Human Movement Science 68 (2019) 102520

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Full Length Article

# Motor variability in elicited repeated bout rate enhancement is associated with higher sample entropy

Anders Emanuelsen, Pascal Madeleine, Michael Voigt, Ernst Albin Hansen*

*Sport Sciences, Department of Health Science and Technology, Aalborg University, Denmark*

ARTICLE INFO

*Keywords:*
Motor behaviour
Movement control
Movement rate
Rhythmic movement
Voluntary

ABSTRACT

In this study we investigated motor variability in individuals who showed (responders) and who did not show (non-responders) a behavioural phenomenon termed repeated bout rate enhancement. The phenomenon is characterized by an increase of the freely chosen index finger tapping rate during the second of two consecutive tapping bouts. It was hypothesized that responders would perform (i) tapping with a lower magnitude, but more complex structure of variability than non-responders and (ii) bout 2 with a lower magnitude and increased complexity of variability than bout 1, as opposed to non-responders. Individuals ($n$ = 102) performed two 3-min tapping bouts separated by 10 min rest. Kinetic and kinematic recordings were performed. Standard deviation (SD), coefficient of variation (CV), and sample entropy (SaEn), representing magnitude and complexity of variability, were computed. For responders, SaEn of vertical displacement of the index finger was higher than for non-responders ($p$ = .046). Further, SaEn of vertical force and vertical displacement was higher in bout 2 than in bout 1 for responders ($p < .001$ and $p$ = .006, respectively). In general, SD of vertical displacement was lower in bout 2 than in bout 1 ($p < .001$). SaEn of vertical force was higher in bout 2 than in bout 1 ($p$ = .009). The present lower SD and higher SaEn values of vertical force and displacement time series in bout 2 as compared to bout 1 suggest differences in the dynamics of finger tapping. Further, it is possible that the increases in SaEn of vertical displacement reflected a greater adaptability in the dynamics of motor control among responders compared with non-responders.

## 1. Introduction

Finger tapping has been used to study characteristics related to voluntary rhythmic movement in asymptomatic individuals (Aoki, Furuya, & Kinoshita, 2005; Hansen & Ohnstad, 2008). For example, previous articles have reported a behavioural phenomenon termed repeated bout rate enhancement (RBRE) (Emanuelsen et al., 2018; Hansen, Ebbesen, Dalsgaard, Mora-Jensen, & Rasmussen, 2015; Mora-Jensen, Madeleine, & Hansen, 2017). Briefly, RBRE is characterized by an increase of the freely chosen tapping rate in the second of two consecutive bouts of finger tapping (Emanuelsen et al., 2018; Hansen et al., 2015; Mora-Jensen et al., 2017). We have recently speculated that increased excitability within the nervous system might explain RBRE (Emanuelsen et al., 2018; Hansen et al., 2015). However, the motor control mechanisms behind RBRE remain for the most undisclosed. Notably, why do approximately 33–36% of individuals (Emanuelsen et al., 2018; Mora-Jensen et al., 2017) not show RBRE? Such individuals are termed non-responders in the present study. It is possible that motor control mechanisms relating to RBRE could be reflected in differences in the

* Corresponding author at: Sport Sciences, Department of Health Science and Technology, Aalborg University, Niels Jernes Vej 12, DK-9220 Aalborg, Denmark.

*E-mail address:* eah@hst.aau.dk (E.A. Hansen).

https://doi.org/10.1016/j.humov.2019.102520
Received 31 January 2019; Received in revised form 9 September 2019; Accepted 10 September 2019
Available online 22 October 2019
0167-9457/ 

capacity to adapt to motor tasks and this can be investigated examining how the motor variability of selected biomechanical parameters is expressed (Srinivasan & Mathiassen, 2012).

Motor control can be described as the integration of sensory information from the cooperative interaction between the central nervous system and the musculoskeletal system to provide systematic regulation of movement (Swinnen, 2012). Thus, actions often leads to changes in the environment, and changes in the environment bring about modifications in action, thus providing the system with an array of possibilities that are reflected in individual motor control strategies for motor behaviour (Swinnen, 2012). An important aspect of motor control is motor variability, which is an intrinsic feature in all biological systems (Komar, Seifert, & Thouvarecq, 2015; Stergiou & Decker, 2011). Motor variability can be defined as '*the normal variations that appear in motor performance through multiple repetitions of a task*' (Stergiou, Harbourne, & Cavanaugh, 2006). A traditional perspective concerning motor learning considers that good performance is reproducible. Thus, motor variability can be considered detrimental to performance (Newell, 1991). However, motor variability can also be seen from a dynamical systems theory perspective, where biological systems are assumed to self-organize according to morphological, biomechanical, and environmental constraints to find a steady and balanced solution for producing a given movement (Stergiou et al., 2006; Stergiou & Decker, 2011). Thus, motor variability can be considered to reflect the ability of the central nervous system to take benefit of the redundancy or abundancy of the motor system (Bernstein, 1967; Latash & Anson, 2006). In the latter framework, motor learning is characterized by a reduction of motor variability that still enables accurate and flexible motor performances (Latash & Anson, 2006; Stergiou & Decker, 2011; Van Emmerik, Rosenstein, McDermott, & Hamill, 2004). Relating motor variability to RBRE in this framework of redundancy/abundancy, leads to the central nervous system being confronted with a choice of how to perform the required motor task (Latash & Anson, 2006). Accordingly, variations in motor control strategies reflects not only motor learning, but also neural adaptability and flexibility towards performing the motor task in a more appropriate and optimized manner (Faisal, Selen, & Wolpert, 2008; Stergiou & Decker, 2011). It thus appears that motor variability can help further, to elucidate the RBRE and the fact that approx. 1/3 of humans does not show the phenomenon.

