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RESEARCH ARTICLE

Age-related differences in finger force control are characterized by reduced force production

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Abstract It has been repeatedly shown that precise finger force control declines with age. The tasks and evaluation parameters used to reveal age-related differences vary between studies. In order to examine effects of task characteristics, young adults (18–25 years) and late middle-aged adults (55–65 years) performed precision grip tasks with varying speed and force requirements. Different outcome variables were used to evaluate age-related differences. Age-related differences were confirmed for performance accuracy (TWR) and variability (relative root mean square error, rRMSE). The task characteristics, however, influenced accuracy and variability in both age groups: Force modulation performance at higher speed was poorer than at lower speed and at fixed force levels than at force levels adjusted to the individual maximum forces. This effect tended to be stronger for older participants for the rRMSE. A curve fit confirmed the age-related differences for both spatial force tracking parameters (amplitude and intercept) and for one temporal parameter (phase shift), but not for the temporal parameter frequency. Additionally, matching the timing parameters of the sine wave seemed to be more important than matching the spatial parameters in both young adults and late middle-aged adults. However, the effect was stronger for the group of late middle-aged, even though maximum voluntary contraction was not significantly different between groups. Our data indicate that changes in the processing of fine motor control tasks with increasing age are caused by difficulties of late middle-aged adults to produce a predefined amount of force in a short time.

Keywords Aging · Precision grip · Force modulation · Task characteristics · Curve fit

Introduction

Precise finger force control is required to manipulate small objects in a skillful, dexterous way. Numerous studies have shown that this precise control of the finger forces is impaired with age (for an overview, see Diermayr et al. 2011), particularly from the fifth decade onwards (Bohannon et al. 2006; Mathiowetz et al. 1985; Ranganathan et al. 2001b). In everyday life, impaired force control particularly affects self-care skills such as buttoning a shirt, using a key, or cutting with a knife and therefore interferes with older peoples' independent living. Finger force control can be measured by force maintenance and modulation tasks, where the fingertip force needs to be adjusted according to a target profile. Although age-related changes in force control seem to depend on task characteristics, like force level, target force modulation profiles, and movement speed (Hu and Newell 2010; Jagacinski et al. 1995; Lindberg et al. 2009), so far only few studies systematically compared age-related changes with respect to different task characteristics and analysis methods. Thus, the aim of the current study was to systematically vary certain task characteristics, that is, the target force level and speed, to get a deeper insight into mechanisms that potentially influence finger force control under these task characteristics and, in turn, age-related changes. Furthermore, we applied different analytical methods to describe tracking accuracy, tracking variability, and temporal and spatial

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performance deviation from the target, aiming to characterize age-related changes.

It is well known that older adults use excessive grip forces, reduced dosing abilities, and slowed movements, all leading to less accurate and more variable performance in force maintenance and modulation tasks as compared to younger adults (Jagacinski et al. 1995; Krampe 2002; Kurillo et al. 2004; Ranganathan et al. 2001b; Shim et al. 2004; Smith et al. 1999; Voelcker-Rehage and Alberts 2005). Deterioration of fine motor control is assumed to be caused by local structural changes in the fingers and changes in the neural control system (Carmeli et al. 2003; Galganski et al. 1993).

Moreover, age-related changes in fine motor control seem to be more visible during complex tasks (for an overview, cf. Diermayr et al. 2011), so that the characteristics of the tasks may play an important role to capture age-related changes.

Recently, Hu and Newell (2010) compared force variability in maintenance and sine wave tasks in a sample of young participants and revealed that the sine wave task with a force level of 20 % and an amplitude of 5 % of the maximum voluntary contraction (MVC) evoked highest error scores, whereas the maintenance task revealed lowest variability. Keogh et al. (2006) also found poorer performance, determined as the degree of force variability and targeting error, in sine wave (0.1 Hz, amplitudes of 5 % of the respective target force level) as compared to maintenance (20 and 40 % of MVC) tasks in young and old adults (precision grip with index finger and middle finger pressed against the thumb), although age-related differences, expressed in relative terms, were lower in sine wave tasks than in maintenance tasks and were most pronounced at 20 % of the MVC. On the contrary, in absolute terms, they (Keogh et al. 2006) and also Vaillancourt and Newell (2003) revealed greater age differences for sine wave tasks than for maintenance tasks (only index finger and thumb; 5, 10, 20, and 40 % of MVC, sine wave tasks with amplitudes of 10 % of the respective target force level and frequency of 1 Hz). Voelcker-Rehage and Alberts (2005) found age-related differences in a sine wave task between 5 and 25 % of MVC. Furthermore, age-related differences in force-increasing phases that require the recruitment of motor units were more pronounced than in force-releasing phases requiring the de-recruitment of motor units (Voelcker-Rehage and Alberts 2005). This was supplemented by findings from Masumoto and Inui (2010) who found a higher variability in valley as compared to peak performance regardless of the force range of a target sine wave (20–40, 10–20, and 10–40 % of MVC) in younger participants (Masumoto and Inui 2010).

