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Dynamical signatures of isometric force control as a function of age, expertise, and task constraints

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Short title: Dynamic signatures of force control

Abstract

From the conceptual and methodological framework of the dynamical systems approach, force control results from complex interactions of various subsystems yielding observable behavioral fluctuations, which comprise both deterministic (predictable) and stochastic (noise-like) dynamical components. Here, we investigated these components contributing to the observed variability in force control in groups of participants differing in age and expertise level. To this aim, young (18 – 25 years) as well as late middle-aged (55 -65 years) novices and experts (precision mechanics) performed a force maintenance and a force modulation task. Results showed that whereas the amplitude of force variability did not differ across groups in the maintenance tasks, in the modulation task it was higher for late middle-aged novices than for experts, and higher for both these groups than for young participants. Within both tasks and for all groups, stochastic fluctuations were lowest where the deterministic influence was smallest. However, while all groups showed similar dynamics underlying force control in the maintenance task, a group effect was found for deterministic and stochastic fluctuations in the modulation task. The latter findings imply that both components were involved in the observed group differences in variability of force fluctuations in the modulation task. These findings suggest that between groups the general characteristics of the dynamics do not differ in both tasks, and that force control is more affected by age than by expertise. However, expertise seems to counteract some of the age effects.

New & Noteworthy

- Stochastic and deterministic dynamical components contribute to force production
- Dynamic signatures differ between force maintenance and cyclic force modulation tasks but hardly between age and expertise groups

- Differences in both stochastic and deterministic components are associated with group differences in behavioral variability
- Observed behavioral variability is more strongly task-dependent than person-dependent

Keywords: isometric force control, dynamics, drift-diffusion coefficients, aging, long-term practice.

Dynamical signatures of isometric force control as a function of age, expertise, and task constraints

1. Introduction

Force control is fundamental for many daily activities, for example self-care skills and job routines. It is the product of the temporary coalition of multiple subsystems (neural, cognitive, muscular, etc.) as well as of the integration of different sensory feedback loops acting on different time scales (Hong, Lee, & Newell, 2007; Vaillancourt & Newell, 2003). These complex interactions are expressed in the produced force which contains fluctuations with a certain magnitude and time-structure (Vieluf, Temprado, Berton, Jirsa, & Sleimen-Malkoun, 2015). These fluctuations are greatly affected by task constraints, such as target profile and force level, as the interactions of subsystems and feedback loops can be differentially structured depending on the tasks (Slifkin & Newell, 1999; Temprado, Vieluf, Bricot, Berton, & Sleimen-Malkoun, 2015; Vieluf et al., 2015). Further, the fluctuations can change due to organismal constraints (e.g., age and expertise) that may affect the individual subsystems as well as the subsystems' interactions and therefor contribute to force control (see Morrison & Newell, 2012 for an overview on aging; and Vieluf, Mahmoodi, Godde, Reuter, & Voelcker-Rehage, 2012 for an experimental study on expertise). At present, the bulk of research on force control has been devoted to study its statistical properties including the structure of the force fluctuations (Slifkin & Newell, 1998; Slifkin & Newell, 1999; Vieluf et al., 2015). In contrast, to our best knowledge, only one study (Frank, Friedrich, & Beek, 2006) has aimed to identify the dynamics, describing the underlying components contributing to variability in the produced force over time. These dynamics provide a phenomenological description of the system at hand, and thus a better understanding of the system at that level of description. Therefore, we here investigate the dynamics underlying force control with respect to task constraints as well as organismal or internal constraints. Specifically, we assessed the dynamics associated with two force production tasks – force maintenance and cyclic force modulation - and how they change as a function of age and expertise.

The present study was conducted according to the conceptual and methodological framework of the dynamical systems approach. Central to this approach is the search for generic phenomenological laws, typically cast in terms of low-dimensional differential equations (see Kelso, 1995 and references therein). The corresponding dynamics, describing the attractor structures, are investigated in terms of system stability and loss thereof. In that regard, an attractor is a dynamical structure to which the system invariantly evolves and (thus) returns to when driven away from it by perturbations or noise. Well-known stable attractors are fixed points and limit cycles. A fixed (or equilibrium) point denotes a position in the system's state space where the rate of change is zero. Stable fixed points thus describe systems that, when not at the fixed point, evolve toward it and remain at the corresponding value of the relevant variable (unless perturbed). In terms of a force control task, this would be expressed as force level that is approached from all other force levels and that is remained for a period of time. Limit cycles are orbits in the phase space, and thus require at least two state variables spanning the state space, and describe oscillatory behavior. Oscillatory behavior, however, can also be described by systems, which contain one state variable only (Strogatz, 1994), and such reduced systems are sometimes used (as we do here) to capture limit cycle behavior (Huys, Studenka, Zelaznik, & Jirsa, 2010). In terms of a force control task, this would mean that for a force modulation task with a sinusoidal pattern, the dynamics can be captured in relation to the target force profile for examples by the Hilbert phase and would result in a stable line, as the rate of change is constant. Of particular interest for our current purposes, applied to force control tasks, this approach posits that the complex neuro-musculo-skeletal system can be formally conceived as a stochastic dynamical system (Wilmer, Frank, Beek, & Friedrich, 2007). Such systems contain deterministic and stochastic dynamical components that interact with each other (van Mourik, Daffertshofer, & Beek, 2006) in order to give rise to a highly organized and adaptable behavior. The deterministic component determines the behavioral solutions—this is the dynamical component that contains the attractor structures alluded to above, as for instance whether the system will converge to a fixed point and provides information about the attractor strength (Frank et al., 2006) or whether the system exhibits sustained oscillations. The stochastic component represents random fluctuations or dynamical noise in the system, which causes the system to fluctuate around its attractor structure. Typically, in the studies on force control, the structure and contribution of these two sources of behavioral variability have widely been neglected. However, their estimation provides valuable information about the underlying dynamics (Stepp & Frank, 2009), and thus knowledge about the studied system, in the present context - the system underlying force control.

To our knowledge, only very few studies have explicitly investigated the dynamics associated with force control (Danion & Jirsa, 2010; Frank et al., 2006); only Frank and colleagues (2006) studied both the deterministic and stochastic components. Specifically, these authors investigated the contribution of the deterministic and stochastic components in an isometric force control task where the participants were asked to maintain a relative force level (10, 20, 40, 60, and 70% of their individual maximum voluntary contraction force (MVC)) for 15 s. Specifically, in this force maintenance task, which was shown to be governed by a stable fixed point dynamics, behavioral fluctuations increased with increasing force level. The authors assumed that this was due to a combination of a weaker deterministic component and higher noise. Regardless, both the deterministic and the stochastic components determined the observed behavioral variability. Frank et al. (2006) pointed out that the dynamic components were scaled as a function of constraints related to the task context (magnitude of the produced force required) as well as the participants (i.e., MVC). Consequently, decomposing the behavior into its deterministic and stochastic components allows (i) to uncover whether different task constraints entail different dynamic behaviors, and (ii) to test whether organismal differences are expressed in one and/or the other component.