Linear statistical metrics such as the standard deviation (SD) and the coefficient of variation (CV) have regularly been used to quantify the magnitude of the variability. From a dynamical systems perspective, a decrease in the magnitude of variability may indicate that movement have reorganized towards a more stable state (Stergiou & Decker, 2011). However, linear metrics of variability do not identify the dynamics of movement control systems and metrics associated with the structural dynamics of motor variability can therefore provide complementary information (Slifkin & Newell, 1999). Entropy measures such as sample entropy (SaEn) provide information about the dynamics of motor variability structure (Madeleine & Madsen, 2009; Norheim, Samani, Bønløkke, Omland, & And Madeleine, 2019). Entropy quantifies the complexity of the signal investigated, with a lower value indicating a structure with low complexity whereas a higher value indicates a more complex structure and, thus, a lower predictability (Richman & Moorman, 2000). A few studies have investigated linear and nonlinear metrics of variability of self-chosen finger tapping. Yamada (1995) reported no changes in the tapping rate and SD of tapping rate between the first and second half of 800 consecutive taps at self-chosen tapping rate. Christman and Weaver (2008) reported lower SD of intertap intervals during tapping performed as fast as possible compared with freely chosen tapping, underlining that tapping rate modulates the absolute magnitude of movement variability. They have also reported that increases in the Lyapunov exponent of intertap intervals during keyboard tapping was associated with better performance on closed-loop motor tasks (movements that are modified in response to sensory feedback). To the best of our knowledge, only a few empirical studies have investigated the change in movement complexity in relation to practice. These studies have provided contradictory findings. For example, postural changes in the amount of centre of pressure in standing position of skilled shooters, indexed by multiscale entropy, has been associated with a reduced movement complexity compared to novices (Ko et al. 2018). Contrary to that, SaEn of upper limb kinematics has been shown to increase with experience during repetitive arm movement (Madeleine & Madsen, 2009). A difference in experience level between participants could possibly explain these contradicting findings. However, the expected result is also dependent on the context of the movement. Thus, shooting is a highly specialized discipline where the amount of available degrees of freedom and motor variability is mostly minimized. This is in contrast to movements where a release of degrees of freedom and motor variability is considered beneficial. Furthermore, shooting is not a repetitive movement like finger tapping. Hence, the findings of Madeleine and Madsen (2009) seem to provide the best comparison in relation to the applied movement of finger tapping in the present study. This is further underlined by the suggestion that the structure of motor variability is generally increasing with experience (Madeleine, 2010). Thus, relating changes in the structure of motor variability as a consequence of experience to RBRE, it could be argued that increased complexity in the second tapping bout could be a reflection of a greater degree of adaptation to the motor task or a more flexible motor pattern.

The aim of the present study was to investigate motor variability in responders and non-responders using both linear and nonlinear metrics applied to kinetic and kinematic time series. We hypothesized that responders would perform tapping with a lower magnitude of variability and a more complex structure of variability than non-responders. Furthermore, it was hypothesized that responders would perform the second tapping bout with a lower magnitude of variability and an increased complexity of variability compared with the first tapping bout, as opposed to non-responders.

## 2. Methods

### 2.1. Participants

A total of 102 asymptomatic individuals (48 men, 54 women, 1.75 ± 0.92 m, 74.6 ± 12.7 kg, 25.5 ± 5.0 years, 89 right-handed, 13 left-handed) participated. The responders (32 men, 36 women, 59 right-handed, 9 left-handed) had a body height of

1.76 ± 0.97 m, a body mass of 74.9 ± 13.0 kg, and were 26.0 ± 5.6 years old. Values for the non-responders (16 men, 18 women, 30 right-handed, 4 left-handed) were 1.74 ± 0.80 m, 73.9 ± 12.0 kg, and 24.5 ± 3.6 years. Handedness was self-reported. All participants underwent the same experimental procedure used to determine if they could be considered as responders or non-responders, see also Section 2.2. The participants were partly from the study by Emanuelsen et al. (2018) and partly from a study investigating the effect of tapping bout duration on elicitation of RBRE Emanuelsen et al. (2019). The participants received written and oral information about the procedures of the study as well as the overall aim. The participants were not informed about the specific aims and hypotheses of the study. The purpose of that was to avoid any deliberate control of the performed finger tapping. Exclusion criteria were any known history of musculoskeletal or neural diseases or disorders, and execution of rhythmic finger movements, such as during playing an instrument or playing computer games, more than one hour weekly. The participants were informed not to consume alcohol or euphoric substances during the final 24 h before testing. Also, they were informed not to consume coffee during the final 3 h before testing. Written informed consent was obtained from the participants. The study conformed to the standards set by the Declaration of Helsinki and the procedures were approved by The North Denmark Region Committee on Health Research Ethics (N-20170017).

### 2.2. Experimental design

Each participant reported to the laboratory once. The test session began by determining the participant's age, body height, and body mass. Next, a demonstration of how to perform finger tapping and of the test procedure in general was provided. To prevent any form of rate enhancement before bout 1, no warm-up was performed before testing. A LED tracker from a motion capture system (Standard VZ-4000v, Phoenix Technologies Inc., Burnaby, BC, Canada) was attached to the midpoint of the nail of the participant's index finger of the right hand. The participant was then seated with the back straight and the forearm resting on the table. It was emphasized that the tapping should *not* be performed as fast as possible, but rather at the participant's "own preferred rhythm" while at the same time "thinking about something else". Moreover, the participant did not receive any instruction about maintaining a constant tapping rate throughout the tapping bouts. Tapping was performed with the index finger of the right hand at a freely chosen rate, while the remaining four fingers of the right hand were in an extended position and resting state on the table. The participant performed a 3-min tapping bout at a freely chosen tapping rate. Finger tapping was performed on a force transducer (FS6–250, AMTI, Watertown, MA, USA). Subsequent to bout 1, the participant rested for 10 min. Following the rest period, a second 3-min tapping bout was performed at a freely chosen tapping rate. In line with Emanuelsen et al. (2018), responders were defined according to a criterion of a minimum increase of 3% of the freely chosen tapping rate from the first to the second tapping bout. Thereby, participants who did not show an increase above 3% were defined as non-responders.

### 2.3. Data acquisition and analysis

The force transducer was checked for linearity and accuracy before the test session, using a range of fixed loads. Tapping force was only measured in the vertical direction. The force signal was amplified 4000 times, analogue low-pass filtered at 1050 Hz, sampled at 2000 Hz and digitalized using a 12 bit NI BNC-2090A A/D-board (National Instruments, Austin, TX, USA). The force recordings were digitally low-pass filtered at 200 Hz. The recordings were made using a custom made software program (Mr. Kick III software, Knud Larsen, Aalborg University, Aalborg, Denmark) in LabVIEW 2015 (National Instruments Co., Austin, TX, USA).

The kinematic data was collected using a single VZ-4000v tracker (Phoenix Technologies Inc., Burnaby, BC, Canada). The motion capture system was calibrated before testing to define a 3D scaled local coordinate system. Vertical displacement of the fingertip in the sagittal plane was measured from the coordinates of the LED-tracker. Data were sampled at 100 Hz, synchronously with the tapping force, using VZSoftTM software (Phoenix Technologies Inc., Burnaby, BC, Canada). Fig. 1 shows an example of recordings of vertical force and fingertip displacement during bout 1 and bout 2 from a single participant in the group of responders.

The tapping rate, vertical force and displacement were analysed in MATLAB version R2018a (The MathWorks Inc., Natick, MA, USA) using a custom-written script. Tapping rate (taps/min) was calculated as the mean tapping rate of three 8-s epochs extracted from the force recordings at the start (0–8 s), mid (86–94 s), and end (172–180 s) of the two tapping bouts in line with previous studies investigating changes over time (Norheim et al., 2019). Force data were down-sampled to 100 Hz to ensure the same temporal resolution of force and kinematics data. Both signals were subsequently filtered using a second-order Butterworth low-pass filter ($F_{cutoff}$ 20 Hz) in line with previous studies (Vaillancourt & Newell, 2003).