Also the target force level seems to be decisive for performance (Galganski et al. 1993; Lindberg et al. 2009), either defined as a certain percentage of the individual MVC (Galganski et al. 1993; Newell and Vernon McDonald 1994; Voelcker-Rehage and Alberts 2005) taking age-related reduction in finger strength into account (Sosnoff and Newell 2006b) or in fixed units (Cole 2006; Lindberg et al. 2009). In force maintenance tasks with fixed (Lindberg et al. 2009: 3, 6, and 9 N) as well as with relative force levels (Galganski et al. 1993: 5, 20, 35, and 50 % of MVC; Slifkin and Newell 2000: 3, 6, 12, 24, and 48 % of MVC), the highest errors or variability was always revealed for the lowest force level. To our knowledge, only one study compared relative and fixed forces (Ranganathan et al. 2001a) and found that age effects were more visible for fixed (2.5, 4, 8 N) than for relative (5, 10, 20 % of MVC) force levels.

In sine wave tasks, the frequency of the target profile is setting the movement speed. On this account, one might assume that the frequency of the sine wave is critical for performance. This was confirmed by Sosnoff et al. (2004) who found increasing variability with increasing frequencies (force range: 5–25 % of MVC, frequencies of 1, 2, 3, and 4 Hz). Jagacinski et al. (1995) revealed that older adults made smaller movements than their younger counterparts in sine wave tracking tasks with different frequencies (0.11, 0.21, 0.43, 0.86 Hz, amplitude: 45° deflection of a joystick, it is consequently not a precision grip task and requires movement). Older adults showed also greater phase shift and greater variability, especially at higher movement speed. Thus, even if it is not explicitly stated, age-related changes in movement speed might be compensated by reduced movement amplitude pointing to a generalized slowing of movements (Cole et al. 1998; Jagacinski et al. 1995).

In force maintenance tasks and sinusoidal tracking tasks, the force exerted is not constantly matched to the target force, but fluctuates around an average value (Semmler et al. 2007). Tracking performance therefore can be measured in absolute terms as standard deviation (SD) or as root mean square error (RMSE) and in relative terms as coefficient of variation (CV) or as relative RMSE (rRMSE) (Enoka et al. 2003). The rRMSE is considered to reflect the overall variability of force tracking performance (cf. Frankemolle et al. 2010). Additionally, the time within the target range (TWR), calculated as the time the participant's force trace is within a given percentage above and below the target line (Kriz et al. 1995), is regarded as a measure of accuracy (Voelcker-Rehage and Alberts 2005).

All of these measures are based on the difference between the applied force and the target force. In maintenance tasks, the systematic deviation can only be caused by continuously too high or too little applied force (Enoka et al. 2003). In sine wave tracking tasks, the systematic deviation can be caused by different reasons. The movement may be performed with another speed as well as with another force level, so that the same deviation can be evoked by different mechanisms. This is not considered by the above-mentioned methods. To our knowledge, only Jagacinski et al. (1995) used regression analysis to approximate the participants' movements conducted with a joystick device to a sinusoidal pattern in order to analyze how phase and amplitude of this curve deviated from a target sine wave. The study showed that older participants lagged behind the sine wave and performed with decreased amplitude. This was interpreted as two different manifestations of general slowing with increasing age (Jagacinski et al. 1995). Similarly, a curve fit can be calculated to the applied force in a sinusoidal grip force tracking task to reveal different parameters of the approximated sine wave: the frequency, the phase shift, the amplitude, and the intercept. Thus, in the current study, besides measuring accuracy (TWR) and variability (rRMSE), a curve fit was applied in order to indicate mechanisms which might be responsible for deviations from the target force.

The aim of this study was to determine age-related differences in sine wave tracking tasks with regard to the task characteristics, that is, sine wave frequency and target force levels. For this purpose, young and late middle-aged participants performed four sine wave tasks with two different frequencies and two target force levels. Typically, age-related changes in fine motor control have been shown to occur progressively and already start in early adulthood (Lindberg et al. 2009). However, there is a lack of knowledge of age-related changes in late middle-age. This age group, however, is of particular importance with respect to prevention of functional decline in older age. Thus, we aimed to investigate young and late middle-aged (55–65 years) adults. Further, we applied different analysis methods to investigate whether time- or spatial parameters evoke systematic tracking errors and how young and older adults differ in the mechanisms causing deviations.

Due to previous findings, irrespective of the task, we assumed lower tracking accuracy and higher tracking variability for late middle-aged in comparison with young adults (e.g., Cole 2006; Sosnoff and Newell 2006a, 2007; Voelcker-Rehage and Alberts 2005). Further, we expected the task characteristics to lead to performance differences. Variability in force production was shown to be strongest at higher movement speeds (frequencies) and at low submaximal force levels (Cole 1991; Galganski et al. 1993; Krampe 2002; Masumoto and Inui 2010; Sosnoff and Newell 2006a; Sosnoff et al. 2004; Voelcker-Rehage and Alberts 2005). Due to age-related slowing, we assumed that the influence of target speed would be more prominent for late middle-aged than for younger adults, leading to an interaction between age and target speed. Based on findings of Ranganathan et al. (2001a), we expected age-related changes to be more prominent when fixed force levels are presented in comparison with relative force levels. For curve fit parameters we assumed that, the frequency of the curve fit relative to the target sine wave should be more reduced in late middle-aged adults than in younger adults. Based on the findings by Jagacinski et al. (1995), we also expected for both age groups deviations to be evoked mainly by a phase shift, so that performance lags behind the target profile, as well as by a decrease in the amplitude for all conditions. These effects were also expected to be more prominent for the group of late middle-aged adults. Regarding the *Y*-intercept in the applied force, we did not expect any differences between the age groups, since all participants should perform at convenient submaximal force levels.