Classically, two task paradigms are considered relevant to study force control, namely the isometric force maintenance task (maintaining a given constant force level over time) and the cyclic force modulation task (producing a periodic time-varying force level). Each of these tasks imposes specific constraints on the participants. However, it remains an open question whether they effectively result from similar or distinct generating mechanisms. As the force maintenance task implies the production of a stationary force with fluctuations around that mean, it is assumed that it is generated by a stable linear fixed-point dynamic (Frank et al., 2006). In contrast, the cyclic task requires a time-varying force generation, and thus exhibits fluctuations around a periodically varying required force, typically a sine wave. Such behavior can in theory be generated in various ways including: (i) a harmonic oscillator, (ii) a (nonlinear) limit cycle dynamics, (iii) two stable fixed points (corresponding to the minimal and maximal force) separated by an unstable fixed point, or (iv) a stable fixed point driven by an external sinusoidal driving force. In any case, a single (linearly) stable fixed point cannot account for sinusoidal force production. Therefore, we expected different dynamic signatures to be revealed when studying the deterministic and stochastic components in the two tasks. Hence, we contend that the findings of Frank et al. (2006) on force maintenance cannot be simply extrapolated to describe cyclic force modulation, or even generalized to different populations.

In that latter regard, numerous studies have indicated that various features of force production change with age as well as with training and expertise (Diermayr, McIsaac, & Gordon, 2010; Keogh, Morrison, & Barrett, 2010; Keogh, Morrison, & Barrett, 2007; Morrison & Newell, 2012; Vieluf et al., 2012). As a main characteristic of age-related differences, variability of the produced force has been shown to increase for both force maintenance and time-varying force modulation (Vaillancourt & Newell, 2002), although age effects were reported to be more prominent in the latter than in the former (Hu & Newell, 2010; J. Keogh, Morrison, & Barrett, 2006). Aging appears to render the fluctuations in force output more regularly in the maintenance task, but less regularly in the cyclic task (Vaillancourt & Newell, 2002). Further, older adults were shown to be less able to adapt to task constraints (Vaillancourt & Newell, 2002). One factor that may slow down age-related deterioration, at least in specific domains, is the long lasting engagement in domain-specific activities (Ericsson & Smith, 1991; Horton, Baker, & Schorer, 2008). For instance, long-term practice in precision mechanics labor was shown to improve the performance in a force maintenance task at low force levels and to reduce the amplitude of force fluctuations (Vieluf et al., 2012). Further, age-related differences were also shown to be less pronounced in these experts than in novices (Vieluf et al., 2012). It is, however, unknown how expertise-related organismal changes express in the dynamics underlying force control. In fact, the observed increased variability in older populations is commonly interpreted as the signature of increased neural noisiness (Li, Huxhold, & Schmiedek, 2004). The approach followed by Frank and colleagues (2006), however, exemplifies that increased variability may be grounded in changes in the deterministic as well as stochastic dynamical component. Indeed, next to identifying the dynamics associated with the different force production tasks, we also aim to explore the dynamical source of the increased variability observed in older populations.

Furthermore, among the age- and expertise-related organismal characteristics, tactile sensitivity (Cole, 1991) and MVC (Sosnoff & Newell, 2006) may also contribute to differences of force control. Hand afferent signals, for instance, are used to adapt and maintain forces (Johansson & Westling, 1987; Westling & Johansson, 1984; Westling & Johansson, 1987). Reduced hand sensitivity alters grip forces; mostly forces higher than necessary are applied to allow for a larger safety margin during grasping. This was shown for older compared to young adults (Cole, 1991), as well as for people with diseased or damaged skin (Brand, 1973; Brink & Mackel, 1987), and anesthetized people (Johansson & Westling, 1984). Sosnoff et al. (2006) showed that the effect of the individuals' MVC on force variability was more robust than the age effect. If and how the two components relate to the dynamics underlying force control is of yet unknown and was tested in this study.

Overall, in the present study, we aimed to identify the deterministic and the stochastic components in force maintenance and in cyclic force modulation task. Further, we aimed to investigate their contribution, if any, to observed changes under different organismal factors (age, expertise, MVC, and tactile sensitivity) by comparing young and late middle-aged novices, as well as late middle-aged experts. In terms of the dynamics, we expected to observe for the force maintenance and the cyclical task, signatures of fixed-point and oscillatory mechanisms, respectively. For group comparisons, we assumed that alterations in the dynamic signatures underlying force control would be already visible in late middle-aged (Lindberg, Ody, Feydy, & Maier, 2009; Vieluf et al., 2012; Vieluf, Godde, Reuter, & Voelcker-Rehage, 2013) through more stochasticity and a weaker deterministic component. In contrast, we expected that middle-aged experts, despite their relatively advanced age, would remain closer to young novices as compared to the older novices as a result of their continuous deliberate use of the hands in daily working routines.

2. Methods and material

2.1. Participants

Thirty-six healthy adults took part voluntarily in the experiment. All participants were right-hand dominant as determined by the Edinburgh Handedness Inventory (Oldfield, 1971), and all reported having normal or corrected-to-normal vision. Participants were recruited by flyers, telephone calls, and newspaper announcements. They were compensated by 8 € per hour. The protocol was approved by the ethics committee of the German Psychological Society and was in agreement with the Declaration of Helsinki. Informed consent was obtained from all participants. The data were collected as a part of the Bremen-Hand-Study@Jacobs (Voelcker-Rehage, Reuter, Vieluf, & Godde, 2013). None of the participants had hobbies involving a high degree of manual dexterity (i.e., needlework, playing a musical instrument, or fine mechanical tasks). Further, none of them reported any neurological disorder. All participants were given a demographic and health questionnaire to obtain information about characteristics of the sample. Selected relevant characteristics of the groups are reported in Table 1.

Based on their age and their occupational field, participants were assigned to three subgroups: young novices (YN:12; 20-26 years; mean age 23.33 ±1.92 years; 8 females), late middle-aged novices (LMN:

12; 57-67 years; mean age 60.91 ±3.02 years; 7 females), and late middle-aged experts (LME: 12; 57-67 years; mean age 60.50 ±3.00 years; 8 females). The groups of young and old novices were formed by service employees, i.e., consultants, office clerks, insurance agents, and vocational trainees in these occupations. The group of experts included precision mechanics who manipulate small objects in a highly dexterous way as part of their daily work routines, i.e., opticians, goldsmiths, watchmakers, hearing care professionals (Reuter, Voelcker-Rehage, Vieluf, & Godde, 2012; Trautmann, Voelcker-Rehage, & Godde, 2011; Vieluf et al., 2012). Based on the definition of Ericsson and Smith (1991) experts were only included when they had at least 10 years of work experience in the specific field. To verify the expertise, we used a questionnaire that assessed the frequency of hand use at work (see Table 1), which showed that our experts had a significantly higher frequency of dexterous hand use than the novices ($p < .001$).

2.2. Experimental setup

A force transducer (Mini-40 Model, ATI Industrial Automation, Garner, NC) was affixed to the experimental table, so that the participant could comfortably grasp it while being seated with the arms placed on arm rests. Participants were instructed to apply forces on the force transducer using a precision grip with their index finger and thumb only, while the other fingers build a fist. The right thumb was placed on the force transducer. The arm position was neutral, so that the index finger and thumb could grasp the force transducer that was affixed orthogonal to the table. The grip force was recorded with an amplitude resolution of 0.06 N and a sampling rate of 120 Hz. An online low-pass filter with a cutoff frequency of 200 Hz was applied. A customized LabView (National Instruments, Austin, TX) program was used to collect force data and provide on-screen visual feedback to the participants. The target force level and the actual grip force produced by the subjects were displayed in light green and yellow, respectively, with line thickness of 1 mm (see Fig. 1, panel A for black and white illustration), over a black background on a 19-inch monitor, with 60 Hz frame rate. The screen was placed at approximately 80 cm in front of the participants, resulting in a visual angle of approximately 45° for the whole screen and 38° for the relevant area, showing the force curves.

