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Vertical finger displacement is reduced in index finger tapping during repeated bout rate enhancement

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ABSTRACT

The present study tested 1) whether a recently reported phenomenon of repeated bout rate enhancement in finger tapping (i.e. a cumulating increase in freely chosen finger tapping frequency following submaximal muscle activation in form of externally unloaded voluntary tapping) could be replicated, and 2) the hypotheses that the faster tapping was accompanied by changed vertical displacement of the fingertip and by changed peak force during tapping. Right-handed, healthy, and recreationally active individuals ($n=24$) performed two 3-min index finger tapping bouts at freely chosen tapping frequency, separated by 10 min rest. The recently reported phenomenon of repeated bout rate enhancement was replicated. The faster tapping (8.8 ± 18.7 taps min^{-1} , corresponding to $6.0\pm 11.0\%$, $p=.033$) was accompanied by reduced vertical displacement (1.6 ± 2.9 mm, corresponding to $6.3\pm 14.9\%$, $p=.012$) of the fingertip. Concurrently, peak force was unchanged. The present study points at separate control mechanisms governing kinematics and kinetics during finger tapping.

1. Introduction

Index finger tapping is a relatively simple motor task that is related to various everyday-activities such as e.g. computer work and playing music. Furthermore, the task is widely applied in studies of both healthy individuals (Hammond & Gunasekera, 2008; Hansen & Ohnstad, 2008; Sundqvist, Johnels, Lindh, Laakso, & Hartelius, 2015; Wing & Kristoffersen, 1973; Zentgraf et al., 2009) and in patients with e.g. Parkinson's disease (Shima, Tamura, Tsuji, Kandori, & Sakoda, 2011; Teo, Rodrigues, Mastaglia, & Thickbroom, 2013).

Recently, a novel phenomenon termed repeated bout rate enhancement was reported in healthy individuals (Hansen, Ebbesen, Dalsgaard, Mora-Jensen, & Rasmussen, 2015). Briefly, the phenomenon constitutes a cumulating increase in freely chosen tapping frequency following submaximal muscle activation and movement consisting of externally unloaded voluntary finger tapping. More specifically, it was found that freely chosen tapping frequency increased 8.2% across four consecutive 3-min tapping bouts that were separated by 10-min rest periods. Further, follow-up experiments showed that tapping frequency in repeated bouts was still increased when rest periods were extended to 20 min. With respect to explaining the results, it was speculated that neural mechanisms could have played a role.

Accordingly, as a working hypothesis, it may be presumed that the increase in freely chosen tapping frequency reflects an increase in central pattern generator (CPG)-mediated movement frequency output (Hansen & Ohnstad, 2008; Shima et al., 2011). An increased CPG-mediated movement frequency output might be caused by increased supraspinal descending central drive (Prochazka & Yakovenko, 2007). Such an increase might be due to a net excitation of supraspinal centres (De Luca & Erim, 1994). However, it is perhaps also possible that the increased

frequency output is caused by net excitation of the spinal CPG itself (Finkel et al., 2014) or by a combination of spinal and supraspinal mechanisms.

Stereotyped rhythmic movement may be characterized as a combination of a movement frequency and a movement pattern (Dominici et al., 2011; Kriellaars, Brownstone, Noga, & Jordan, 1994; McCrea & Rybak, 2008; Perret & Cabelguen, 1980). Further in the present case of finger tapping, aspects of the movement pattern may be considered to be reflected by the kinematics and kinetics of the finger tapping (Sardroodian, Madeleine, Mora-Jensen, & Hansen, 2016). Kinematic and kinetic characteristics of the finger tapping were not measured in our previous study (Hansen et al., 2015). Consequently, knowledge on the effect of repeated bout rate enhancement on such aspects of movement pattern will add to the understanding of the phenomenon. Thus, it seems obvious complementing the latter prior investigation with measurements of kinematics and force production during repeated bout rate enhancement. In addition, as in general with novel findings, it is desired to reproduce the results, to support the validity of the novel finding.

Accordingly, the aim of the present study was twofold. First, it was investigated whether the recently reported phenomenon of repeated bout rate enhancement in finger tapping (Hansen et al., 2015) could be replicated. Second, it was investigated whether the increased finger tapping frequency during repeated bout rate enhancement would result in changes in tapping kinematics and kinetics. Regarding the latter, we hypothesized that faster finger tapping would be accompanied by changed vertical displacement of the fingertip and peak tapping force. This relatively unspecified hypothesis was at first based on previous articles reporting reduced displacement with increased movement frequency in male individuals performing cyclic finger (Haken, Kelso, & Bunz, 1985) and hand movements (Kay, Kelso,

Saltzman, & Schöner, 1987) as well as increased displacement of fingers during piano playing at increased tempo in skilled pianists (Bella & Palmer, 2011).