Methods

Participants

Twelve young adults, 18–25 years of age (8 females, mean age = 20.58, SD = 1.78), and 14 late middle-aged adults, 55–65 years of age (7 females, mean age = 58.43, SD = 2.90), all without any neurological disorder and with normal or corrected-to-normal vision, participated in the study. The participants neither performed tasks with a high demand of fine motor control in their job nor had hobbies requiring manual dexterity. All were part of the active work force. The participants were recruited by newspaper announcements and flyers. They were compensated by 8 € per hour. All subjects took part voluntarily and provided their informed consent to the procedure of the study, which was approved by the ethics' committee of the German Psychological Society.

Screenings

Participants were given a demographic and health status questionnaire to obtain information about characteristics of the sample and self-reported health status. No participant had to be excluded from the study due to his or her health status. All participants were right-handed, tested with the Edinburgh Handedness Inventory (Oldfield 1971). Frequencies of hand writing and typing were assessed with a questionnaire revealing no differences between younger and late middle-aged adults (typing: $t(24) = 0.40$, $p = .69$, $w^2 = .01$), except that younger participants wrote more often by hand ($t(24) = 2.30$, $p = .03$, $w^2 = .19$) than late middle-aged adults. Clinical manual dexterity was assessed using the Purdue Pegboard Test (Model 32020, Lafayette Instruments, Lafayette, IN, USA). The mean number of pins placed with the dominant hand during three trials of 30 s was calculated. As expected, performance differed significantly between the age groups ($t(24) = 2.60$, $p = .02$, $w^2 = .24$). Late middle-aged adults placed less pegs ($M = 14.24$, SD = 1.30) than younger adults ($M = 15.47$, SD = 1.08).

Apparatus and setup for testing isometric force modulation

A six degree of freedom force transducer (Mini-40 Model, ATI Industrial Automation, Garner, NC, USA) was used for measuring grip force during an isometric force tracking task. It was affixed in a comfortable position to the participant in front of a computer. The grip force was recorded with an amplitude resolution of 0.06 N and a sampling rate of 120 Hz. To collect the force data and provide visual feedback to the participant, a customized LabView (National Instruments) program was used. The target force level and the actual grip force produced by the subjects were displayed on a 19″ monitor approximately 80 cm directly in front of the participants. The x-axis of the target force presentation had a width of 30 cm and was presenting 5 s, that is, the participants saw the target line 0.5 s in advance and up to 4.5 s of the past force matching. The y-axis had a height of 15 cm and was presenting 0–14 N for the fixed forces and adjusted individually for the relative forces by the computer program to optimally use the screen space.

Tasks

Maximum voluntary contraction

Participants performed a precision grip (i.e., thumb and index finger only) with their dominant (right) hand to exert an isometric force against the force transducer. Initially, the MVC of each participant was determined using data from three maximum precision grip trials, 5 s each. The peak force achieved out of the three trials was considered as the MVC and was used for calculating the relative target force levels.

Sinusoidal tracking tasks

Four different target sine waves were selected as target force profiles (cf. Fig. 2). They differed in two parameters: the force range and the speed of the target sine waves. Force levels were either relative to the MVC [10–20 %; corresponds for this sample to 5.36–10.72 N (cf. results of MVC measurement)] or fixed (2–12 N). As previous studies have shown, these force levels can be maintained relatively easily, and they evoke no fatigue (Voelcker-Rehage and Alberts 2005). Two different frequencies were used: a slower frequency of 0.2 Hz and 1 Hz as the faster condition. The presentation of the target sine wave started at the minimum of the sine wave and lasted 20 s. Participants were instructed to match their grip force to the target as accurately as possible. Each of the four conditions was presented 30 times in one block. The order of the blocks was randomized for all participants.

Procedure

Each participant was tested individually in a session with a duration of 2 h. The participants sat on a chair, their arms rested on prepared armrests so that the hand could reach the fixed force transducer easily. To become comfortable with the task in general, participants performed five practice trials with an average target speed and target force (0.6 Hz, 5–10 N) before the actual experiment started. The rest between each trial was about 1 s and between each block about 30 s.

Data analysis

All data were filtered by using a low-pass filter based on Woltring's algorithm (Voelcker-Rehage et al. 2006). The primary motor outcome variables for the force tracking task were TWR and rRMSE. In order to analyze systematic deviations from the target curve, a nonlinear curve fit was calculated for the applied force data, using the least squares method to find the best fit (Matlab, 2010, MathWorks, Natick, MA, USA). The parameters of the target sine wave (amplitude, intercept, phase shift, and frequency) were used as starting parameters of the fit. By this, the amplitude, the period length or frequency, the phase shift, and the intercept of the curve fitted to the applied force were calculated. The individual parameters were subtracted from the target parameters, and these difference values were further analyzed (Δ amplitude, Δ frequency, Δ phase shift, Δ intercept).