2.3. Task and procedure

Touch detection threshold was measured in a separate session prior to the data acquisition of the force task. The threshold was defined by the use of 18 von-Frey-filaments (custom made, calibrated filaments) representing a force range on a logarithmic scale from 0.177 to 63.743 mN. The tactile threshold was determined by use of the two-down, one-up procedure with six points of return, (Leek, 2001; see Reuter et al., 2012 for a detailed description of the procedure).

We first measured the MVC of the right hand with the index finger opposing the thumb. The MVC was determined in three maximum precision grip trials, 5 s each. Participants were given at least 2 min rest between each maximal effort. The applied force was averaged for the last 3 s of each trial, and the highest value among the three trials was considered as the MVC. No differences between YN (mean = 53.59 ± 16.33 N), LMN (mean = 59.90 ± 24.95 N), and LME (mean = 57.90 ± 20.05 N) MVCs were observed, $F(1,33) = 0.642$, $p = .75$, $\eta_p^2 = .017$.

In the experiment, participants' task was to match their produced force with the target line as precisely as possible. Target force level and the produced grip force in time moved from the left to the right on the screen. The target line was displayed 0.5 s in advance and up to 4.5 s after trial completion. The y-axis ranged from 0 to 14 N in both conditions. The target curve was either a straight line at 2 N or a sine wave ranging from 2 to 12 N with a frequency of 1 Hz. Note that for the force maintenance task, we chose the lowest force that was requested in the cyclic task because, following previous findings (Galganski, Fuglevand, & Enoka, 1993; Lindberg et al., 2009; Slifkin & Newell, 2000, Vieluf et al., 2015), we expected age-effects to be higher for this force level than for the mean force level (7 N). It also allowed us to avoid fatigue. To fulfill these two tasks, participants were required to perform either constant force maintenance or cyclic force modulation. Each task included 40 trials of 5 s each. In-between the trials, a fixation cross was presented for 5 s. An auditory stimulus together with the disappearance of the fixation cross signaled the start of the trial. Participants were instructed to reach the target line as quickly as possible. As all of them were already familiar with the setup from previous experiments (Vieluf et al., 2012; Vieluf et al., 2013), only the first two trials of each condition were considered as task adaptation and were accordingly excluded from further analysis.

[Insert Fig. 1 about here]

2.4. Data Analysis

2.4.1. Raw data processing

Data were analyzed using Matlab R2012b (MathWorks, Natick, MA, USA). Data were filtered offline with a 4th order Butterworth filter at 30 Hz. The first 2 s of each trial were discarded to exclude the ramp phase. The analyses were consequently conducted on the last 3 s of each trial. All variables were determined per trial and then averaged per condition. Outliers were detected on a trial basis. For the force maintenance task, trials exceeding the mean variability, calculated per participant per condition, by ±2.5 times the standard deviation (SD) were excluded from further analysis (see Frank et al. 2006 for similar procedure). For the sinusoidal force task, outliers were identified as either trials in which the force dropped below 0.05 N so as to exclude trials where force was released, or trials in which the amplitude within a cycle was lower than 5 N.

2.4.2. General characteristics of performance

The mean of the produced force, based on real force values, and the SD of the deviations between the applied and the target force were calculated to capture, globally, accuracy and the amount of variability of force production.

For the cyclic force modulation task, we computed the Hilbert phase of the applied force, q_{AF}, and the target, q_T, for each trial, to get the phase angle as a function of time. The relative Hilbert phase was next calculated as $q_{rel} = q_{AF} - q_T$. Positive values thus indicate that the applied force lags the target. We next calculated the mean and uniformity, a measure of dispersion, of q_{rel} using circular statistics (Mardia, 1975). These measures provide information about the accuracy and the variability of the relation between the target curve and the applied forces. Descriptive statistics for all the general characteristics of performance are reported in Fig. 2.

2.4.3. Dynamics characterization

We used the Kramers-Moyal expansion to investigate the dynamics associated with both force tasks (cf. Daffertshofer, 2010; Frank et al., 2006; Friedrich & Peinke, 1997). Force production, and human movement in general, is inherently stochastic; its dynamics comprises a deterministic and a stochastic component. By implication, the future (force) state is conditional upon the probability for the state to be at a certain instant at a specific point in the state space, which is described by probability distributions that can be calculated from experimental data. The Kramers-Moyal expansion allows for the identification of the deterministic and stochastic dynamical components for the conditional probability matrix. The conditional probability matrix thus describes transition probabilities. For the force modulation task, the analysis was done on the Hilbert phase transformed data. For each trial, for both tasks separately, the two-dimensional conditional probability matrix *P*(AF',t+Dt|AF,t), which denotes the probability to find the system at state AF' at a time t+Dt given its state AF at an earlier time step t, was computed using a bin size of (5 · SD(AF))/N, with N=7,, the range of the AF space sampled was from -2.5 □ SD to 2.5 □ SD, and N=11, the range of the AF space sampled was from -pi to pi, for the maintenance and dynamic task, respectively. Next, for each participant the average conditional probability matrix across all trials was computed. Each participant and hands' deterministic and stochastic dynamics (also referred to as drift and diffusion coefficients) were then calculated based on *P*(AF',t+Dt|AF,t):

$$D^n = \lim_{\Delta t \to 0} \frac{1}{\Delta t} \int \frac{\left(AF' - AF\right)^n}{n!} P\left(AF', t + \Delta t \mid AF, t\right) dx' . \qquad \text{[Eq 1.]}$$

The deterministic (drift) and stochastic (diffusion) dynamics were obtained for n=1 and 2, respectively. To evaluate the fixed point's stability in the force maintenance task, the slope of the deterministic dynamical component (the drift coefficient) across the three middle bins (i.e., where the coefficient changed sign) was determined by a linear regression.

After a first exploration and based on the observed results for the deterministic dynamics in the cyclic task, we followed up by testing for the possible existence of two fixed points that might have been falsely found to be absent in the deterministic dynamics. Fixed points are identified by a change in sign in the sequence of drift coefficients that capture the deterministic dynamics. If the dynamics are not fully stationary, and an actually existing fixed point's location (slightly) changes from cycle to cycle, the drift coefficients may locally approach zero but never change sign. If this is the case, that is, if fixed points are present (but not detected by the Kramers-Moyal expansion), then it can be expected that the Hilbert phase, which continually increases for a (nonlinear) oscillator, locally reveals phase reversals at the location of the fixed point(s). Stochastic fluctuations will cause the system to overshoot the fixed point, which, due to its stability, will attract the system towards it. To test for the possibility that the attractor is shifted in time between different trials, we identified inflection points in the Hilbert phase evolution (see Fig. 1D) per phase of the sine wave's cycle. Occurrences are given in percentage relative to the total number of cycle (38 trials * 3 cycles = 114). Note that more than one inflection point can occur per cycle. However, there was never more than one inflection point per phase detected.