The magnitude of the variability was quantified using linear statistical measures of data dispersion (SD and CV). The SD and CV of the vertical force and displacement were computed as measures representing the absolute (i.e. amplitude of movement and the applied force level) and relative (i.e. in relation to the mean) magnitude of the variability, respectively. Nonlinear analysis of the vertical force and displacement was conducted to measure the structure of the variability of time series. For that purpose, the SaEn, a single non-negative number reflecting the complexity of the signal, was calculated (Richman & Moorman, 2000). A low SaEn value indicates low complexity while a high SaEn value reflects high complexity. For completeness, it should be mentioned that entropy by some researchers has been suggested to quantify predictability/regularity rather than complexity (Pincus & Goldberger, 1994; Yentes et al., 2013). SaEn quantifies the likelihood that two sequences that are similar in an embedding dimension m remain close (given a tolerance distance r) to the next incremental comparison in an embedding dimension m + 1 (Richman & Moorman, 2000). In the present study, the window length was set to 800 data points in line with previous recommendations (Norheim et al., 2019; Pincus & Goldberger, 1994; Richman & Moorman, 2000). See Supplementary material in Appendix A for further description concerning SaEn computation. To test the consistency of the input parameters m and r for calculations of SaEn, we performed a sensitivity analyses.

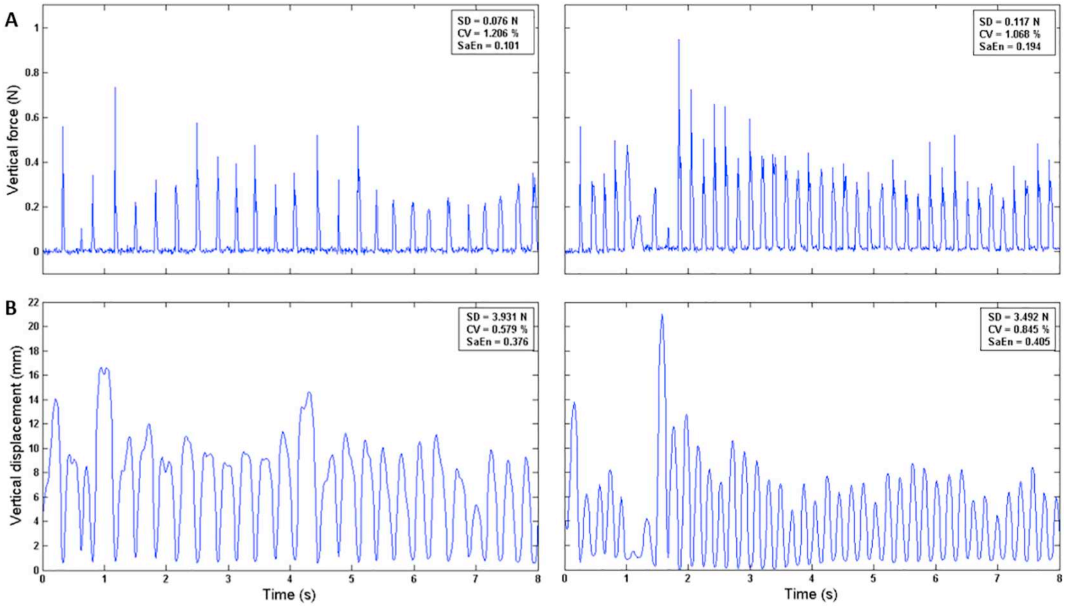


**Fig. 1.** Data example of recordings of two 8-s epochs at the start (0–8 s) of bout 1 and bout 2, from a single individual in the group of responders. Panel A represents the vertical force (N) in bout 1 (left) and bout 2 (right). Of note, small fluctuations in force (approx. 0.005 N) represent noise. Panel B represents the vertical displacement (mm) in bout 1 (left) and bout 2 (right). Tapping rate in bout 1 was 196.6 taps/min and 313.6 taps/min in bout 2.

Based on the recommendations from Yentes et al. (2013), the embedding dimension was set at m = 2 while the tolerance distance were set at 0.15, 0.20 and 0.25 times SD. As expected, the values of SaEn of vertical force and displacement were affected. However, the changes were mostly consistent and in line with Richman and Moorman (2000). Furthermore, a few values of significance changed but no systematic changes were found (see Supplementary material in Appendix B). Thus, only SaEn with embedding dimension m equal to 2 and tolerance distance r set at 0.20 × SD were statistically analysed. To measure the changes in the magnitude and structure of the variability, i.e. SD, CV, and SaEn of vertical force and displacement, values were computed over three 8-s epochs (and not the number of cycles) representing the start, mid, and end for both tapping bouts to enable within-bout assessment of the temporal changes in variability.

### *2.4. Statistical analysis*

The Shapiro-Wilk test was applied to evaluate whether data resembled a normal distribution. The performed tests revealed that all variables, except from SaEn of the vertical displacement, were not normally distributed. Thus, to not normally distributed data, log10 transformations were applied for data to resemble a normal distribution (Bland & Altman, 1996). A three-way repeated measures analysis of variance (ANOVA) was performed to assess the effects of group (responders vs non-responders), bout (bout 1 vs bout 2), and time (start, mid, and end) on the mean tapping rate, as well as on SD, CV, and SaEn of the vertical force and vertical displacement. If significant main effects or interactions were identified using ANOVAs, post hoc pairwise comparisons using Bonferroni adjustment were then performed. The statistical analyses were performed using IBM SPSS 25.0 (SPSS Inc., Chicago, IL, USA). Data are presented as mean ± SD, unless otherwise indicated. $p < .05$ was considered statistically significant.

## 3. Results

For the following results section, only post hoc analyses performed as follow-up on statistically significant main effects are presented.

### *3.1. Responders versus non-responders*

The main effects of the three-way repeated measures ANOVA on tapping rate are presented in Table 1 while mean ± SD values are depicted in Fig. 2. The main effects on the SD and CV for vertical force and displacement are presented in Table 2. SD of vertical force and displacement is depicted in Fig. 3. The post hoc analyses revealed that the responders performed tapping at a higher rate (on average 16.5%) compared with the non-responders ($p < .001$).

The main effects on SaEn for vertical force and displacement are also presented in Table 2. SaEn of vertical force and displacement is depicted in Fig. 4. The post hoc analyses showed that the SaEn of vertical displacement was higher for the responders (on average

**Table 1**
Results of the three-way repeated measures ANOVA of tapping rate. Bold text indicates statistical significance.

| | Tapping rate | | |
|---|---|---|---|
| | Mean | | |
| | F | P | $\eta_p^2$ |
| Group | **7.90** | **0.006** | **0.073** |
| Bout | **10.78** | **0.001** | **0.097** |
| Time | **35.29** | **< 0.001** | **0.261** |
| Group × bout | **90.81** | **< 0.001** | **0.476** |
| Group × time | **3.82** | **0.039** | **0.037** |
| Bout × time | 0.16 | 0.813 | 0.002 |
| Group × bout × time | 0.12 | 0.845 | 0.001 |