The first five trials of each condition were regarded as skill acquisition and were excluded from the analysis. Force data were assessed from 1 s after the start of the trial until completion of the trial (by 1 s the target force had been achieved). Outliers within the trials of one person and in the group of young and late middle-aged adults were defined as standardized z-scores in excess of 3.29 and were replaced according to the last observation carried forward method (Tabachnick and Fidell 2001).

Statistical analyses were done with SPSS for Windows, version 20.0 (IBM Corp., Armonk, NY, USA). We calculated a mixed-factors ANOVA with age (young, old) as between-subjects factor and speed (slow, fast) and force range (fixed, relative) as within-subjects factors for the variables TWR and rRMSE and for the variables Δ amplitude, Δ frequency, Δ phase shift, and Δ intercept. We included MVC as a covariate in our ANOVA models, but as it has no significant effect, results are not reported. To test for differences in MVC we calculated a t test for independent samples. Significant main effects and interaction effects were followed by Bonferroni-corrected pairwise comparisons, and unless stated otherwise, reported differences are significant at $p < .05$. Bivariate correlations between the target line conditions were calculated for TWR and rRMSE for both groups separately. To analyze how much of the variation in the rRMSE and TWR can be explained by systematic tracking errors, a stepwise linear regression analysis was calculated. Age was included in the first step and the differences of the curve fit parameters in the second step as predictors. All η^2 values are partial η^2 values. In all analysis, we considered p values $<.05$ as significant and p values between $\geq.05$ and ≤ 0.1 as marginally significant.

Results

Maximal voluntary contraction

The t test for independent samples revealed no difference in the MVC between the group of young ($M = 54.11$, SD = 10.50) and late middle-aged ($M = 53.25$, SD = 16.37) participants ($t(24) = 0.16$, $p = .88$, $w^2 = .01$).

Influence of age and task characteristics on sine wave tracking variability (rRMSE) and tracking accuracy (TWR)

Main effects of age, speed, and force range were found for TWR and rRMSE (for descriptive results cf. Fig. 1; Table 1; for statistics cf. Table 2). As shown by the ANOVA, younger adults performed significantly better than late middle-aged adults as revealed by higher TWR and lower rRMSE in all tasks (cf. Table 1; Fig. 1). Accuracy was significantly lower and variability was significantly higher in the fast conditions than in the slow conditions and for the fixed as compared to the relative force ranges in both age groups (cf. Table 1; Fig. 1). Further, a significant interaction of speed and force range for both TWR and rRMSE indicated a stronger speed effect for fixed forces. Marginally significant interactions between the factors age and speed and between the factors age and force range were found, but only for the rRMSE, pointing to stronger age-related differences for conditions with higher speed and fixed force ranges.

Correlation analysis revealed for the late middle-aged adults that both, TWR and rRMSE, highly correlated across all task characteristics indicating a general increase in variability and decrease in accuracy with aging (cf. Table 3). In contrast, for the young adults, only the slow/relative condition correlated with the fast/fixed and the fast/relative conditions, perhaps pointing to different execution strategies in younger adults.

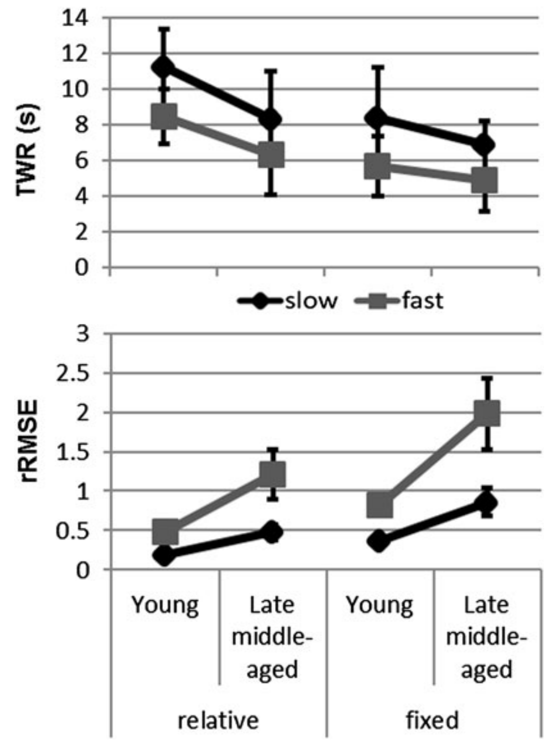

Fig. 1 Tracking accuracy (*top*) and variability (*bottom*) of young and late middle-aged adults under the four different task conditions