2.4.4. Statistical analyses

Statistical analyses were conducted in STATISTICA (StatSoft, Tulsa, OK, USA). Analyses of variance (ANOVA) with the between factor group (3; YN, LMN, LME were calculated for the variables describing the general performance of the task (mean force level of the applied forces, SD, mean relative phase, and variability of relative phase). To characterize the dynamics, Group (3; YN, LMN, LME) × Bins (7; equally spaced from -2.5*SD to 2.5*SD) repeated measures ANOVAs were conducted on the drift and diffusion coefficients (i.e., those representing the deterministic and stochastic component of the dynamics) of the force maintenance task as well as an analysis of variance by group for the slope around the fixed point (indicating the fix point). Group (3; YN, LMN, LME) × Bins (11; equally spaced from -pi to pi) repeated measures ANOVAs were conducted on the drift and diffusion coefficients. For the statistical analysis of the number of inflection points of the cyclic task we calculated a Group (3; YN, LMN, LME)

× Phase (4; minimum, ascending phase, maximum, descending phase) repeated measures ANOVA. Effect sizes are given as partial Eta squares (η_p^2). Whenever sphericity was violated, Greenhouse-Geisser correction was applied. The level of significance was set to $p < 0.05$. Significant effects were followed by Newman Keuls' post-hoc test. To gain insight into a potential relation between tactile sensitivity and muscular strength to the level of noise, we correlated the tactile threshold and the MVC with the mean stochastic impact (represented by the diffusion coefficients) of force maintenance and force modulation. Additionally, the slope around the fixed point was correlated with the tactile threshold. Note, correlations are reported for all participants irrespective of their group as preliminary results showed no difference between groups. Merging the groups still allowed us to get a global picture of possible relations between strength and tactile sensitivity with the characteristics of force control.

3. Results

3.1. Force maintenance task

3.1.1. General characteristics of performance

The mean applied force differed between groups, $F(2,33) = 3.56$, $p = .04$, $\eta_p^2 = .177$, (Fig. 2A). LMN overshot the target force level more than YN ($p = .03$). However, a follow up one sample *t*-test showed that all groups overshot significantly (YN: $p = .02$; LMN: $p < .01$; LME: $p = .03$). SD did not differ between groups, $F(2,33) = 0.48$, $p = .62$, $\eta_p^2 = .028$, (Fig. 2A).

[Insert Fig. 2 about here]

3.1.2. Dynamics: deterministic and stochastic components

[Insert Fig. 3 about here]

For the deterministic (i.e., drift) component, the curve across bins shows a nearly straight line that crosses the horizontal axis at 0, indicating the presence of a fixed-point attractor at that force level (Fig. 3A). Statistical analysis showed that the coefficients differed between bins, $F(2,33) = 373.73$, $p < .01$, $\eta_p^2 = .205$, (all post-hoc comparisons $p < .01$). The slope around the fixed point, which quantifies the strength of the attractor, did not differ between groups, F(2,33) = 0.73, p = .49, η_p^2 = .042. The bin by group interaction was not significant, F(12,198) = 0.40, p = .96, η_p^2 = .024. With regard to the stochastic (i.e., diffusion) component of the dynamics, analysis revealed significant main effect of bins, F(6,198) = 28.00, p <.01, η_p^2 = .607. Values were the lowest at the fixed point and increased away from it on both sides toward the outer bins (all $p < .01$, except for the comparison of bins 2 and 6 as well as bins 3 and 5; Fig. 3B). Thus, in the force maintenance task for the examined force level, the behavior of all groups was generated by a fixed-point dynamics with equivalent attractor strength. Additionally, all participants, independent of their group, F(2,33) = 1.11, p = .34, η_p^2 = .063, presented a behavior with a comparable level of stochasticity (i.e., noise). Again, the interaction was not significant, F(12,198) = 0.20, p = .97, η_p^2 = .012.

3.1.3. Correlations of dynamic signatures with tactile threshold and MVC

The correlation between the slope through the fixed point and the tactile threshold was significant (*R* = .370; *p* = .026; Fig. 4A). In contrast, the slope through the fixed point correlated only marginally with MVC (*R* = .294; *p* = .081; Fig. 4B).

[Insert Fig. 4 about here]

3.2. Cyclic force modulation task

3.2.1. General characteristics of performance

The mean force level differed between groups, F(2,33) = 4.25, p = .02, η_p^2 = .205. LMN applied lower mean forces than YN (*p* = 0.02) and marginally lower than LME (*p* = 0.06). LMN (*p* < .01) and LME (p = .03) were more variable than YN. Mean forces were significantly lower than prescribed for LMN (*p* < 0.01) and LME (*p* = 0.03), but not for YN (*p* = 0.07) (Fig. 2B). Variability differed between groups, F(2,33) = 7.12, p < .01, η_p^2 = .302. Further, the mean relative phase between target and applied force did not differ between groups, F(2,33) = 2.24, p = .12, η_p^2 = .120. However, its variability (uniformity) differed between groups, F(2,33) = 5.01, p = .01, η_p^2=. 233, as it was lower for YN than LMN (*p* = .01) and LME (*p* = .03) (Fig. 2C).

3.2.2. Dynamics: deterministic and stochastic components

The deterministic dynamical component, the corresponding drift coefficients plotted as a function of bins based on the Hilbert phase, revealed a bimodal structure with no zero crossing of the horizontal axis (Fig. 3C). Thus, the observed profiles offered no evidence for a fixed-point dynamic, and are suggestive of a limit cycle dynamics (see below). Post-hoc analysis, following up on the significant effect of bins, F(10,330) = 127.73, p < .01, η_p^2=. 795, revealed all *p*'s < .01, except for the comparison of bins 1 and 10, 3 and 9, 4 and 7 as well as 5 and 6. Further, group differences were revealed, F(2,33) = 7.20, p < .01, η_p^2=. 304, which indicated that YN showed lower drift coefficients (representing the deterministic dynamics) than LMN (*p* < .01) and LME (*p* = .01). The group by bin interaction was not significant, F(20,330) = 1.19, p = .31, η_p^2=. 067.

The diffusion coefficient, which captures the stochastic component of the dynamics, showed a similar M-pattern as the drift component (representing the deterministic dynamics) in all groups (Fig. 3D). Again, the main effect of bins, F(10,330) = 110.50, p < .01, η_p^2=. 770, reached significance with all *p*'s < .01, except for the comparison of bins 1 and 10, 2 and 3, 3 and 9, 4 and 7 as well as 5 and 6. The main effect of group reached significance, F(2,33) = 7.17, p < .01, η_p^2= .303. YN showed lower coefficients than the LMN (*p* < .01) and LME (*p* < .01), suggesting overall less noisy dynamics in the young group. The interaction of group and bin was not significant, F(20,330) = 1.08, p < .38, η_p^2= .061.

