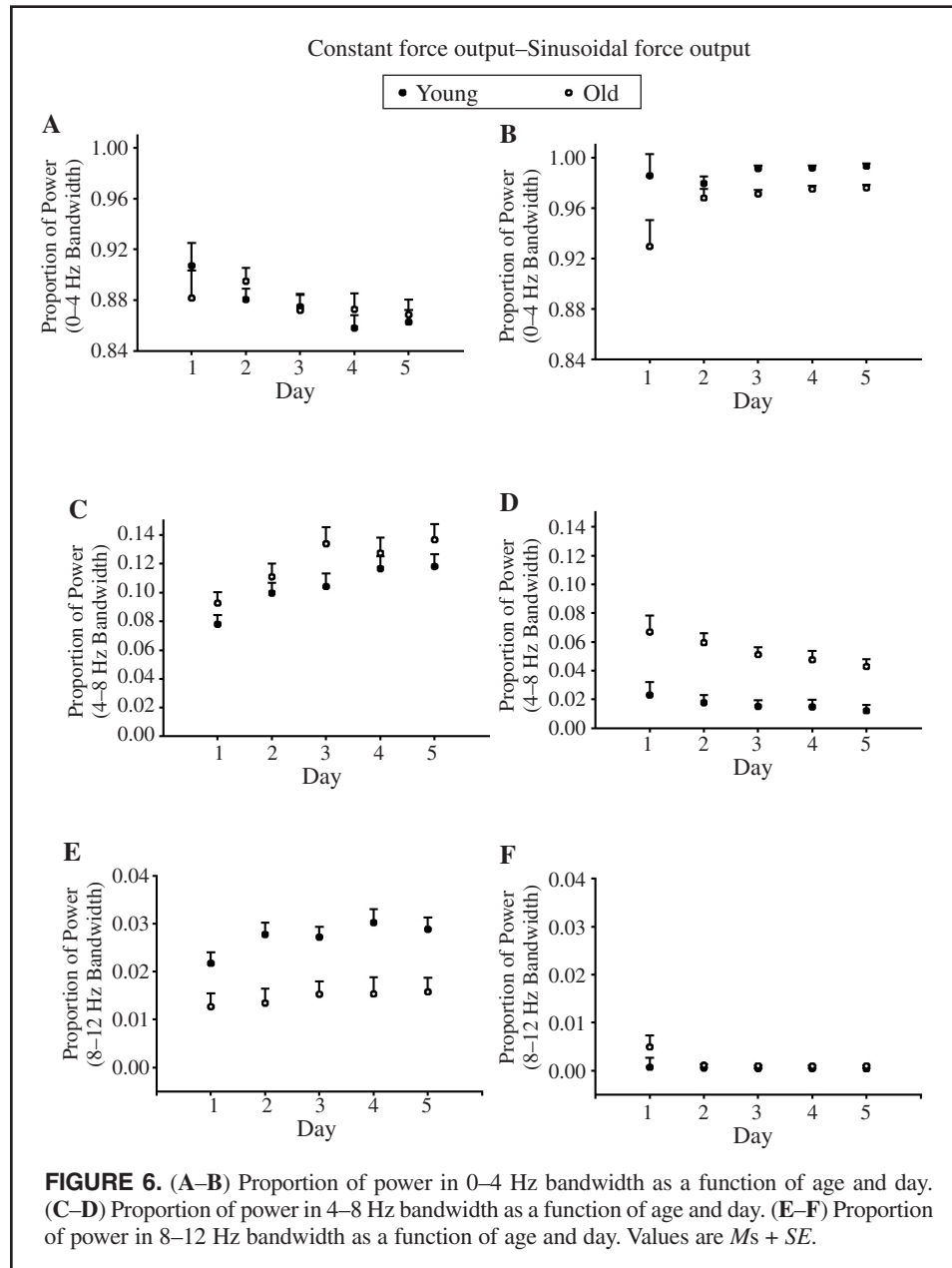
older adults (0.088). The lack of an Age × Day interaction indicates that the older adults' loss of adaptability persists throughout practice.