Influence of age and task characteristics on curve fit parameters

In order to explore causes for the above-described differences in variability and accuracy, we calculated a curve fit to the applied forces and calculated deviations from the target force profile in terms of amplitude, intercept, phase shift, and frequency (cf. Table 1; Fig. 2). ANOVA revealed a main effect of age for Δ amplitude, Δ phase shift, and Δ intercept, and a marginally significant effect for Δ frequency (cf. Table 2 for statistics). Late middle-aged participants revealed lower amplitudes and intercepts and higher phase shifts and frequencies than young adults. Moreover, results showed a main effect of force range and speed for all variables except Δ phase shift. Regardless of age, Δ amplitude and Δ intercept were lower and Δ frequency was higher in the slow as compared to the fast conditions as well as in the relative compared to the fixed condition. Interaction between speed and force indicated that Δ amplitude and Δ intercept were differently influenced by target speed and force range showing the highest Δ amplitude in the fast and relative condition and the highest Δ intercept in the slow and fixed condition. Further a marginally significant interaction of speed and force for Δ frequency was revealed with highest deviations for the slow and fixed condition. Only a marginally significant interaction between age and force range was shown for Δ

Table 1 Means (*M*) and standard deviations (SD) and mean target values for tracking accuracy (TWR), variability (rRMSE), and the deviation of the curve fit parameters from the target sine wave [Δ amplitude (*A*), Δ intercept (*Y*), Δ frequency (*F*), Δ phase shift (*S*)]

Measure	Target	Younger adults *M* (SD)	Older adults *M* (SD)	Target	Younger adults *M* (SD)	Older adults *M* (SD)
		Relative/slow			Fixed/slow	
TWR (s)		11.21 (2.21)	8.34 (2.65)		8.42 (2.77)	5.68 (1.70)
rRMSE		0.19 (0.08)	0.48 (0.36)		0.37 (0.20)	0.86 (0.65)
ΔA (N)	2.66	0.33 (0.23)	0.66 (0.29)	5.00	0.89 (0.37)	1.46 (0.63)
ΔY (N)	8.04	0.12 (0.11)	0.49 (0.78)	7.00	0.13 (0.16)	0.30 (0.25)
ΔF (Hz)	0.20	<0.01 (<0.01)	<0.01 (<0.01)	0.20	<0.01 (<0.01)	<0.01 (<0.01)
ΔS (s)	1.25	0.05 (0.11)	0.15 (0.37)	1.25	0.07 (0.05)	0.13 (0.09)
		Relative/fast			Fixed/fast	
TWR (s)		8.48 (1.54)	6.35 (2.26)		6.88 (1.36)	4.92 (1.75)
rRMSE		0.48 (0.32)	1.21 (1.16)		0.83 (0.34)	1.98 (1.68)
ΔA (N)	2.66	0.57 (0.29)	0.86 (0.43)	5.00	0.32 (0.24)	0.84 (0.70)
ΔY (N)	8.04	0.12 (0.12)	0.24 (0.24)	7.00	0.24 (0.23)	0.86 (0.82)
ΔF (Hz)	1.00	<0.01 (<0.01)	<0.01 (<0.01)	1.00	<0.01 (<0.01)	<0.01 (<0.01)
ΔS (s)	0.25	0.09 (0.05)	0.14 (0.09)	0.25	0.02 (0.02)	0.06 (0.07)

The target values are the criterion values of the target sine wave (for *A*, *Y*, *F*, *S*)

Table 2 Results of the repeated-measure ANOVA with the main effects age, speed, and force for TWR and rRMSE and the deviations of the curve fit parameters for the target sine wave [Δ amplitude (*A*), Δ intercept (*Y*), Δ frequency (*F*), Δ phase shift (*S*)]

Measure	Age				Speed				Force			
	F	*df*	*p*	η^2	*F*	*df*	*df*	η^2	*F*	*df*	*p*	η^2
TWR	12.26	1	<.01	.34	50.16	1	<.01	.68	69.20	1	<.01	.74
rRMSE	6.06	1	.02	.20	18.83	1	<.01	.44	26.30	1	<.01	.52
ΔA	7.37	1	.01	.24	48.77	1	<.01	.67	20.14	1	<.01	.46
ΔY	6.59	1	.02	.22	4.92	1	.04	.17	6.80	1	.02	.22
ΔF	3.94	1	.06	.14	4.55	1	.04	.16	4.55	1	.04	.16
ΔS	4.90	1	.04	.17	1.27	1	.27	.05	1.81	1	.19	.07
	Age × speed				Age × force				Speed × force			
	F	*df*	*p*	η^2	*F*	*df*	*df*	η^2	*F*	*df*	*p*	η^2
TWR	2.33	1	.14	.09	0.09	1	.76	<.01	6.11	1	.02	.20
rRMSE	3.34	1	.08	.12	3.49	1	.07	.13	10.15	1	<.01	.30
ΔA	0.01	1	.93	<.01	3.82	1	.06	.14	33.74	1	<.01	.58
ΔY	2.82	1	.11	.11	1.97	1	.17	.08	9.17	1	<.01	.28
ΔF	1.87	1	.18	.07	2.98	1	.10	.11	2.89	1	.10	.11
ΔS	0.04	1	.84	<.01	0.22	1	.65	.01	0.67	1	.420	.03
	Age × speed × force											
	F	*df*	*p*	η^2								
TWR	<.01	1	.97	<.01								
rRMSE	1.48	1	.24	.06								
ΔA	0.54	1	.47	.02								
ΔY	1.87	1	.18	.07								
ΔF	1.81	1	.19	.07								
ΔS	0.47	1	.50	.02								