[Insert Fig. 5 about here]

Analysis of inflection points revealed a significant interaction of phase and group, F(6,99) = 2.46, p = .03, η_p^2=. 130, (Fig. 5). Overall and within each group the number of inflection points was higher for the minima than for the maxima as well as for the descending and the ascending phases (all *p* < .01). The number of inflection points observed for the minima was the highest for YN, followed by LMN, and the lowest for LME (all *p* < .01). The frequency of occurrence for the minima was between 30 and 40% of the cycles, and for all the other phases, inflection points occur during about 3 to 10% of the trials. For the ascending phase LMN showed the most inflection points and LME more than YN (all $p < .01$). In the descending phase and around the maxima most inflection points were found for the LME and more by the LMN than by the YN (all $p < .01$). This last analysis clearly distinguishes the minima phase, that is, around the reversal point, and shows the presence of group specificities with regard to how the dynamics is expressed.

3.2.3. Correlations of dynamic signatures with tactile threshold and MVC

Mean stochastic (i.e., diffusion) coefficients correlated positively with the tactile threshold ($R = .374$; $p = .025$) but not with MVC ($R = .227$; $p = .183$), suggesting that subjects with higher discrimination capacities had a lesser stochastic dynamics (see Fig. 4, indicate panel).

4. Discussion

We studied the dynamic signatures of isometric force control in terms of extracted deterministic and stochastic dynamics in a constant force maintenance and a cyclic force modulation task performed by young and late middle-aged novices (YN and LMN), as well as late middle-aged experts (LME). In order to allow for comparison with the bulk of the existing literature, we also performed more conventional analysis characterizing the overarching force control properties. In the sections below, we first discuss the latter results, followed by those pertaining to the influence of force task constraints as well as those to age- and expertise-related differences in separate sections.

4.1. Effects of age and expertise on the force accuracy and variability

Consistent with previous findings, we found that some age-related differences in force control occur already during the late middle-aged life span (Lindberg et al., 2009; Vieluf et al., 2013). This age effect was more pronounced in the arguably more demanding cyclic force modulation task than in the force maintenance task (see Diermayr et al., 2010 for an overview of consistent findings). In the force maintenance task LMN applied higher forces than the other groups, but revealed no differences in variability. Note, however, that we examined force maintenance at very low levels, which the LMN did not fully comply with: they showed higher overshooting forces than the other two groups (see Lindberg et al., 2009 for similar results for a force level of 3 N). Converging findings in this regard have been also found during lifting (Cole, Rotella, & Harper, 1999), where it supposedly expresses the safety margin to prevent the object from slipping (Cole & Beck, 1994). Furthermore, the higher forces might be a way to compensate for tactile sensitivity loss with aging (Cole, 1991) as observed in this group of participants (Reuter et al., 2012). Indeed, it has been shown that force control was more variable at these low levels than at higher levels (Galganski, Fuglevand, & Enoka, 1993; Lindberg et al., 2009; Slifkin & Newell, 2000, Vieluf et al., 2015). These previous results motivated the choice of a low force level. However, it remains of interest to test the dynamics at a comparable mean force level for both tasks. Going back to our results, the higher applied forces in the LMA might have been a strategic way of compensating for age-related deficits and therefore reduced some of the age effects especially for variability measures.

In the cyclic task, where, in contrast to the force maintenance task, the LMN applied lower mean forces than the two other groups, they showed higher variability (e.g., Voelcker-Rehage & Alberts, 2005) as well as higher variability of the relative phase. Finally, the influence of fine motor expertise on the dynamics of force control was investigated to gain further insights into how motor functioning can be stabilized. According to the use-it-or-lose-it hypothesis (Salthouse, 1985; Salthouse, 2006) and the deliberate practice approach (Ericsson & Smith, 1991), a frequent and continuous use contributes to maintaining skills. Continuous use of the hands to manipulate small objects in a dexterous way has been shown to lead to higher performance (Cannonieri, Bonilha, Fernandes, Cendes, & Li, 2007; Jäncke, Schlaug, & Steinmetz, 1997; Krampe, 2002). As expected, our findings confirmed that age effects were less pronounced for experts. Their performance was in-between young and late middle-aged novices. Consequently, LME showed weaker age effects. However, based on the limitations that emerge in group comparisons (as a young expert group does not exist due to the 10 years of experience criterion), we can only conclude that continued specific activities seem to postpone or counteract to some degree some age-related changes. In fact, LME did not show differences in accuracy, i.e., higher mean force levels in the maintenance task and lower mean force levels in the cyclic task, but were more variable in terms of force production and relative phasing than the young novices during the cyclic task. This might indicate a weaker coupling between the applied force and the stimulus with increasing age as previously reported for a bimanual force modulation task (Vieluf, Godde, Reuter, Temprado, & Voelcker-Rehage, 2015). However, overall we did not observe strong age and expertise effects. We assume that this could be, at least partly, due to the fact that participants were already familiar with the task—as parts of the age- and expertise-related differences may result from different strategies or different amount of attention allocation to complete force control tasks. Furthermore, it may well be that age and expertise related differences would surface under different force levels and, for the cyclic task, frequency of the requested force modulation. Furthermore, our findings cannot be systematically extended to more senior elderly. This remains to be explored in future work.

4.2. Dynamic signatures of force maintenance and cyclic force modulation tasks

To investigate the tasks' dynamics we computed the deterministic and stochastic dynamical components associated with both force control tasks. Additionally, we identified inflection points in the Hilbert phase for the cyclic task as a mean to explore the possible existence of (moderately) non-stationary fixed points. In line with our hypothesis, we observed different dynamics for both tasks. The force maintenance task revealed a clear fixed-point dynamic, with smaller magnitude of stochastic fluctuations (noise) around the fixed point than away from it (see Frank et al., 2006 for consistent results). In other words, the magnitude of the random fluctuations was proportional to the strength of the flow (and thus was smallest near the fixed point). That is, large force deviations relative to the requirement are counteracted with more vigor than small ones, which intuitively seems a smart solution to the task at hand.

For the cyclic force modulation task, clearly different dynamics were observed. Specifically, no fixed points could firmly be established as attested by the deterministic dynamics; the corresponding drift coefficients were always positive. This result suggests that the sinusoidal force modulation is governed by an oscillatory, likely limit cycle, generating mechanism. Note that in the case of a perfect harmonic oscillator, the drift coefficients are of equal (non-zero) value across the entire space. This was clearly not the case: the coefficients revealed two local maxima and two minima. These local peaks reflect the fast ascending and descending phases of force production and the slower evolution in the cyclic force production around the force maxima and minima, respectively.

Consequently, if the underlying dynamics are generated by an oscillator, it is non-harmonic (Stepp & Frank, 2009). These local minima in the deterministic dynamics may indicate a location in phase space that just fails to be (in this case) a stable fixed point, in more technical terms, a ghost attractor (cf. Strogatz, 1994; Collins, Park, & Turvey, 2010; Huys, Studenka, Zelaznik, & Jirsa, 2010). In its presence, the system locally slows down considerably. Under that premise, one could predict that when modulating the frequency of the sinusoidal target (most likely by decreasing it), at some critical value (a bifurcation point) the drift coefficients would end up crossing the horizontal zero line, as fixed points are created. A similar scenario was found in movement tasks when slowing down the movement frequency for a cyclic movement task (see Huys et al., 2010 in the context of circle drawing). One way to investigate the dynamics in further detail would be to systematically vary target frequency and the force levels required with the aim to identify the potential bifurcation(s).