Secondly, it was based on the finding showing that timing and force development are tightly intertwined in tapping (Sternad, Dean, & Newell, 2000).

2. Method

2.1. Participants

Twenty four (11 males, 13 females) right-handed healthy and recreationally active individuals (see Table 1 for descriptive characteristic) participated in the present study. The present participants are the same as those in a previous report (Sardroodian et al., 2016). None of the participants had any history of neural or muscular diseases, or disorders related to the upper extremity. Besides, none of the participants used their right index finger to a large extent, for more than one hour daily, for example for playing computer games or performing similar work involving a computer mouse. The participants did not use their fingers for playing music instruments more than one hour weekly. The participants were informed about the procedures of the study as well as the overall aim that was to broaden our knowledge on control of rhythmic finger movement. Still, the participants were not informed about specific aims and hypotheses of the study. The reason of that was to avoid particular conscious control of the performed finger tapping. Written informed consent was obtained from each participant before entering the study. The study conformed to the standards set by the Declaration of Helsinki and it was approved by the North Denmark Region Committee on Health Research Ethics (N-20110025).

2.2. Overall procedure

Each participant reported to the laboratory for two sessions that were conducted on two separate days. The first session, which was performed on the first day, consisted of familiarization. The second session, which was performed on the second day, was a test session. Each participant reported to the laboratory at approximately the same time of the day for both sessions, as indicated by an average time difference of 3 ± 36 min. Further, the two sessions were separated by 7.2 ± 0.6 days. Participants were instructed not to consume coffee three hours prior to the sessions. In addition, they were instructed not to consume alcohol or euphoriant substances twelve hours prior to the sessions.

2.3. Familiarisation

First, the participant was given a brief introduction to the laboratory equipment that was used. Second, body height, body mass, and age were determined. Third, the participant was familiarized with the finger tapping procedure. The latter was done by performing two 2-min finger tapping bouts that were separated by 2 min rest. For all finger tapping, the participant was instructed to sit comfortably in an office chair, in front of a table. The back of the participant was kept straight. The right forearm was resting on the table in a way that the right shoulder and elbow joints were flexed approximately 50 and 45 degrees, respectively. The experimental setup is illustrated in Figure 1. The participant was informed to tap at a comfortable and preferred frequency with his or her right index finger. It was stressed to the participant that tapping was *not* supposed to be performed as fast as possible but rather at his or her “own rhythm” while at the same time “thinking about something else”.

2.4. Test session

First, a LED-tracker (part of a motion capture system) was attached to the nail of the participant's right index finger and turned roughly 45° to the right which enabled a motion capture system (Visualeyez™ system, Phoenix Technologies Inc., Burnaby, BC, Canada) to detect the tracker during tapping. Next, an initial 3-min finger tapping bout was performed. Tapping, including information to the participant, was performed as described above. The initial tapping bout was followed by 10 min rest. Thereafter, a second 3-min tapping bout was performed. Tapping was done on a FS6–250 force transducer (Advanced Mechanical Technology Inc., Watertown, MA, USA). This sensor has a capacity of 556 N in the y direction (vertical direction in our setup) and a sensitivity of 2.51 $\mu\text{V}/[\text{V}\times\text{N}]$. The sensor was checked for accuracy and linearity every week using a range of fixed loads. A red mark on the force transducer indicated where to tap.

2.5. Data collection

Index finger movement in the vertical direction, in the sagittal plane, was measured using the motion capture system and sampled at 200 Hz. Before testing, the motion capture system was calibrated to define a 3D scaled local coordinate system.

Accordingly, the coordinates in the sagittal plane, of the active marker placed on the nail, were used to measure the vertical displacement of the fingertip.

Force in the vertical direction was measured by the force transducer, amplified 4000 times, low-pass filtered at 1050 Hz, digitalised by a 12 bits NI BNC-2090A A/D-board (National Instruments, Austin, TX, USA), and sampled at 2000 Hz. Sampling was performed during the final 90 s of the tapping bout using a LabVIEW-based (National Instruments Co., Austin, TX, USA) custom-programmed software, named "Mr. Kick III" (Knud Larsen, SMI, Aalborg University, Denmark).