Table 3 Correlation of variability and accuracy under different conditions [relative/slow (*R/S*), relative/fast (*R/F*), fixed/slow (*F/S*), fixed/fast (*F/F*)]

Condition	*R/S*	*R/F*	*F/S*	*F/F*
rRMSE				
Relative/slow	–	.607*	.557*	.568*
Relative/fast	.382	–	.961**	.970**
Fixed/slow	.438	.026	–	.936**
Fixed/fast	.594*	.343	.530	–
TWR				
Relative/slow	–	.705**	.605*	.775**
Relative/fast	.438	–	.842**	.825**
Fixed/slow	.639*	.343		.776**
Fixed/fast	.769**	.470	.470	–

Correlations for older adults are shown above the main diagonal; correlations for younger adults are shown below the main diagonal

** $p < .01$; * $p < .05$

amplitude and Δ frequency. For Δ frequency, young adults deviated more from the target force profile during the fixed conditions, whereas the late middle-aged adults deviated more during the relative conditions. For Δ amplitude, the differences between fixed and relative condition was higher for late middle-aged than for younger adults. Combined, the systematic deviations from the target force profiles seem to depend on task characteristics and age.

Association of accuracy and variability with curve fit parameters

Stepwise hierarchical regression analysis revealed that the TWR could be explained by the curve fit parameters. The explained variance by the curve fit parameters differed, however, between the four tasks. Age had no significant effect. For the condition slow and relative ($F(5,20) = 13.38$, $p < .01$, $R^2 = .77$), Δ amplitude ($p < .01$) and Δ phase shift ($p = .01$) made significant contributions to explain the variance. For the condition slow and fixed ($F(5,20) = 16.74$, $p < .01$, $R^2 = .81$), Δ frequency ($p = .02$) and Δ amplitude ($p < .01$) contributed significantly. For the condition fast and relative ($F(5,20) = 12.19$, $p < .01$, $R^2 = .75$), Δ frequency ($p = .01$) and Δ intercept ($p < .01$) contributed significantly, and for the condition fast and fixed ($F(5,20) = 10.07$, $p < .01$, $R^2 = .72$), only Δ amplitude ($p < .01$) significantly explained the variance. Thus, mainly force-related parameters contribute to TWR.

Variance in tracking variability (rRMSE) could also be significantly explained by single curve fit parameters, but

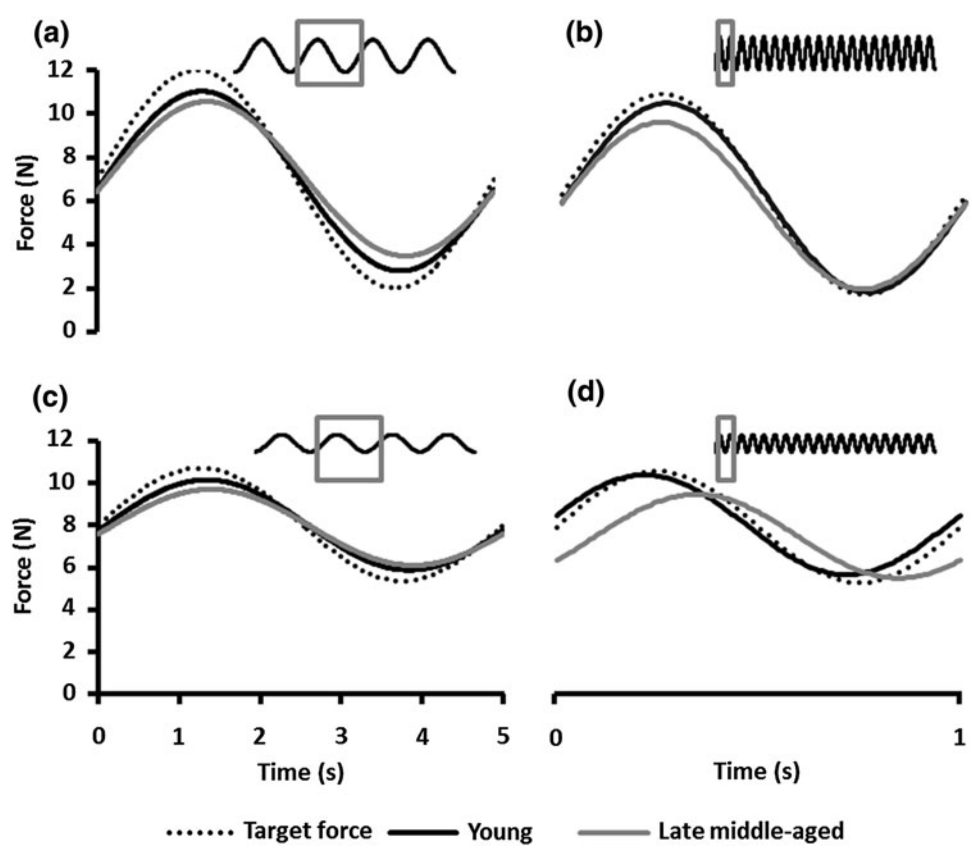

Fig. 2 Fitted curves for young and late middle-aged adults under the condition **a** slow/fixed, **b** fast/fixed, **c** slow/relative, and **d** fast/relative. The curve on the right pictures the target curve profile for the length of 20 s