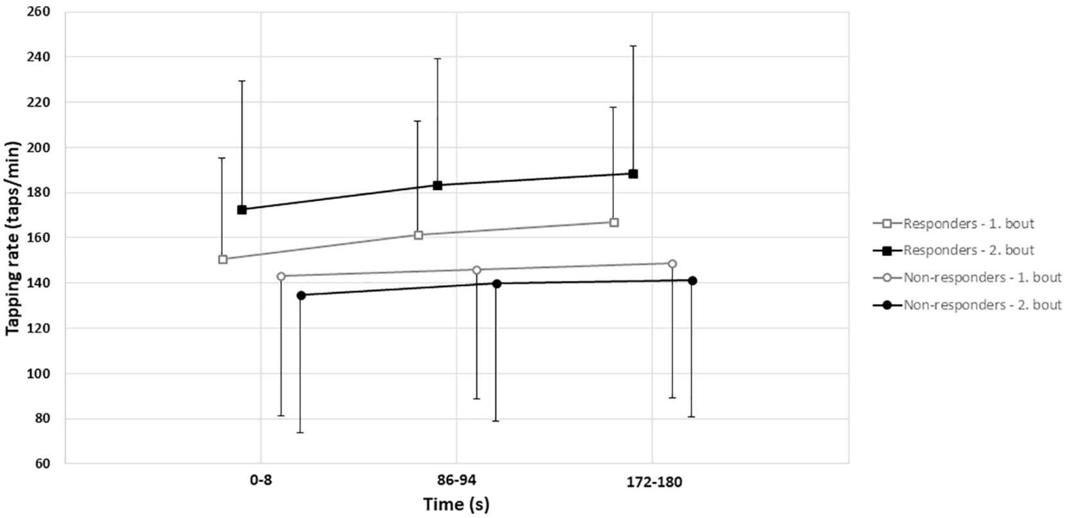


**Fig. 2.** Mean tapping rates ( ± SD) during the start (0–8 s), the middle (86–94 s), and the end (172–180 s) of each tapping bout, for both responders ($N$ = 68) and non-responders ($N$ = 34). Data points have been horizontally staggered for clearness. For further clearness, descending and ascending SD bars have been removed for the responders and non-responders, respectively.

13.6%) compared with the non-responders ($p$ = .046).

### 3.2. Effect of bout

The post hoc analyses showed that the tapping rate was higher in bout 2 (on average 4.5%) compared with bout 1 ($p$ < .001). Also, the SaEn of vertical force was higher in bout 2 (on average 6.0%) than in bout 1 ($p$ = .009). Furthermore, the SD of vertical displacement was lower in bout 2 (on average 6.6%) compared with bout 1 ($p$ < .001).

### 3.3. Effect of time

The post hoc analyses revealed that the tapping rate increased from start to mid (on average 4.6%), from start to end (on average 6.7%), and from mid to end (on average 2.2%) ($p$ < .001, $p$ < .001, and $p$ = .001, respectively) Moreover, the SD of vertical force increased from start to end, and from mid to end ($p$ < .001 and $p$ < .001, respectively). There was a main effect of time on the SaEn of vertical force, however the post hoc analyses showed that no simple effects were found. Moreover, the CV of vertical displacement decreased from mid to end (on average 4.7%) ($p$ < .001).

### 3.4. Interactions between group, bout and time

The post hoc analyses of interactions revealed that the responders performed bout 2 at a higher tapping rate (on average 11.5%) than bout 1 ($p$ < .001), whereas the non-responders performed bout 2 at a lower tapping rate (on average 5.0%) than bout 1 ($p$ = .002). For the responders, the SaEn of vertical force was higher for bout 2 (on average 17.4%) compared with bout 1 ($p$ < .001), whereas SaEn of vertical force remained unchanged for the non-responders. Furthermore, the SaEn of vertical displacement was higher in bout 2 (on average 6.2%) compared with bout 1 for the responders ($p$ = .001), whereas SaEn of vertical force remained

**Table 2**
Results of the three-way repeated measures ANOVA of vertical force and vertical displacement. Bold text indicates statistical significance.

| | Vertical force | | | | | | | | | Vertical displacement | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SD | | | CV | | | SaEn | | | SD | | | CV | | | SaEn | | |
| | F | P | $\eta_p^2$ | F | p | $\eta_p^2$ | F | p | $\eta_p^2$ | F | p | $\eta_p^2$ | F | p | $\eta_p^2$ | F | p | $\eta_p^2$ |
| Group | 0.74 | 0.390 | 0.007 | 0.05 | 0.819 | 0.001 | 0.24 | 0.624 | 0.002 | 0.03 | 0.857 | 0.000 | 0.03 | 0.873 | 0.000 | **4.08** | **0.046** | **0.039** |
| Bout | 0.01 | 0.925 | 0.000 | 3.62 | 0.060 | 0.035 | **7.14** | **0.009** | **0.067** | **16.74** | **< 0.001** | **0.143** | 0.00 | 0.974 | 0.000 | 1.81 | 0.182 | 0.018 |
| Time | **16.77** | **< 0.001** | **0.144** | 0.16 | 0.796 | 0.002 | **4.04** | **0.032** | **0.039** | 2.19 | 0.131 | 0.021 | **3.56** | **0.045** | **0.034** | 0.73 | 0.440 | 0.007 |
| Group × bout | 0.03 | 0.875 | 0.000 | 2.03 | 0.157 | 0.020 | **23.50** | **< 0.001** | **0.190** | 0.51 | 0.478 | 0.005 | 3.74 | 0.056 | 0.036 | **7.80** | **0.006** | **0.072** |
| Group × time | 0.48 | 0.552 | 0.005 | 0.13 | 0.822 | 0.001 | **3.77** | **0.039** | **0.036** | 0.36 | 0.628 | 0.004 | 0.02 | 0.944 | 0.000 | 0.31 | 0.657 | 0.003 |
| Bout × time | **3.37** | **0.039** | **0.033** | **5.12** | **0.009** | **0.049** | 0.35 | 0.674 | 0.003 | **7.92** | **0.001** | **0.073** | 0.13 | 0.852 | 0.001 | 0.05 | 0.923 | 0.000 |
| Group × bout × time | 0.76 | 0.462 | 0.008 | 0.73 | 0.469 | 0.007 | 0.28 | 0.720 | 0.003 | 1.51 | 0.224 | 0.015 | 3.14 | 0.052 | 0.030 | 0.53 | 0.550 | 0.005 |

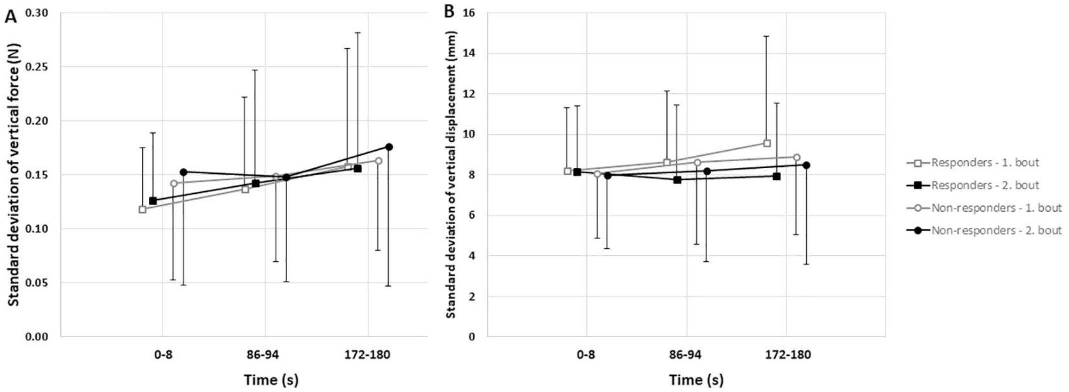


**Fig. 3.** Standard deviation ( ± SD) during the start (0–8 s), the middle (86–94 s), and the end (172–180 s) of each tapping bout, for both responders ($N = 68$) and non-responders ($N = 34$). Panel A represents vertical force (N). Panel B represents vertical displacement (mm). Data points have been horizontally staggered for clearness. For further clearness, descending and ascending SD bars have been removed for the responders and non-responders, respectively.