2.6. Data analysis

The detailed procedure for kinematic and kinetic data analysis has been reported previously (Sardroodian et al., 2016). Figure 2 represents an example of recordings of force profile and vertical displacement. Briefly, the kinematic data were analysed using MATLAB version R2013a (The MathWorks Inc., Natick, MA) according to a previously described procedure (Sardroodian et al., 2016). Briefly, the build-in “Findpeaks” MATLAB function was used to detect the maxima and the minima during the last 90 s of the tapping bout. The function allows settings of minimum peak height and minimum distance between peaks. Following automated detection, all the detected maxima and minima were visually verified. Subsequently, the vertical displacement (in mm) of the fingertip was calculated by subtracting the average minimum value from the average maximum value. Furthermore, the tapping frequency (in taps min^{-1}) was calculated by dividing the total number of maxima during the 90 s data recording by 1.5 min.

Force recordings were analysed using custom-programmed LabVIEW-based software (“Tap Analyser”, Aalborg University, Aalborg, Denmark). Force recordings were digitally low-pass filtered at 200 Hz. Taps during the last 15 s of the recording period were analysed. Four force profile characteristics were computed in LabVIEW from each single finger tap: (a) Peak force (in N), (b) time to peak force (in ms), (c) duration of the finger contact phase (in ms) and (d) rate of force development (RFD; in Ns^{-1}) (Sardroodian et al 2016). The first derivative of the force signal dF/dt was computed in LabVIEW using the 2nd order central method. The maximum rate of force, the onset of force corresponding to the time where the rate of force was below the predefined threshold of 25N/s and the zero crossing of the rate of force

corresponding to the maximum force were extracted from each finger tap. Based on the afore-mentioned values, the peak force was determined as the maximal impact force during the initial impact phase (Dennerlein, Mote, & Rempel, 1998; Jindrich, Zhou, Becker, & Dennerlein, 2003). The time to peak force was determined as the time from the force onset to the peak force. The duration of the finger contact phase was computed as the time from the force onset to the force offset. Finally, the RFD was calculated by dividing the maximum force by the time elapsed from the onset of force to the maximum force. Average values for each of the four force profile characteristics were calculated across all the analysed the taps, for each participant.

2.7. Statistical analysis

Data were tested for normal distribution using the Shapiro-Wilk test. That analysis showed that the following variables were not normally distributed: RFD, duration of the finger contact phase, time to peak force, and vertical displacement. The remainder of the variables were normally distributed. Student's paired two-tailed t-tests were used to evaluate differences between the two tapping bouts in cases of normally distributed data. In cases of not normally distributed data, Wilcoxon signed rank tests were applied. Statistical analyses were performed using Excel 2013 (Microsoft Corporation, Redmond, WA, USA) and SPSS version 22 (SPSS Inc., Chicago, IL, USA). Data are presented as average \pm SD. $p < .05$ was considered statistically significant.

3. Results

3.1. Kinematics

Tapping frequency increased by 8.8 ± 18.7 taps min^{-1} ($p = .033$), corresponding to $6.0 \pm 11.0\%$, from the first to the second bout (Table 2). In parallel, the vertical displacement of the fingertip was reduced by 1.6 ± 2.9 mm ($p = .012$), corresponding to $6.3 \pm 14.9\%$, from the first to the second bout (Table 3).

3.2. Kinetics

No significant differences were found for peak force and the remainder majority of the kinetic characteristics (p -values between .180 and .683). Only the duration of the finger contact phase was changed in form of a reduction by 6.4 ± 13.6 ms ($p = .032$), corresponding to $4.7 \pm 12.2\%$, from the first to the second bout (Table 4).

4. Discussion

The present study replicated a phenomenon recently termed as repeated bout rate enhancement (Hansen et al., 2015). The phenomenon refers to an increase in finger tapping frequency during consecutive bouts of tapping. In addition, it was found that the faster tapping was accompanied by changes in kinematics, in form of reduced vertical finger displacement, while kinetic variables, of e.g. peak force, remained unchanged.

Mechanisms behind the phenomenon cannot be revealed by the applied techniques and can therefore only be speculated upon. A previous study investigated changes in keystroke duration in touch-typing as well as physiological state of the ring finger flexor and extensor muscles following 15-min exercise bouts (Chang, Johnson, Katz, Eisen, & Dennerlein, 2009). The 15-min exercise bouts consisted of isometric constant and fluctuating force productions of up to 30% of the force produced at a maximal voluntary contraction. Chang *et al.* (2009) reported that