The absence of identified fixed points may also be explained otherwise. For one, it may be that the force production is governed by two stable fixed points (corresponding to the extrema of the target force), but that these fixed points slightly drift over time. In that case, the minima at the target extrema will be less pronounced and zero-crossing may vanish as a result (Huys et al., 2010). However, inflection points, indicating no rate of change in the force profile, were mostly observed around the minimum and were relative rare at the maximum. This finding is in line with findings by Masumoto and Inui (2010), who reported higher variability at the minima than for the maxima, but argues against the existence of a fixed point at the maximum, and thus against a (symmetric) bi-stable system. Alternatively, the dynamics may adhere to a fixed point that is driven by the sinusoidal target so that the phase flow changes at the time scale of the force production. Under this scenario the dynamics could be expected to be symmetrical and show an approximately homogenous distribution of inflection points. The pronounced difference in the occurrence of inflection points around the force minima and maxima thus argues against this hypothesis. Furthermore, in line with the ideas derived from the study by Danion and Jirsa (2010), the bimodal structure might be related to the combination of feed-forward and feed-backward control, and that these control modes are differently strong involved during different phases of the sine wave and lead to different relations of whether the applied force leads or lags the target force.

Regardless, the dynamics governing the sinusoidal target force task could not be unambiguously identified and awaits future investigation. However, at this point we can state that it is clearly different from the one observed in the static force production task, and are asymmetric in terms of the up/down versus minima/maxima phases as well as in terms of the 'depth' of the two minima (see Fig. 3C). Note, while we cannot make definitive statements about the attractor structures involved—the current results favor a nonlinear oscillator, though the drift coefficients still clearly indicate the deterministic dynamics of the participants' behavior. This is expressed by a strong slowing down, almost plateauing, at the force minimum, and to a less extent at the force maximum, and a faster rate of force change during the ascending and descending phases.

Noise was lower around the local minima in the drift coefficient than away from them. This finding indicates that for the sinusoidal force modulation task, the two components of the fast dynamics show higher noise than the slow dynamics. In other words, the magnitude of the stochastic fluctuations was proportional to the deterministic force. Thus, at least qualitatively, the relation between the deterministic and stochastic component of the dynamics appeared to be similar in both tasks even though their dynamics were qualitatively distinct.

Interestingly, we found a significant correlation between the tactile threshold and the degree of stability of the fixed point, i.e., the lower the tactile threshold the more stable the fixed point (in the static force production task), indicating that sensory capacities and stochasticity are somehow related. This suggests that tactile sensitivity might contribute to the stabilization of force control. In other words, it links perceptual ability to the deterministic dynamics of force control. In contrast, no evidence was found that tactile sensitivity is related to the stochastic component. Additionally, the marginally significant correlation between the stability of the fixed point and the MVC provided first indication that stronger subjects may be more prone to generate a more stable force dynamics. Taken together, individual organismal characteristics seem to influence force control in a way that the stronger and the more sensitive the participant, the more stable his/her expressed dynamics would be. However, further research is needed to gain deeper insights into a potential causal relation between these components of force control and the underlying dynamics.

4.3. Effects of age and expertise on the expressed dynamics

In general, some group-related dynamical differences were expressed in a task-dependent manner, but the nature of the dynamics underlying force control did not differ between groups. Accordingly, for the examined populations, we conclude that the expressed behavior stemmed from the same generating mechanisms, which were determined by the task.

In the force maintenance task, no differences in dynamic signatures were observed between groups. In contrast, for the cyclic task, both the deterministic and stochastic components (i.e., drift and diffusion coefficients) were higher for older novices than for the two other groups. The higher drift coefficient for the older novices suggests that the rate of the change of their force production was higher than that of the other two groups. This result is somewhat puzzling given that all groups tracked a target force oscillating with 1 Hz, and that the elderly are generally known for their slower rate of force production (Ng & Kent-Braun, 1999; Stelmach, Teasdale, Phillips, & Worringham, 1989). One potential explanation for this finding is that the older novices were slower in adapting to the stimulus frequency, and were therefore still catching up with the target in the 3 seconds of data analyzed. Alternatively, it might be indicative of a different deficit, that is, the incapability of continuous slow force tracking. In line with this idea older adults would be less capable in smoothly ramping-up or down their produced forces according to the displayed sine wave. Such assumption could be grounded on age-related alterations in force production smoothness, which has been found to be more apparent at low force levels, as are the ones used in the present study (Brown, 1996; Galganski et al., 1993; Kinoshita & Francis, 1996). Notice that the group differences in the mean drift components, however, were very small (mean ± SD of 7.58 ± 6.91 versus 7.40 ± 6.51 for the young and novice elderly, respectively). The limited length of our data (recall, the last 3 seconds of 5 recorded seconds were analyzed) did not allow us to meaningfully verify this result using further analyses, e.g., power spectrum, but it certainly deserves to be explored in future studies including longer trials, different movement frequencies, as well as different force levels. Regardless, our finding suggests that concomitant changes in the deterministic as well as stochastic dynamical components could be causing motor behavior to become more variable in numerous tasks with increasing age (Christou & Tracy, 2006; Vaillancourt & Newell, 2003). It should be noted that in the force maintenance task no dynamical differences were found between groups. Unless the older novice participants were successfully compensating by applying higher forces, this could imply that the latter task lacks the sensitivity to bring this to the fore, at least for the force level tested here. Another explanation could be that aging does not increase stochasticity per se, and thus that stochasticity is not a personal or age-related task-independent property, but rather a property described over the performer and task in combination.

Finally, we found that in both tasks the experts had similar dynamics (both deterministic and stochastic) as the young novices. We conclude that continued specific activities seem to postpone or counteract to some degree some age-related changes in the components of force control dynamics.

Taken together, our findings suggest that although the nature of the dynamical processes underlying force modulation can be preserved with age, at least up to a certain age, the behavior can be more or less prone to stochastic influences, as well as a different parameterization of the attractor states. It should be noted that it remains unclear how the different dynamical components relate to the functional organization of the sensorimotor function. If we tentatively speculate that, the deterministic and stochastic component reflect processes and interactions between them that are (more) directly task-relevant and those that are not, respectively, then the here-used framework may be potentially linked to the idea of “dedifferentiation”, that is, “a process by which structures, mechanisms of behavior that were specialized for a given function lose their specialization and become simplified, less distinct or common to different functions” (Sleimen-Malkoun, Temprado, & Hong, 2014). Under this hypothesis, the consequences of structural age-related changes in the nervous system will be expressed differently in different task contexts. Moreover, there are suggestions that the behavioral repertoire decreases with age (see Sleimen-Malkoun et al., 2014). That is, age but also expertise may change the number and/or nature of behaviors of the repertoire. Analysis of the dynamics along the lines described here provide for the means to investigate these issues in future work.