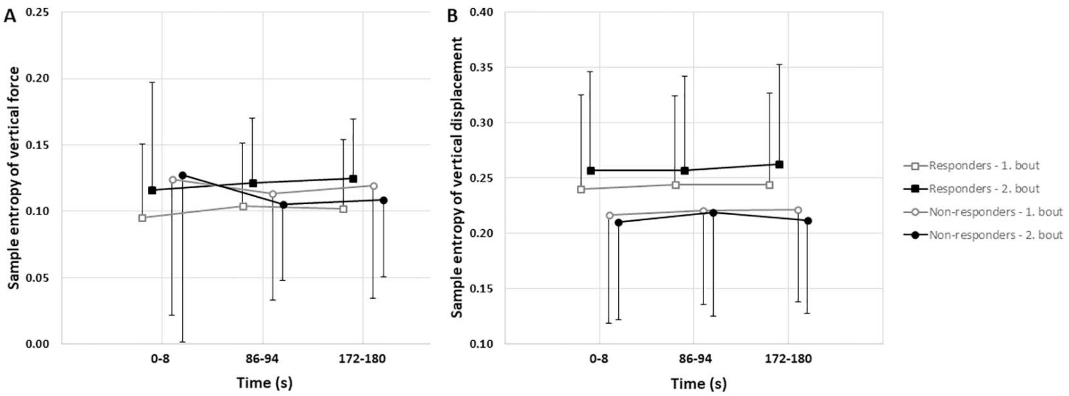


**Fig. 4.** Sample entropy ( ± SD) during the start (0–8 s), the middle (86–94 s), and the end (172–180 s) of each tapping bout, for both responders ($N = 68$) and non-responders ($N = 34$). Panel A represents vertical force (N). Panel B represents vertical displacement (mm). Data points have been horizontally staggered for clearness. For further clearness, descending and ascending SD bars have been removed for the responders and non-responders, respectively.

unchanged for the non-responders.

The responders increased their tapping rate from start to mid, from start to end and from mid to end across both bouts ($p < .001$, $p < .001$ and $p < .001$, respectively), whereas the non-responders increased their tapping rate from start to mid and from start to end ($p = .043$ and $p = .027$, respectively). Also, for the responders, the SaEn of vertical force increased from the start to mid (on average 5.8%) and from start to end (on average 6.5%), ($p = .002$ and $p = .002$, respectively), whereas SaEn of vertical force remained unchanged for the non-responders.

The post hoc analyses finally revealed that during bout 1, the SD of vertical force increased from the start to mid (on average 8.4%), from start to end (on average 18.6%) and from mid to end (on average 11.2%) ($p = .047$ and $p < .001$ and $p < .001$, respectively). In addition, the SD of vertical force during bout 2 increased from the start to end (on average 16.3%) and from mid to end (on average 12.7%) ($p = .011$ and $p < .001$, respectively). Post hoc analyses of the bout × time interaction of CV of tapping force revealed no significant differences. The SD of vertical displacement increased during bout 1 from the start to end (on average 11.8%) and from mid to end (on average 6.6%) ($p = .013$ and $p = .013$, respectively).

## 4. Discussion

In the present study, both linear and nonlinear metrics were used to investigate motor variability in a group of individuals that showed RBRE as well as in another group that did not show RBRE. The main finding of the present study was that RBRE responders and non-responders demonstrated differences in motor variability. Thus, a common observation was that the structure of the variability (SaEn) differed between responders and non-responders, whereas the magnitude of the variability (SD and CV) of the vertical force and displacement mostly did not change between groups. Increased complexity in the structure of the variability depicted by the higher SaEn values could be further interpreted as an increased ability to integrate available degrees of freedom and thus be a reflection of motor adaptability to the task. The findings do not reflect a good or bad performance, but describe differences in characteristics of motor variability between responders and non-responders. Furthermore, the structure of variability (SaEn) of the vertical force and displacement was higher in bout 2 compared with bout 1 for the responders, whereas the magnitude of variability (SD and CV) did not change between bouts.

### *4.1. Responders versus non-responders*

The RBRE is reflected in an increase of the tapping rate between two tapping bouts. The responders had on average an 11.5 ± 6.3% increase in tapping rate, whereas the non-responders had on average a 5.0 ± 4.8% decrease in tapping rate from bout 1 to bout 2. With respect to motor variability, the present findings can be interpreted in the framework of the central nervous systems ability to integrate its redundancy or abundancy (Bernstein, 1967; Latash & Anson, 2006; Newell & Vaillancourt, 2001). Contrary to what was hypothesized, the SD and CV of the vertical force and index finger displacement mostly did not differ among responders and non-responders. Though, we found a reduced SD of vertical displacement from bout 1 to bout 2. Concomitantly, we saw an increased SaEn of vertical force from bout 1 to bout 2 for the responders, in addition to an increase in SaEn of vertical displacement for responders compared with non-responders. This could be a reflection of responders displaying greater ability to utilize available degrees of freedom as opposed to the non-responders (Van Emmerik & Van Wegen, 2002). The finding that responders performed finger tapping with a greater complexity of vertical force and displacement in bout 2 as compared to bout 1 may be a reflection of increased exploration and thus greater dynamic control of the motor pattern of the finger.

Our results can also be interpreted in relation to effects of practice (Bernstein, 1967; Van Emmerik & Van Wegen, 2002). The performed tapping bouts could represent a period of practice and the rest period a consolidation phase (Karni & Sagi, 1993). Effects of practice can be observed and identified across different domains at different time scales. Thus, changes in behavioural movement patterns are observable within minutes to years (Madeleine, 2010; Newell, Liu, & Mayer-Kress, 2001). Therefore, it could be speculated that the non-responders did not exhibit RBRE due to either a too short period of tapping, too short consolidation period of motor strategies, or a combination hereof. On the contrary, it is possible that the responders processed the information provided to the motor system within the tapping session, thus displaying an ability to develop their motor repertoire. This is further highlighted by the fact that SaEn of vertical force and displacement increased between bouts and that SaEn of vertical force increased with time for the responders whereas SaEn remained unchanged for non-responders (see also Section 4.2). Of note, this further implies that different abilities in motor adaptation capacity of the nervous system to adapt to the task are present between responders and non-responders. Such motor adaptation among responders may be protective towards the development of musculoskeletal disorders (Madeleine, 2010; Srinivasan & Mathiassen, 2012).