force elicited by electrical twitch stimulation decreased (up to 26%) besides that keystroke duration decreased (5%). Changes were attributed to muscle fatigue. At the same time, however, it was emphasised that there are many other potential determinants for changes in e.g. keystroke duration. A comparison with the present study is prevented since differences between the two studies were markedly with respect to extent of muscle activation and character of the applied tapping/typing task. Due to the modest extent of the muscle activation in the present study, muscle fatigue appears not to have been of particular relevance. Rather, it is tentatively suggested that mechanisms are of neural origin, as advanced in the Introduction and in our recent paper (Hansen et al., 2015). With regard to interpretation of the present results, it has previously been argued that analysis of motor behaviour may be used to increase our understanding of how the nervous system is organized and functions (Goulding, 2009). Along that line, the present study applied an operational approach that links experimental observations to theory (Kelso & Schöner, 1988). The same kind of approach has been carried out previously (Jeka, Kelso, & Kiemel, 1993; Sardroodian, Madeleine, Voigt, & Hansen, 2015).

The novel finding here was that faster tapping during repeated bout rate enhancement was accompanied by changes in kinematics, while not in kinetics. These findings partly supported our hypothesis. Reduced displacement with increased movement frequency, as in the present study, has been reported previously in male individuals performing cyclic finger (Haken et al., 1985) and hand movements (Kay et al., 1987). As a part of the changed movement pattern, the duration of the finger contact phase decreased. The reason for the divergence from the previously reported increase of finger displacement during faster piano playing (Bella & Palmer, 2011) might be that the task of piano playing requires fine spatial

and temporal control. This requires performers to produce correct pitches, accurate timing, and an intended artistic expression. In addition, piano playing requires external work to be performed to move the piano key. Finally, the study by Bella and Palmer (2011) was performed on skilled pianists while the present study was performed on recreationally active individuals.

Contrary to what we hypothesized, the faster tapping did not result in a change in peak tapping force. One might expect that a change in one characteristic, e.g. frequency, will cause a change in another characteristic, e.g. force, in a tapping task, since timing and development of force are tightly intertwined (Sternad et al., 2000). On the other hand, observations of changes in movement frequency at the same time as preservation of force profiles, or *vice versa*, during stereotyped rhythmic movement have been observed before (Hansen et al., 2014; Sardroodian et al., 2016). Furthermore, Sternad et al. (2000) also reported that force and frequency in rhythmic uni-manual tapping were largely independent (Sternad et al., 2000), in line with other previous observations (Keele, Ivry, & Pokorny, 1987), as well as the present observations. If stereotyped rhythmic movements, including tapping, are CPG-mediated, and CPGs are organised in two components; one responsible for rhythmic movement frequency and another responsible for rhythmic movement pattern (Dominici et al., 2011; Kriellaars et al., 1994; McCrea & Rybak, 2008; Perret & Cabelguen, 1980), the present findings point at largely separate and independent control of kinematics (frequency and displacement) and force during finger tapping.

Of note is that the average tapping frequency in the present study was approximately 20% lower than in the preceding study by Hansen et al. (2015). The reason for this is not obvious. A difference between the two studies was that tapping was performed on an iPhone in the preceding study while it was performed on a

force transducer in the present study. Most likely of greater importance, the participants were not the same in the two studies.

Indeed, more motor behavioral and control studies need to be performed to further elucidate the phenomenon of repeated bout rate enhancement. These studies could e.g. focus on whether or not the phenomenon persists if the other hand is used in the repeated bout. They could also focus on the effect of different durations of bouts and rest periods on the phenomenon. Results from such studies would supplement animal studies investigating post exercise excitation of rhythmic movement mediated by central pattern generators (Kueh, Barnett, Cymbalyuk, & Calabrese, 2016; Aboodarda, Copithorne, Pearcey, Button, & Power, 2015).

5. Conclusion

In conclusion, the results from the present study replicated a recently reported phenomenon of repeated bout rate enhancement in finger tapping (Hansen et al., 2015). Thus, tapping frequency increased by around 9 taps min^{-1} , corresponding to a 6% enhancement. The change in tapping frequency was accompanied by reduced vertical displacement and unchanged peak force. It is possible that these findings support separate and independent control of kinematics and kinetics during index finger tapping.

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FIGURE CAPTIONS

Fig. 1. Experimental setup for index finger tapping.

Fig. 2. Examples of recordings of force and vertical displacement during tapping.

TABLES AND FIGURES**Table 1**

Descriptive characteristics of the participants

	Average	SD
Age (years)	23.5	2.9
Height (m)	1.74	0.09
Body mass (kg)	71.8	10.7

Table 2

Finger tapping frequencies during tapping

	Average	SD
Frequency (taps min⁻¹)		
<i>First bout</i>	162.7	50.7
<i>Second bout</i>	171.6*	55.3

*Different from first bout, $p = .033$.