4.3. Conclusion

The underlying dynamics of force control vary qualitatively in response to task constraints. Within this study, we confirmed that a fixed point dynamics underlies force maintenance, as previously shown by Frank et al. (2006), while the dynamics underlying the cyclic force modulation task was found to resemble that of a non-harmonic oscillator. The latter finding indicates the combination of one slow and one fast dynamics while tracking a regularly time-varying force target. Age effects were found to be more pronounced in the cyclic, arguably more complex task. Compared to young novices, the older experts appeared mainly more variable. Overall, the dynamics underlying force control appeared similarly organized between groups; the observed differences were limited to small differences in the deterministic and stochastic dynamics in the cyclic task only, suggesting that, among others, the adaptation to task constraints varies. This result suggests that behavioral fluctuations cannot be uniquely traced back to system noise. It may indicate that increased variability in aged populations is not solely a matter of a task-independent increase of noisiness, but suggests that the magnitude and structure of noise is specific to ‘the actor in action’, that is, pertains to the actor in a task-dependent fashion. However, it seems plausible that qualitative differences between different populations (age, expertise) may appear when task parameters are pushed towards their limits.

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Conflict of interest

The authors declare no competing financial interests.

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Table 1. Group characteristics.

	YN		LMN		LME		Statistics				YN - LMN	YN - LME	LMN - LME
	Mean	SD	Mean	SD	Mean	SD	df	F	*p*	η_p^2			
Education (years)	13	1.38	15	3.46	16	3.05	2,33	2.87	.07	.156		(*)	
Handedness (% of tasks performed with right hand)	97.92	3.75	99.33	2.42	93.75	10.75	2,33	2.23	.12	.996			
Subjective hand usage at job	16.25	6.15	14.33	6.17	30.75	4.86	2,33	29.13	<.01	.932		*	*
MVC right	53.56	16.33	59.90	24.95	57.90	20.06	2,33	0.29	.75	.017			
Tactile threshold	75.86	41.84	226.13	251.10	144.88	66.72	2,33	34.6	.07	.151	(*)		
Physical activity	7.70	1.23	7.78	1.79	7.59	1.79	2,33	0.04	.75	.017			

* significant post hoc and (*) marginally significant post hoc result tested via Bonferroni corrected pairwise comparison following up an ANOVA

Figure legends

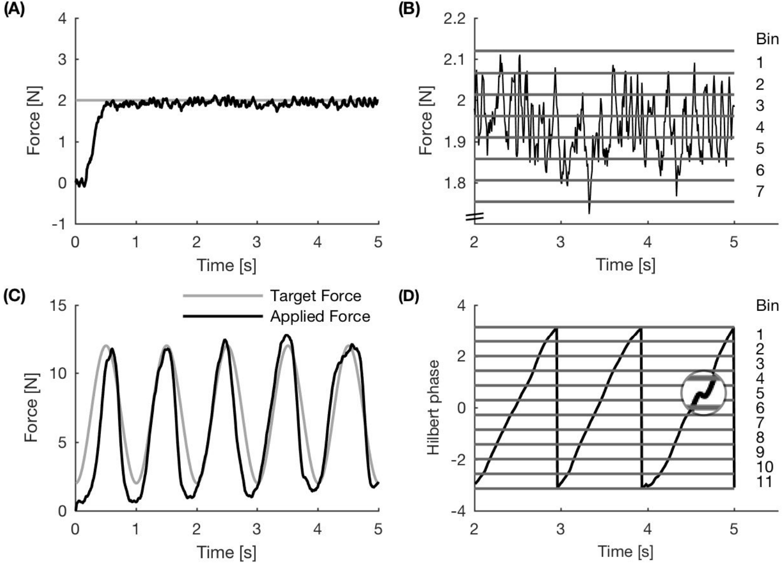
Fig. 1. Exemplary performance and binning. All panels show representative force-time-curves from one representative participant (target line: light grey and applied force: black) over the whole trial and zoomed into the part analysed with exemplary binning for force maintenance (A, B) and cyclic force modulation, with highlighted inflection point (C, D) tasks.

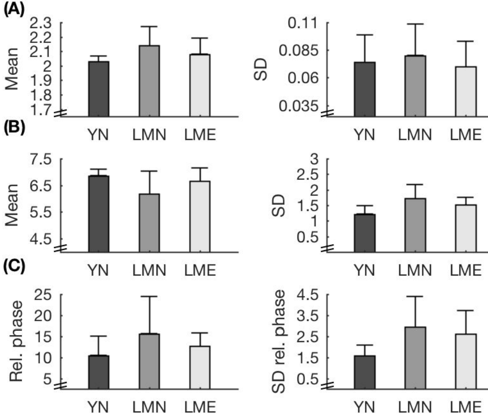
Fig. 2. General characteristics of force maintenance. Means and standard deviations (SD) of the general properties of force production per group are provided.

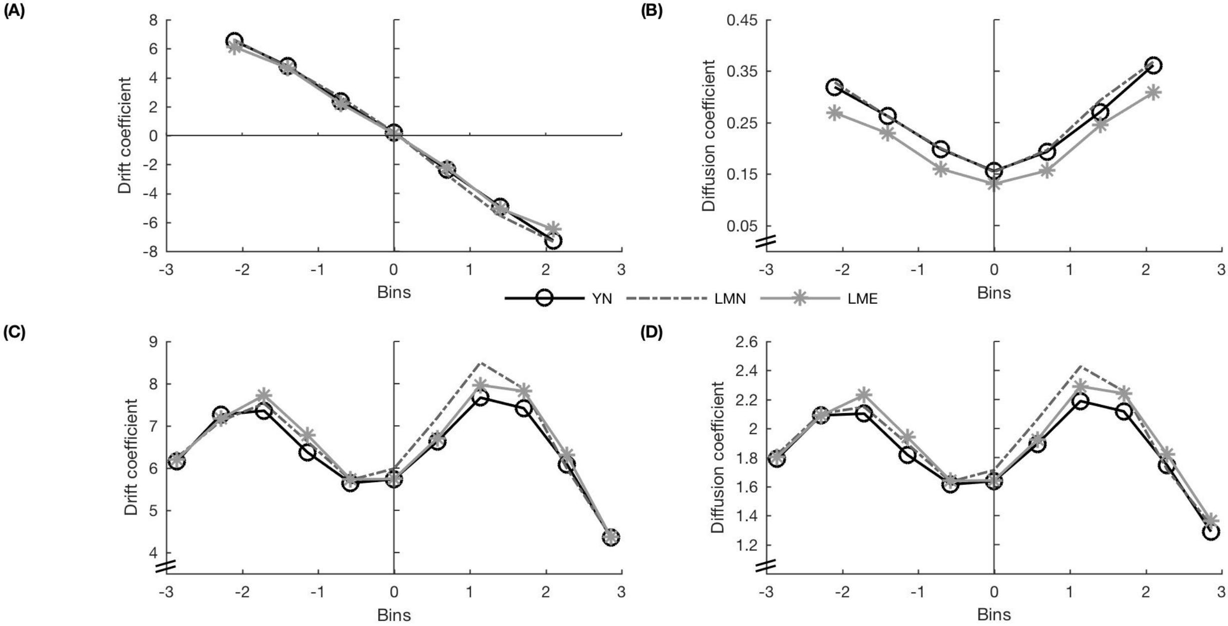
Fig. 3. Dynamics of force maintenance and cyclic force modulation. Group means of the drift and diffusion coefficients for force maintenance (A, B) and cyclic force modulation (C, D) tasks are presented for young (left) and late middle-aged (middle) novices as well as late middle-aged (right) experts.