Figure 5 illustrates the normalized power spectra of the same representative data as shown in Figure 1. It is clear in Figure 5 that there are distinct effects of age, practice, and task on the frequency structure of force output. Although the majority of power is found in the low frequency bandwidth (< 4 Hz), there are subtle task and age differences seen in the 4–8 Hz bandwidth. To examine whether these individual differences were observed across the age groups, we conducted more detailed analysis.

Figures 6A and 6B depict changes in the proportion of power ($POP_{0-4\ Hz}$) in the 0–4 Hz bandwidth as a function of age, task, and training. Three observations can be made from the figure: (a) The sinusoidal task has greater $POP_{0-4\ Hz}$ overall, (b) change in the $POP_{0-4\ Hz}$ as a function of training is mediated by task, and (c) there is a greater $POP_{0-4\ Hz}$ in the young adult group in the sinusoidal task. Statistical analysis confirmed these observations, revealing a main effect for task, $F(1, 72) = 258.1$, $p < .001$, $\eta^2 = .80$; for interactions between task and age, $F(1, 72) = 4.4$, $p < .05$, $\eta^2 = .04$; and for day and task, $F(4, 288) = 25.3$, $p < .01$, $\eta^2 = .28$. The sinusoidal task (0.976) had greater $POP_{0-4\ Hz}$ in the 0–4 Hz

FIGURE 4. Adaptability determined by subtracting Approximate Entropy of sinusoidal force output from that of constant force output. Values are Ms + SE.

FIGURE 5. Representative normalized power spectrum force production of the young and old participants' data depicted in Figure 1. (**A**) Constant force production. (**B**) Sinusoidal force production. Day 1 indicates the spectrum of the force production on the first day of testimony, whereas Day 5 indicates the spectrum of the force production on the last day.

FIGURE 6. (**A–B**) Proportion of power in 0–4 Hz bandwidth as a function of age and day. (**C–D**) Proportion of power in 4–8 Hz bandwidth as a function of age and day. (**E–F**) Proportion of power in 8–12 Hz bandwidth as a function of age and day. Values are Ms + SE.

bandwidth than did the constant force task (0.880). The interaction between task and age resulted from the younger adults having greater $POP_{0-4\ Hz}$ (0.988) than did the older adults only in sinusoidal force production (0.964). The Day × Task interaction resulted from a decrease in $POP_{0-4\ Hz}$ with training in the constant force task (0.891 to 0.862) and an increase in $POP_{0-4\ Hz}$ (0.958 to 0.985) in the sinusoidal task with training.

Similar to the 0–4 Hz bandwidth, the POP in the 4–8 Hz bandwidth ($POP_{4-8\ Hz}$) of the force spectrum was influenced by age, task, and practice. It is clear in Figures 6C and 6D that the old group had greater $POP_{4-8\ Hz}$ than the young group (0.087 vs. 0.060, respectively), $F(1, 72) = 16.6$, $p < .05$, $\eta^2 = .20$. The constant force task was found to have greater $POP_{4-8\ Hz}$ than the sinusoidal task (0.112

vs. 0.035, respectively), $F(1, 72) = 150.96$, $p < .001$, $\eta^2 = .69$. We also observed an interaction between task and day, $F(4, 268) = 22.82$, $p < .01$, $\eta^2 = .25$. This interaction resulted from an increase in $POP_{4-8\ Hz}$ in the constant task with practice, but a decrease in $POP_{4-8\ Hz}$ in the sinusoidal task with practice.