specific contributions differed from results for TWR. Similar to TWR for the slow and relative condition ($F(5,20) = 18.28$, $p < .01$, $R^2 = .82$), Δ amplitude ($p = .03$) and Δ phase shift ($p = .01$) significantly explained variance accompanied by the frequency ($p < .01$). In the condition slow and fixed, Δ amplitude ($p < .001$), Δ phase shift ($p = .01$), and Δ frequency ($p = .02$) made significant contributions to explain the variance ($F(5,20) = 63.54$, $p < .01$, $R^2 = .94$). In both sine wave tasks with the fast frequencies, the variance could be explained (fixed forces: $F(5,20) = 21.91$, $p < .01$, $R^2 = .85$; relative forces: $F(5,20) = 25.73$, $p < .01$, $R^2 = .87$) by Δ frequency (fixed: $p < .01$, relative $p < .01$) and (marginally) significant by Δ intercept (fixed: $p = .09$, relative: $p < .01$).

Thus, the rRMSE depended highly on temporal systematic errors and the TWR on force related (spatial) parameters. Thereby, the force range seemed not to interact with the type of systematic errors, whereas the speed of the task seemed to be decisive to predict the error causing mechanism. In the slow sine wave tasks, Δ amplitude, Δ phase shift, and Δ frequency were the decisive factors for accuracy and variability, and in the fast conditions this applies to Δ intercept.

Discussion

The aim of this study was to investigate the influence of task characteristics on age-related differences in different outcome measures of sine wave force modulation tasks at submaximal force levels. For this purpose, force modulation parameters were varied regarding force range and frequency of the sine wave. As expected, accuracy was in all tasks lower and variability higher for late middle-aged adults than for young adults. A curve fit revealed that late middle-aged adults showed higher deviations from the target curve with respect to amplitude, intercept, and phase shift than younger adults, irrespective of the task condition. Speed and force range of the target force profile affected performance in all outcome measures, besides the phase shift of both young and late middle-aged adults. Regardless of age, performance was lower in the fast conditions and the conditions with the fixed force range. Most of the variance in tracking accuracy and variability could be explained by systematic deviations in amplitude and phase shift. We found only a tendency that age-related differences depended on task characteristics, with highest differences between the age groups in the fast/fixed condition and lowest in the slow/relative condition (marginally significant interaction between age and force and age and speed, respectively). Within the group of late middle-aged adults, high correlations between all tasks indicated a more general age-related decline, whereas the lower correlations in younger adults indicate high intra-individual variability across the tasks.

Extending previous findings (e.g., Cole 1991; Galganski et al. 1993), we revealed that age-related differences in precision grip performance (TWR, rRMSE) in all task conditions became visible already in late middle-aged adults younger than 65 years of age. Our findings are in line with Lindberg et al. (2009) demonstrating lower force modulation abilities in precision grip tasks for middle-aged as compared to young adults. One might argue that age-related differences are influenced by a lower MVC of late middle-aged adults (Kapur et al. 2010; Sosnoff and Newell 2006b). This argument, however, does not hold for our study, as MVCs were not significantly different between the age groups. Thus, irrespective of MVC, other factors such as decreased somatosensory functioning, less efficient muscle recruitment, increasing size of motor units, and a slowing of their contractile properties might be responsible for the age-related differences in hand functioning and fine motor control in force modulation tasks (Manning and Tremblay 2006; Reuter et al. 2012; Shim et al. 2004). To test the functional relevance of our force modulation tasks, we calculated a correlation between the performance in the Purdue Pegboard test and the accuracy and variability in the force tasks. Besides the rRMSE of the slow/variable condition, all correlations were significant (always $p \leq .01$). This indicates that the precision grip tasks used in this study are ecologically valid and that force modulation is an essential part of daily grasping.

The force range and the speed of the target curve affected fine motor control. Accuracy was lower and variability higher for both age groups in the fixed conditions as compared to the relative ones and in the fast conditions as compared to the slow ones. This difference was more prominent in late middle-aged adults (cf. Fig. 1). Differences between fixed and relative force conditions are somehow surprising since the mean MVC of young and late middle-aged adults was comparable. One reason might be variations in individual MVC levels as shown by relatively high SDs (cf. Table 1) within the age groups (SD = 10.50 for young adults and SD = 16.37 for late middle-aged adults), particularly for the group of late middle-aged adults. Thus, each individual seems to perform optimally at relative force levels adjusted to his or her MVC but not at the fixed force level due to the high inter-individual variations within the age groups.