It should be noted that inter-individual differences in e.g. age, gender, and body composition have been reported to influence motor variability, e.g. how the central nervous system discriminates, decodes and transforms sensory input into neural activity and consequently interpret them into motor actions (Coté, 2014; Sandlund, Srinivasan, Heiden, & Mathiassen, 2017). Thus, it is possible that the reason why some individuals can be characterized as responders while others can be characterized as non-responders may also be ascribed to differences in inter-individual inherent attributes.

### *4.2. Effect of bout in responders*

The observed increase in SaEn of vertical force and displacement along a reduced SD of vertical displacement from bout 1 to bout 2, could indicate a transition in the level of practice characterized by release of degrees of freedom for increased adaptability of the motor behaviour (Harbourne & Stergiou, 2003). Thus, the development of level of practice and the release of degrees of freedom (Harbourne & Stergiou, 2003) can explain the increase in SaEn over bouts. The underlying sequence of initial exploration, identification of a solution and subsequent ability to release degrees of freedom to adapt to the dynamics of the motor task seems applicable to the novel findings describing RBRE in terms of motor variability.

We found an increase in the SD of vertical displacement from the start to end and mid to end in bout 1. Concomitantly an increase in the SD of the vertical force was found between all three epochs in bout 1. This could further be a reflection of initial exploration for both groups. However, no changes in the SD of vertical displacement was found in bout 2, whereas the SD of the vertical force increased from the start to end and from the mid to end in bout 2. Although not obvious, these results suggest different temporal changes of vertical displacement and force during repetitive finger tapping movements underlining the importance of reporting both kinetic and kinematics data.

Although the present findings do not provide explanations and, perspectives on neurophysiological mechanisms on motor control, aspects of RBRE could be speculated upon. The freely chosen tapping rate during voluntary index finger tapping has been suggested to be controlled by spinal central pattern generators in an interrelationship with descending drive from supraspinal centres, as well as sensory feedback (Hansen & Ohnstad, 2008; Shima, Tamura, Tsuji, Kandori, & Sakoda, 2011). It has previously been argued that RBRE does not necessarily reflect motor learning due to the simplicity of the task and the extent of automation of the task along with the short duration of tapping (Hansen et al., 2015). Further, we have recently discussed that increased excitability within the nervous system might explain RBRE (Emanuelsen et al., 2018). The present results showed that responders had higher SaEn values of vertical force and displacement in bout 2 compared with bout 1. The complexity of a dynamic system may be influenced by the number of structural components and coupling among these (Vaillancourt & Newell, 2002). Thus, considering SaEn as a reflection of complexity, the suggested increased excitability could reflect increased dynamic coupling between the structural components (e.g. spinal central pattern generator) of the system governing finger tapping over bouts among the responders. The first bout of finger tapping could serve as ‘movement-based priming’, i.e. a repetitive movement causing a release of neurochemicals that changes cortical excitability and thus induces neuroplastic effects that may enhance the effect of ensuing movement as shown in RBRE (Jordan & Stinear, 2018; Stoykov & Madhavan, 2015). Moreover, a mechanism termed ‘repetition priming’ has been proposed, where changes in the excitability of the spinal networks in the feeding program in *Aplysia*, through reconfiguration of intrinsic neuromodulators, is caused by episodic repetitive behaviour (Cropper, Jing, Perkins, & Weiss, 2017; Siniscalchi, Cropper, Jing, & Weiss, 2016). Furthermore, Cropper et al. (2017) suggested that the mechanisms of ‘repetition priming’ are similar in human behaviour when performing episodic repetitive movements. Thus, the increase in SaEn of vertical force and displacement, along with a reduced magnitude in the SD of vertical displacement, could be seen as a reflection of an effective ‘movement-based priming’ among responders. This was most likely due to changes in the excitability of either supraspinal, spinal or a combination of supraspinal and spinal mechanisms. Of note, an increased excitability of the nervous system may not only occur among the responders. Thus, it is possible that an increased excitability of the nervous system is simply more prominent in the responders compared with the non-responders.

### *4.3. Strengths and limitations*

Although it has previously been reported, that the number of data points, embedding dimension and tolerance distance used to calculate SaEn affect the outcome (McCamley, Denton, Arnold, Raffalt, & Yentes, 2018; Powell et al., 2018; Raffalt, McCamley, Denton, & Yentes, 2019), the present sensitivity analyses underlined that the SaEn of vertical force and displacement were consistent independently of the tolerance level. Of note, SaEn values were computed over 8-s epochs (800 points) based on the original literature on approximate and sample entropy as well as on a recent paper showing that SaEn values of a kinetic signal is stable around a data length of 800 points (Norheim et al., 2019; Pincus & Goldberger, 1994; Richman & Moorman, 2000). Future studies investigating the effects of data length or number of cycles are necessary, as there are contradictory reports about the reliability of SaEn (Raffalt et al., 2018; Samani, Srinivasan, Mathiassen, & Madeleine, 2015). Further, it should be mentioned that other entropy measures, such as e.g. symbolic entropy (Alcaraz, 2018) could be used even though the selection of the threshold value is still a matter of debate (Aziz & Arif, 2006; Deffeyes et al., 2009). In addition, we acknowledge that the periods with no finger contact were included in the calculations of SD and CV of the force recordings. This was due to several reasons: 1) When performing finger tapping there is a natural non-contact phase, hence excluding the non-contact phase would not represent finger tapping as a cyclic movement. Zeroing the force signals during the non-contact phases will also change the time-series temporal characteristics. 2) To couple the SD and CV to SaEn values, the same time series are required and the signal needs to be in its entirety (Pincus & Goldberger, 1994). 3) It would not be possible to make parallel analysis of the force and the kinematic time series if the non-contact phases were excluded. A correlation analysis between the relative difference in rate enhancement, for both the responders and non-responders, and the relative differences in SD and CV was performed. The correlation analysis revealed that the variations of tapping rate did not relate to the changes in the SD and CV of the force recordings with the exception of SD at start among responders. Hence, the inclusion of the non-contact phase most likely did not introduce substantial methodological bias affecting the calculations of the absolute and relative magnitude of variability.

In the present study, 48 men and 54 women took part. Gender differences in the coordination of motor control have been reported (Semmler, Kutzscher, & Enoka, 1999; Svendsen & Madeleine, 2010). However, the men/women ratios for responders and non-responders were exactly the same so we do not think that gender differences influenced the present findings. In addition, it should be emphasized that the present findings provide knowledge on the motor control of finger tapping and cannot readily be generalized to other stereotyped rhythmic motor tasks. For example, different conditions in terms of e.g. movement directions, pace of movement, and cognitive demands have been reported to influence the motor variability of repetitive motor tasks (Srinivasan & Mathiassen, 2012).