Table 3

Vertical displacement of fingertip during tapping

	Average	SD
Displacement (mm)		
<i>First bout</i>	23.2	8.9
<i>Second bout</i>	21.5*	8.0

*Different from first bout, $p = .012$.

Table 4

Force profile characteristics during tapping

	Average	SD
RFD (N s⁻¹)		
<i>First bout</i>	347.4	169.4
<i>Second bout</i>	361.3	173.7
Time to peak force (ms)		
<i>First bout</i>	5.8	2.8
<i>Second bout</i>	5.0	0.6
Peak force (N)		
<i>First bout</i>	1.0	0.3
<i>Second bout</i>	1.0	0.4
Contact phase duration (ms)		
<i>First bout</i>	107.7	27.6
<i>Second bout</i>	101.3*	24.2

RFD, rate of force development. *Different from first bout, $p = .032$.

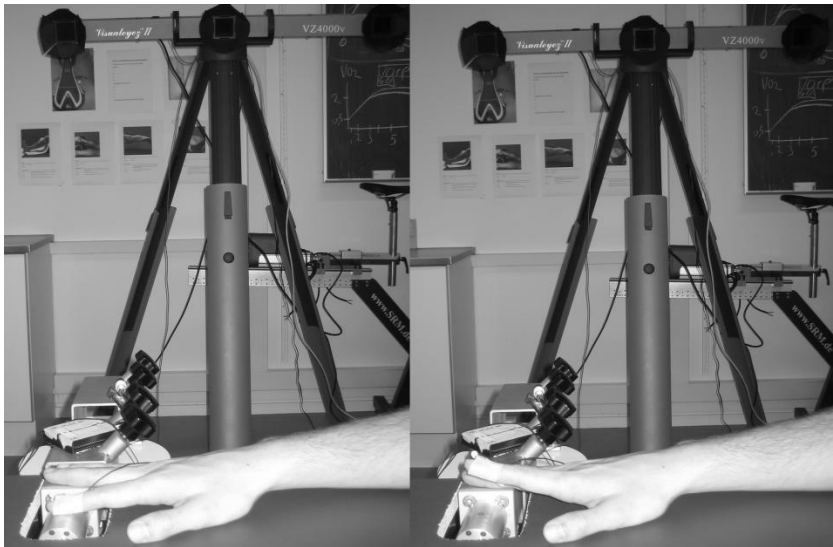


Fig. 1.

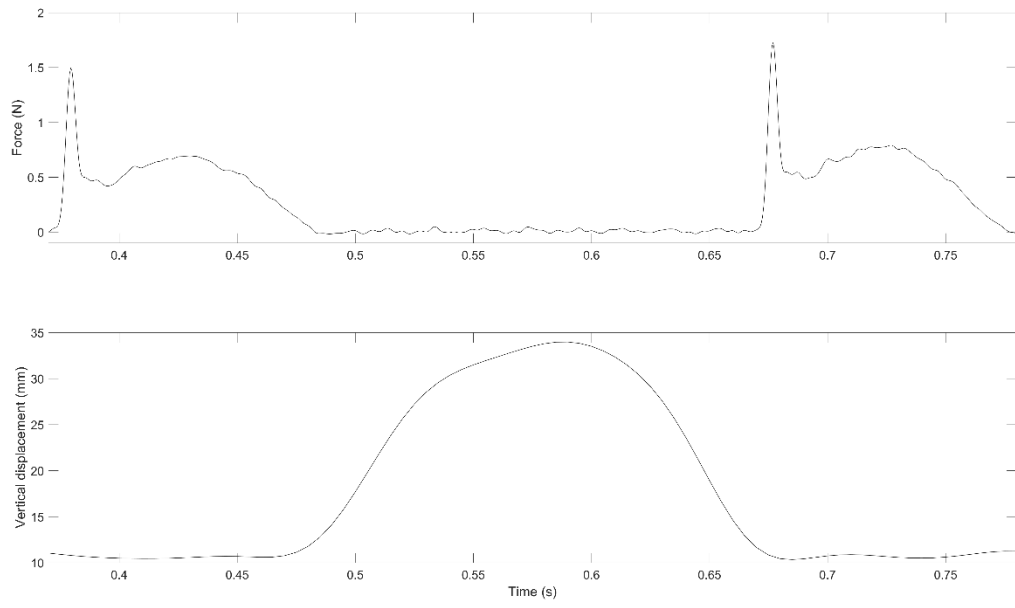


Fig. 2.