It is clear in Figures 6E and 6F that age, task, and practice influence the proportion of power in the 8–12 Hz bandwidth ($POP_{8-12\ Hz}$). We noted a main effect for task, $F(1, 72) = 133.69$, $p < .001$, $\eta^2 = .66$; for age, $F(1, 72) = 9.75$, $p < .05$, $\eta^2 = .125$; for interactions between task and day, $F(4, 276) = 9.76$, $p < .05$, $\eta^2 = .12$; and for task and age, $F(1, 72) = 16.72$, $p < .05$, $\eta^2 = .20$. Constant force output had greater $POP_{8-12\ Hz}$ than did sinusoidal force production (0.021 vs. 0.001, respectively), and young adults had greater $POP_{8-12\ Hz}$

than did older adults (0.014 vs. 0.008, respectively). The interaction between task and day resulted from an increase in POP$_{8-12\,Hz}$ with training in the constant task, but a reduction in POP$_{8-12\,Hz}$ with training in the sinusoidal task. The Age × Task interaction stemmed from the older adults's having lower POP$_{8-12\,Hz}$ in the constant force task (0.015 vs. 0.027), but greater POP$_{8-12\,Hz}$ in the sinusoidal force output (0.002 vs. 0.0001). Because of the minimal amount of power in the 8–12 Hz bandwidth, caution should be used in interpreting these results.

Discussion

Aging and the Loss of Adaptability Hypothesis

The current investigation examined whether the decline in older adults' ability to adapt to task constraints (Newell et al., 2006; Vaillancourt & Newell, 2002) would be influenced with short-term practice. To address this empirical question, young and old adults produced constant and sinusoidal isometric force output over five consecutive testing sessions. Overall, we found that older adults have greater magnitude of force variability across tasks over the practice period. As expected, older adults were also found to have less structure in their constant force output and greater structure in their sinusoidal force output. The age differences in the dynamic structure persisted throughout the practice period. The persistence of the Age × Task interaction is indicative of an age-related loss of adaptability that is not overcome with practice.

The interaction between task and force structure is counter to the predictions of the loss of complexity hypothesis of aging (Lipsitz & Goldberger, 1992), which suggests that older adults should have increased structure (i.e., decreased complexity) in all sensorimotor tasks. The current findings are congruent with the loss of adaptability hypothesis of aging (Vaillancourt & Newell, 2002). This hypothesis proposes that age-related differences in sensorimotor function are characterized by an inability to constrain sensorimotor output to task demands (Sosnoff, Vaillancourt, & Newell, 2004; Vaillancourt & Newell). There is growing evidence in support of the loss of adaptability hypothesis. For example, Sosnoff and Newell had young and old adults produce continuous isometric force output to target waveforms with varying frequency dependent structures. Sosnoff and Newell (2008) found that the older adults were less able to modulate their sensorimotor output to the specific task demands. The authors concluded that with advanced age there is a declining ability to use the faster time scales of sensorimotor control, but the particular directional effect of the loss or gain of complexity of force output is moderated by the differential impact of task demands. However, a critique of the evidence supporting the loss of adaptability hypothesis was that older adults' lack of adaptability was because of lack of familiarity with the task and not the aging process itself. The persistent decreased adaptability demonstrated by the older adults following practice in the current investigation makes this critique less likely.

Aging and Practice-Related Changes in Motor Variability

It is well established that older adults have greater magnitude and structure of motor variability than do their younger counterparts (Enoka et al., 2003; Vaillancourt & Newell, 2003). In our investigation, we found a reduction in the magnitude of force variability in both age groups with practice, which is consistent with previous literature (Christou et al., 2007; Keen et al., 1994; Keogh, Morrison, & Barrett, 2007; Kornatz et al., 2005; Tracy, Byrnes, & Enoka, 2004). A multitude of peripheral and central factors contribute to age-related differences in motor variability (Enoka et al.; Galganski, Fuglerand, & Enoka, 1993; Knight & Kamen, 2007; Laidlaw, Bilodeau, & Enoka, 2000; Semmler, Kornatz, Meyer, & Enoka, 2006; Sosnoff & Newell, 2006a; Sosnoff et al., 2004; Taylor, Christou, & Enoka, 2003; Vaillancourt & Newell, 2003). With the short practice duration of 5 days, the changes in behavior were neural and not structural in nature (Duchateau, Semmler, & Enoka, 2006).