Sosnoff et al. (2004) reported that the speed of the sine wave influences tracking performance, determined by RMSE. We also found that a higher speed of the sine wave, that is, a higher frequency, led to lower accuracy and higher variability at both the fixed and relative force levels. It was shown that the visual feedback influences the precision of visuo-motor force matching (Sosnoff and Newell

2007) and mediates age-related differences in these tasks (Kennedy and Christou 2011; Ofori et al. 2010). In our study, the sine wave moved constantly from right to left on the screen. For all conditions, the participant saw the same time window, but the number of completely shown sine waves differed between 1 in the slow and 5 in the fast conditions. The resulting relative magnification of a single sine wave in the slow conditions might have enabled more precise correcting movements and thus might explain to some degree that lower task speed led to lower deviations from the target. Further, the speed effect might have enhanced the effect of fixed versus relative forces; an interaction effect of speed and force range revealed mutual inter-dependency between both factors. As expected, we found lower accuracy and higher variability in the fast as compared to the slow and in the fixed as compared to the relative condition. In the fast and fixed condition, larger force changes in a shorter time were required, whereas in the slow and relative condition, on average, the force amplitude that needed to be adjusted per time was the lowest. Following these results, the amount of force adjusted per time is likely to be the most important performance predictor as it includes temporal and force level requirements of the tracking task. Our findings that the task conditions themselves influence the performance outcomes may explain divergent results in various studies.

We hypothesized that age-related differences are more prominent in the fast than in the slow conditions and that the fixed conditions should be more sensitive to age-related differences than the relative conditions. However, we only found a tendency for an interaction between age and speed as well as age and force range (for rRMSE). Similar to findings of Ranganathan et al. (2001a) and Vaillancourt and Newell (2003), this interaction points toward the fact that the more difficult the task is, the more pronounced are the age-related differences. Besides this, correlation analysis for performance variability and accuracy in different task conditions for the age groups separately revealed for the young adults low inter-task correlations (and thus high intra-individual variability), indicating that individuals were differently affected by variation in the task conditions. On the contrary, late middle-aged adults who performed poorly in one task were also the ones who performed poorly in all other tasks (high inter-task correlation). This finding is in line with a study by Sosnoff and Newell (2006c) demonstrating an increasing association between different fine motor tasks with increasing age. Consequently, first, the ability of late middle-aged adults to precisely modulate fingertip forces seems to decrease in general, and second, age-related differences, however, are more visible in more difficult tasks.

By curve fit analysis, we examined how temporal (phase shift, frequency) and spatial (intercept, amplitude) parameters of the applied force were varied between the different tracking tasks and age groups. The temporal parameters of the curve fit showed relatively small deviations as compared to the spatial parameters. This prioritization of temporal parameters could be due to the high importance of temporal parameters, which affect the visual match.

Regression analysis revealed that the tracking accuracy (TWR) depended on the spatial parameters, especially on the deviation of the intercept. This indicates that the target sine wave was tracked on a lower force level. The deviation of frequency explained the tracking variability. Combined, the exact timing of force modulation seems to be more crucial for the force tracking variability, whereas the deviations of spatial parameters induce comparably high and constant tracking deviations, leading to lower accuracy. We assume that the temporal parameters, especially the frequency, match basically the optimal timing because the curves were presented visually and the timing parameters are likely to be more substantial for the visual control. We expected the frequency in the fast conditions to be reduced, but our results revealed that the frequency was enhanced in the fast conditions. The reason might be that the fast frequency equals a more rhythmic task while the slow one requires a more constant production of force.

Close to the findings of Jagacinski et al. (1995), the parameters amplitude and phase shift were affected by age. Late middle-aged participants performed the sine wave tracking with lower amplitudes than the younger participants and lagged more behind the target curve. In addition, we found an age-related difference in the deviation of the intercept. Late middle-aged adults were more likely to reduce the average of their applied force, especially in the fixed conditions, whereby the minimum of the curve was reached approximately right and the deviation from the target was higher at the maximum, as the time was not sufficient to produce enough force. The frequency was only marginally affected by age, supporting the assumption that generally the frequency is the parameter that is kept constant because of its high visual control. Thus, late middle-aged adults performed the task in a smaller scale, but with an appropriate timing, demonstrated by reduced force but low deviation in frequency. When the amount of force produced in the given time was reduced, the described age-related differences can be regarded as slowing (Jagacinski et al. 1995).

Conclusion

Overall, our study revealed that fine motor control in a precision grip force modulation task is strongly depended on task characteristics, that is, speed and force range. We also confirmed age-related differences already between young adults and late middle-aged adults (55–65 years of age). These age-related differences seem to become more visible in the fast/fixed than the slow/relative condition, probably indicating age-related slowing. Furthermore, a high inter-task correlation within the group of late middle-aged but not of younger adults indicates that fine motor control is generally worse in late middle-aged adults, whereas younger adults reveal a high intra-individual variability (low inter-task correlation). The different analysis methods gave insights into potential underlying mechanisms of age-related differences in finger force control, pointing to difficulties of late middle-aged adults to produce a sufficient amount of force in a given time. Our results indicate the importance of systematically varying task characteristics in future studies to gain deeper insights into their influence on force modulation performance. Additionally, a continuous age range up to higher ages would allow getting a closer look into the characteristics of the progressive start of age-related decline.

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