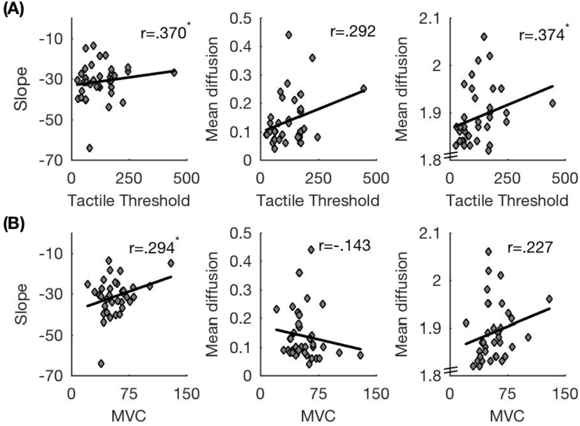
Fig. 4. Correlations. The slope around the fixed point (left) and the mean diffusion coefficients (middle) of force maintenance task as well as the mean diffusion coefficients of the cyclic force modulation (right) were plotted against the tactile threshold (A) and the MVC (B).

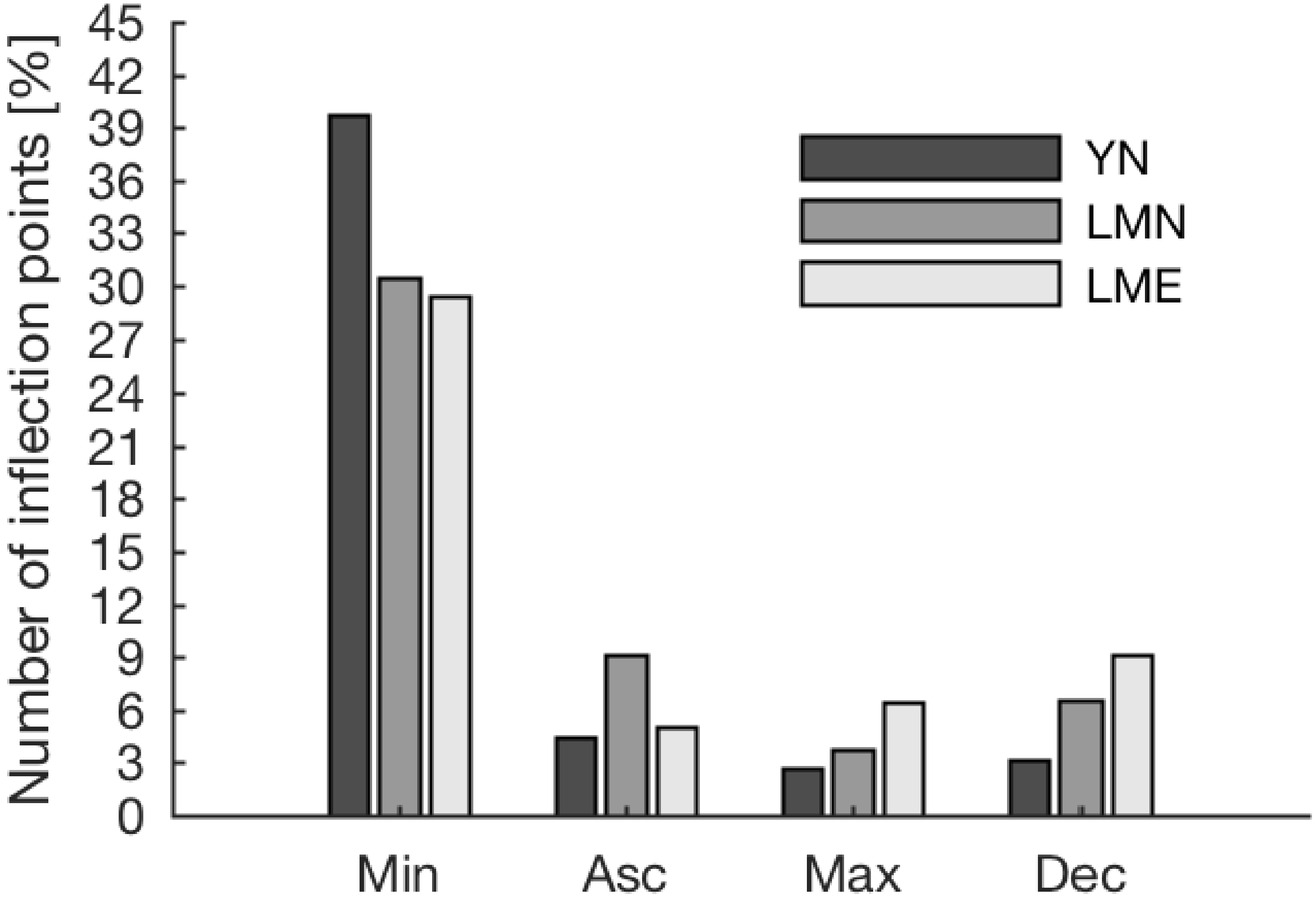
Fig. 5. Number of inflection points. Showing number of inflection points relative to the number of performed cycles for each of the phases of the sine wave per group.


(A)
Force [N]
4
3
2
1
0
-1
0
1
2
3
4
5
Time [s]
(B)
Force [N]
2.2
2.1
2
1.9
1.8
2
3
4
5
Time [s]
Bin
1
2
3
4
5
6
7
(C)
Target Force
Applied Force
Force [N]
15
10
5
0
0
1
2
3
4
5
Time [s]
(D)
Hilbert phase
4
2
0
-2
-4
2
3
4
5
Time [s]
Bin
1
2
3
4
5
6
7
8
9
10
11


(A)
Mean
2.3
2.2
2.1
2
1.9
1.8
1.7
YN
LMN
LME
SD
0.11
0.085
0.06
0.035
YN
LMN
LME
(B)
Mean
7.5
6.5
5.5
4.5
YN
LMN
LME
SD
3
2.5
2
1.5
1
0.5
YN
LMN
LME
(C)
Rel. phase
25
20
15
10
5
YN
LMN
LME
SD rel. phase
4.5
3.5
2.5
1.5
0.5
YN
LMN
LME


(A)
Drift coefficient
8
6
4
2
0
-2
-4
-6
-8
-3
-2
-1
0
1
2
3
Bins
(B)
Diffusion coefficient
0.45
0.35
0.25
0.15
0.05
-3
-2
-1
0
1
2
3
Bins
YN
LMN
LME
(C)
Drift coefficient
9
8
7
6
5
4
-3
-2
-1
0
1
2
3
Bins
(D)
Diffusion coefficient
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
-3
-2
-1
0
1
2
3
Bins


(A)
Slope
-10
-30
-50
-70
0
250
500
Tactile Threshold
r=.370*
Mean diffusion
0.5
0.4
0.3
0.2
0.1
0
0
250
500
Tactile Threshold
r=.292
Mean diffusion
2.1
2
1.9
1.8
0
250
500
Tactile Threshold
r=.374*
(B)
Slope
-10
-30
-50
-70
0
75
150
MVC
r=.294*
Mean diffusion
0.5
0.4
0.3
0.2
0.1
0
0
75
150
MVC
r=-.143
Mean diffusion
2.1
2
1.9
1.8
0
75
150
MVC
r=.227


Number of inflection points [%]
45
42
39
36
33
30
27
24
21
18
15
12
9
6
3
0
YN
LMN
LME
Min
Asc
Max
Dec