### *4.4. Conclusions*

In conclusion, the analysis of motor variability in individuals showing/not showing RBRE, revealed that SaEn of the vertical displacement was higher for responders than non-responders. Besides for the responders, the SaEn of the vertical force and displacement was higher in bout 2 compared with bout 1. In addition, the SD of vertical displacement was lower and SaEn of vertical force was higher in bout 2 compared with bout 1. A common observation emerging from the present results is that SaEn differed between responders and non-responders. On the contrary, the SD and CV of the vertical force and displacement mostly did not differ between groups. Thus, SaEn of vertical force and displacement provide a possible way to describe the difference of motor variability between individuals showing/not showing RBRE. The present findings indicate that individuals showing RBRE most likely exhibit a greater adaptability in the dynamics of motor control compared with individuals not showing RBRE. For future research, investigation of RBRE in patients with neuromuscular diseases or disorders, such as e.g. Parkinson's disease, could be relevant. For example, characteristics in a patient group compared with healthy controls could be studied to further investigate whether RBRE could be a possible progression marker in early Parkinson's disease patients.

## Acknowledgments

The participants are thanked for their cooperation. The present research is supported by The Ministry of Culture Research Committee in Denmark (grant No. FPK.2017-0005).

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.102520.

## References


Alcaraz, R. (2018). Symbolic entropy and its applications. *Entropy, 20*, 568. https://doi.org/10.3390/e20080568.

Aoki, T., Furuya, S., & Kinoshita, H. (2005). Finger-tapping ability in male and female pianists and nonmusician controls. *Motor Control, 9*(1), 23–39. https://doi.org/10.1123/mcj.9.1.23.

Aziz, W., & Arif, M. (2006). Complexity analysis of stride interval time series by threshold dependent symbolic entropy. *European Journal of Applied Physiology, 98*, 30–40. https://doi.org/10.1007/s00421-006-0226-5.

Bernstein, N. A. (1967). The co-ordination and regulation of movements. *The co-ordination and regulation of movements*. Oxford: Pergamon Press.

Bland, M. J., & Altman, D. J. (1996). Transforming data. *BMJ, 312*, 770. https://doi.org/10.1136/bmj.312.7033.770.

Christman, S. D., & Weaver, R. (2008). Linear versus non-linear measures of temporal variability in finger tapping and their relation to performance on open- versus closed-loop motor tasks: Comparing standard deviations to Lyapunov exponents. *Laterality: Asymmetries of Body, Brain and Cognition, 13*(3), 255–281. https://doi.org/10.1080/13576500701865210.

Coté, J. N. (2014). Adaptations to neck/shoulder fatigue and injuries. *Advances in Experimental Medicine and Biology, 826*, 205–228. https://doi.org/10.1007/978-1-4939-1338-1_13.

Cropper, E. C., Jing, J., Perkins, M. H., & Weiss, K. R. (2017). Use of the Aplysia feeding network to study repetition priming of an episodic behavior. *Journal of Neurophysiology, 118*(3), 1861–1870. https://doi.org/10.1016/j.brainresrev.2009.08.002.

Deffeyes, J. E., Harbourne, R. T., DeJong, S. L., Kyvelidou, A., Stuberg, W. A., & Stergiou, N. (2009). Use of information entropy measures of sitting postural sway to quantify developmental delay in infants. *Journal of Neuroengineering and Rehabilitation, 6*(34), 1–13. https://doi.org/10.1186/1743-0003-6-34.

Emanuelsen, A., Voigt, M., Madeleine, P., & Hansen, E. A. (2019). *Effect of tapping bout duration during freely chosen and passive finger tapping on elicitation of repeated bout rate enhancement.* (Submitted).

Emanuelsen, A., Voigt, M., Madeleine, P., Kjær, P., Dam, S., Koefoed, N., & Hansen, E. A. (2018). Repeated bout rate enhancement is elicited by various forms of finger tapping. *Frontiers in Neuroscience, 12*, 526. https://doi.org/10.3389/fnins.2018.00526.

Faisal, A. A., Selen, L. P. J., & Wolpert, D. M. (2008). Noise in the nervous system. *Nature, 9*(4), 292–303. https://doi.org/10.1038/nrn2258.

Hansen, E. A., Ebbesen, B. D., Dalsgaard, A., Mora-Jensen, M. H., & Rasmussen, J. (2015). Freely chosen index finger tapping frequency is increased in repeated bouts of tapping. *Journal of Motor Behavior, 47*(6), 490–496. https://doi.org/10.1080/00222895.2015.1015675.

Hansen, E. A., & Ohnstad, A. E. (2008). Evidence for freely chosen pedalling rate during submaximal cycling to be a robust innate voluntary motor rhythm. *Experimental Brain Research, 186*(3), 365–373. https://doi.org/10.1007/s00221-007-1240-5.

Harbourne, R. T., & Stergiou, N. (2003). Nonlinear analysis of the development of sitting postural control. *Developmental Psychobiology, 42*(4), 368–377. https://doi.org/10.1002/dev.10110.

Jordan, H. T., & Stinear, C. M. (2018). The effects of bilateral priming on motor cortex function in healthy adults. *Journal of Neurophysiology, 120*(6), 2858–2867. https://doi.org/10.1152/jn.00472.2018.

Karni, A., & Sagi, D. (1993). The time course of learning a visual skill. *Nature, 16*(365), 250–252. https://doi.org/10.1038/365250a0.

Ko, J.-H., Han, D.-W., & Newell, K. M. (2018). Skill level changes the coordination and variability of standing posture and movement in a pistol-aiming task. *Journal of Sports Sciences, 36*(7), 809–816. https://doi.org/10.1080/02640414.2017.1343490.

Komar, J., Seifert, L., & Thouvarecq, R. (2015). What variability tells us about motor expertise: Measurements and perspectives from a complex system approach. *Movement & Sport Sciences, 89*(3), 65–77. https://doi.org/10.1051/sm/2015020.

Latash, M. L., & Anson, J. G. (2006). Synergies in health and disease: Relations to adaptive changes in motor coordination. *Physical Therapy, 86*(8), 1151–1160. https://doi.org/10.1093/ptj/86.8.1151.

Madeleine, P. (2010). On functional motor adaptations: From the quantification of motor strategies to the prevention of musculoskeletal disorders in the neck-shoulder region. *Acta Physiologica, 199*(679), 1–46. https://doi.org/10.1111/j.1748-1716.2010.02145.x.

Madeleine, P., & Madsen, T. M. T. (2009). Changes in the amount and structure of motor variability during a deboning process are associated with work experience and neck–shoulder discomfort. *Applied Ergonomics, 40*(5), 887–894. https://doi.org/10.1016/j.apergo.2008.12.006.

McCamley, J. D., Denton, W., Arnold, A., Raffalt, P. C., & Yentes, J. M. (2018). On the calculation of sample entropy using continuous and discrete human gait data. *Entropy, 20*, 764. https://doi.org/10.3390/e20100764.