Elevated levels of motor unit firing rate variability are traditionally suggested to play a role in age-related differences in the magnitude of force variability (Laidlaw et al., 2000; Moritz, Barry, Pascoe, & Enoka, 2005). However, recent evidence casts doubt on this notion. For example, Barry, Pascoe, Jesunathadas, and Enoka (2007) showed that decreased rate coding, and not motor unit firing rate variability, is the underlying mechanism driving age-related differences in force control. Training-related improvements in age differences in force variability have been attributed to both decreases in motor unit firing rate variability (Kornatz et al., 2005) and changes in rate coding (Kamen & Knight, 2004). Knight and Kamen (2007) showed that older adults demonstrated a reduced modulation of firing rate in comparison with young adults in a sinusoidal force task. This decreased firing rate modulation was related to increased force variability. In a separate investigation, the authors noted that training-induced improvements in a force-matching task were related to improvements in motor unit firing rate modulation and firing rate variability in young adults (Kamen & Knight). Therefore, the practice-related improvements in the magnitude of constant and rhythmical force variability observed in the present study could result from improvements in motor unit firing rate modulation.

Although there were task-related improvements in the structure of force variability in both age groups, it is not clear which neuromuscular mechanism is responsible. There is evidence that the neuromuscular mechanisms contributing to the structure of force variability are distinct from those driving the magnitude of force fluctuations (Sosnoff et al., 2006). One mechanism that may be responsible for improvements in the structure of force variability is motor unit synchrony. *Motor unit synchrony* refers to simultaneous (or near simultaneous) discharge of motor

units and is believed to reflect common inputs to the motor unit pool by way of the corticospinal pathway (Sears & Stagg, 1976). As such, motor unit synchrony influences the timing of fluctuations in force output. Age-related differences in the magnitude of force variability are not related to motor unit synchrony (Semmler, Steege, Kornatz, & Enoka, 2000), so changes in motor unit synchrony could potentially change the structure of force variability independently of the magnitude of force variability. In addition, the findings of Semmler et al. (2006), who demonstrated that older adults were less able to adapt the amount of motor unit synchrony to various contraction types, are congruent with the loss of adaptability hypothesis. Although speculative, it is possible that changes in motor unit synchrony could explain overall improvements in the structure of force variability and loss of neuromuscular adaptability.

Analysis of the frequency structure of isometric force production reveals specific processes (Miall et al., 1985; Slifkin et al., 2000; Sosnoff & Newell, 2005). For example, the low frequency bandwidth (0–4 Hz) of force production represents sensorimotor processing (i.e., feedback processing; Miall et al.; Slifkin et al.), and the 8–12 Hz bandwidth is representative of physiological tremor (Slifkin et al.). In the present investigation, we hypothesized that older adults would have greater low-frequency power synonymous with overreliance on sensorimotor processing. Our hypothesis was on the basis of Vaillancourt and Newell's (2003) observation that older adults' lack of neuromuscular adaptability was associated with elevated low-frequency power.

In contrast with this prediction, we found minimal age differences in low-frequency power. Rather, age differences in power distribution occurred in a task-dependent manner. For instance, older adults had less POP in the 0–4 Hz bandwidth in the sinusoidal force task, but greater POP in 4–8 Hz and 8–12 Hz in comparison with the young adults. Given the minimal amount of power in the 8–12 Hz bandwidth (< 2%), the practical importance of any age differences in this bandwidth are questionable. The Age × Task interaction further suggests that older adults are less able to constrain their sensorimotor output to task constraints (Sosnoff et al., 2004). A possible explanation of the discrepancy between investigations is found in Hong, Lee, and Newell (2007), who demonstrated that the direction of force application differentially influences the structure of force variability. Therefore, it is possible that the differences observed between Vaillancourt and Newell's (2003) work and the present investigation result from the use of different movements (abduction vs. flexion) of the same effector.

In summary, this investigation yielded a single important finding. Older adults demonstrated a decreased ability to adapt their sensorimotor output to task demands even with short-term practice. The findings are congruent with the loss of adaptability hypothesis of aging, which claims that age-related deficits in motor output result from older adults'

decreased ability to adapt their output to task demands (Vaillancourt & Newell, 2002).

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