Mora-Jensen, M. H., Madeleine, P., & Hansen, E. A. (2017). Vertical finger displacement is reduced in index finger tapping during repeated bout rate enhancement. *Motor Control, 21*(4), 457–467. https://doi.org/10.1123/mc.2016-0037.

Newell, K. M. (1991). Motor skill acquisition. *Annual Review of Psychology, 42*, 213–237. https://doi.org/10.1146/annurev.ps.42.020191.001241.

Newell, K. M., Liu, Y., & Mayer-Kress, G. (2001). Time scales in motor learning and development. *Psychological Review, 108*(1), 57–82. https://doi.org/10.1037//0033-295X.108.1.57.

Newell, K. M., & Vaillancourt, D. E. (2001). Dimensional change in motor learning. *Human Movement Science, 20*(4), 695–715. https://doi.org/10.1016/S0167-9457(01)00073-2.

Norheim, K. L., Samani, A., Bønløkke, J. H., Omland, Ø., & Madeleine, P. (2019). The effects of age and musculoskeletal pain on force variability among manual workers. *Human Movement Science, 64*, 19–27. https://doi.org/10.1016/j.humov.2018.12.006.

Pincus, S. M., & Goldberger, A. L. (1994). Physiological time-series analysis: What does regularity quantify? *AJP - Heart and Circulatory Physiology, 266*(4), 1643–1656. https://doi.org/10.1152/ajpheart.1994.266.4.H1643.

Powell, D. W., Szekely, B., Blackmore, S. E., Nelson, A., Schallert, A., Lester, D. B., ... Puppa, M. (2018). Effects of sampling rate and movement frequency on entropic measures of regularity. *Journal of Nature and Science, 4*(5), e504.

Raffalt, P. C., Alkjær, T., Brynjólfsson, B., Jørgensen, L., Bartholdy, C., & Henriksen, M. (2018). Day-to-day reliability of nonlinear methods to assess walking dynamics. *Journal of Biomedical Engineering, 140*(12), https://doi.org/10.1115/1.4041044.

Raffalt, P. C., McCamley, J., Denton, W., & Yentes, J. M. (2019). Sampling frequency influences sample entropy of kinematics during walking. *Medical & Biological Engineering & Computing, 57*, 759–764. https://doi.org/10.1007/s11517-018-1920-2.

Richman, J. S., & Moorman, R. J. (2000). Physiological time-series analysis using approximate entropy and sample entropy. *American Journal of Physiology, Heart and Circulatory Physiology, 278*(6), 2039–2049. https://doi.org/10.1152/ajpheart.2000.278.6.H2039.

Samani, A., Srinivasan, D., Mathiassen, S. E., & Madeleine, P. (2015). Nonlinear metrics assessing motor variability in a standardized pipetting task: Between- and within-subject variance components. *Journal of Electromyography and Kinesiology, 25*(3), 557–564. https://doi.org/10.1016/j.jelekin.2015.01.005.

Sandlund, J., Srinivasan, D., Heiden, M., & Mathiassen, S. E. (2017). Differences in motor variability among individuals performing a standardized short-cycle manual task. *Human Movement Science, 51*, 17–26. https://doi.org/10.1016/j.humov.2016.10.009.

Semmler, J. G., Kutzscher, D. V., & Enoka, R. M. (1999). Gender differences in the fatigability of human skeletal muscle. *Journal of Neurophysiology, 82*(6), 3590–3593.

Shima, K., Tamura, Y., Tsuji, T., Kandori, A., & Sakoda, S. (2011). A CPG synergy model for evaluation of human finger tapping movements. *2011 annual international conference of the IEEE engineering in medicine and biology society*. *2011*. *2011 annual international conference of the IEEE engineering in medicine and biology society* (pp. 4443–4448). . https://doi.org/10.1109/IEMBS.2011.6091102.

Siniscalchi, M. J., Cropper, E. C., Jing, J., & Weiss, K. R. (2016). Repetition priming of motor activity mediated by a central pattern generator: The importance of extrinsic vs. intrinsic program initiators. *Journal of Neurophysiology, 116*(4), 1821–1830. https://doi.org/10.1152/jn.00365.2016.

Slifkin, A. B., & Newell, K. M. (1999). Noise, information transmission, and force variability. *Journal of Experimental Psychology: Human Perception and Performance, 25*(3), 837–851. https://doi.org/10.1037/0096-1523.25.3.837.

Srinivasan, D., & Mathiassen, S. E. (2012). Motor variability in occupational health and performance. *Clinical biomechanics, 27*(10), 979–993. https://doi.org/10.1016/j.clinbiomech.2012.08.007.

Stergiou, N., & Decker, L. M. (2011). Human movement variability, nonlinear dynamics, and pathology: Is there a connection? *Human Movement Science, 30*(5), 869–888. https://doi.org/10.1016/j.humov.2011.06.002.

Stergiou, N., Harbourne, R., & Cavanaugh, J. (2006). Optimal movement variability: A new theoretical perspective for neurologic physical therapy. *Journal of Neurologic Physical Therapy, 30*(3), 120–129. https://doi.org/10.1097/01.NPT.0000281949.48193.d9.

Stoykov, M., & Madhavan, S. (2015). Motor priming in neurorehabilitation. *Journal of Neurologic Physical Therapy, 39*(1), 33–42. https://doi.org/10.1080/00222895.2016.1250716.

Svendsen, J. H., & Madeleine, P. (2010). Amount and structure of force variability during short, ramp and sustained contractions in males and females. *Human Movement Science, 29*(1), 35–47. https://doi.org/10.1016/j.humov.2009.09.001.

Swinnen, S. P. (2012). Motor control. *Encyclopedia of Human Behavior*. Oxford: Elsevier.

Vaillancourt, D. E., & Newell, K. M. (2002). Changing complexity in human behavior and physiology through aging and disease. *Neurobiology of Aging, 23*(1), 1–11. https://doi.org/10.1016/S0197-4580(01)00247-0.

Vaillancourt, D. E., & Newell, K. M. (2003). Aging and the time and frequency structure of force output variability. *Journal of Applied Physiology, 94*(3), 903–912. https://doi.org/10.1152/japplphysiol.00166.2002.

Van Emmerik, R. E. A., Rosenstein, M. T., McDermott, W. J., & Hamill, J. (2004). A nonlinear dynamics approach to human movement. *Journal of Applied Biomechanics, 20*(4), 396–420. https://doi.org/10.1123/jab.20.4.396.

Van Emmerik, R. E. A., & Van Wegen, E. E. H. (2002). On the functional aspects of variability in postural control. *Exercise and Sport Sciences Reviews, 30*(4), 177–183.

Yamada, N. (1995). Nature of variability in rhythmical movement. *Human Movement Science, 14*(3), 371–384.

Yentes, J. M., Hunt, N., Schmid, K. K., Kaipust, J. P., McGrath, D., & Stergiou, N. (2013). The appropriate use of approximate entropy and sample entropy with short data sets. *Annals of Biomedical Engineering, 41*(2), 349–365. https://doi.org/10.1007/s10439-012-0668-3.