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RESEARCH ARTICLE

Timing at peak force may be the hidden target controlled in continuation and synchronization tapping

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Abstract Timing control, such as producing movements at a given rate or synchronizing movements to an external event, has been studied through a finger-tapping task where timing is measured at the initial contact between finger and tapping surface or the point when a key is pressed. However, the point of peak force is after the time registered at the tapping surface and thus is a less obvious but still an important event during finger tapping. Here, we compared the time at initial contact with the time at peak force as participants tapped their finger on a force sensor at a given rate after the metronome was turned off (continuation task) or in synchrony with the metronome (sensorimotor synchronization task). We found that, in the continuation task, timing was comparably accurate between initial contact and peak force. These two timing events also exhibited similar trial-by-trial statistical dependence (i.e., lag-one autocorrelation). However, the central clock variability was lower at the peak force than the initial contact. In the synchronization task, timing control at peak force appeared to be less variable and more accurate than that at initial contact. In addition to lower central clock variability, the mean SE magnitude at peak force (SEP) was around zero while SE at initial contact (SEC) was negative. Although SEC and SEP demonstrated the same trial-by-trial statistical dependence, we found that participants adjusted the time of tapping to correct SEP, but not SEC, toward zero. These results suggest that timing at peak force is a meaningful target of timing control, particularly in synchronization tapping. This result may explain the fact that SE at initial contact is typically negative as widely observed in the preexisting literature.

Keywords Continuation tapping · Sensorimotor synchronization · Timing at peak force · Timing at initial contact · Negative synchronization error · Timing variability

Introduction

Rhythmic movements such as speaking, playing musical instruments, and dancing, pervade our daily life. Although we seem to perform these tasks effortlessly, successfully executing them requires precise timing control and motor production. For example, dancing involves coordinating one's actions to an external event, whereas speaking requires performing a sequence of actions at specified times. How this exquisite sensorimotor function is achieved or what happens when it fails has been the focus of study for over a century (see Repp 2005; Repp and Su 2013; Wing 2002, for reviews). In laboratory experimentation,

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the rhythmic finger-tapping task has been a primary window into understanding this complex yet seemingly simple human action. In the present study, we use rhythmic finger-tapping tasks to explore the most salient parameter required in motor timing control.

In most rhythmic finger-tapping tasks, participants either successively tap their fingers at a given speed to produce a certain time interval usually after initially pacing to an external signal and subsequently continuing with the beat turned off (known as a continuation paradigm) (Wing and Kristofferson 1973) or tap their fingers to synchronize to an external auditory signal (i.e., known as sensorimotor synchronization paradigm) (Dunlap 1910; Stevens 1886). Since finger tapping is usually marked by discrete events, many studies using these two paradigms have examined timing control at specific event points in the tap, referred to as event timing (Ivry et al. 2002; Zelaznik et al. 2002, 2005). Not surprisingly, these event points include: (1) the time point at the initial contact between finger and tapping surface (Aschersleben 2003; Aschersleben and Prinz 1997; Repp 2003; Semjen et al. 1998, 2000); and (2) the time point when a key is pressed (Hary and Moore 1987; Mates et al. 1994). However, one important and underlying variable in the tap movement is its force. That is to say, a relatively overlooked aspect of the tap is the time when the tapping force reaches its peak.

Finger tapping has been suggested as a periodic oscillation with a virtual movement of force beyond the contact surface (Vaughan et al. 1996, 1998). Put another way, the end point of force—the point where the force rises to its peak—may be a notable event that requires precise timing control (Repp 2005). Although two previous studies examined the timing profiles of peak force (Keele et al. 1987; Sternad et al. 2000), the question in front of us is whether the force peak, rather than the initial contact widely used in the literature, is the timing target controlled during finger tapping. Identifying the primary control target is essential to understand motor timing functions as the timing characteristics of finger tapping depends on which event point is controlled. For example, if the timing of peak force is the target during finger tapping, it is arguable that previous findings of timing functions, such as the negative synchronization error (see, Repp 2005, for a review), may need to be revisited, because it may not be a function so much of anticipation but a function of how the finger contact is controlled. Moreover, timing control has been widely found to be associated with force production (Inui et al. 1998; Keele et al. 1987; Sternad et al. 2000; Therrien and Balasubramaniam 2010), but the underlying mechanisms were unknown. Our hypothesis that the timing of peak force is precisely controlled during finger tapping could provide evidence supporting the interdependence between force and timing control. That is, a variation occurring at the point of peak force would lead to the simultaneous force and timing changes.

To identify the primary control target, we compared the timing control at the force peak to that at the initial contact when participants tap their fingers on a force transducer to maintain a given rate after external cues are withdrawn (i.e., continuation task) or to synchronize their tapping to an external metronome (i.e., sensorimotor synchronization task). Timing control was first measured by the inter-response interval (IRI) in both tasks (Semjen et al. 2000). Obviously, the IRI at the controlled target, compared to the uncontrolled event, would be (1) more accurate (i.e., closer to the given rate); (2) less variable; and, (3) demonstrating stronger trial-by-trial statistical dependence (i.e., negative lag-one autocorrelation) that indicates a more stable central clock (Wing and Kristofferson 1973). We then measured the synchronization error (SE) in the sensorimotor synchronization task (see, Repp 2005, for a review). In addition to the three aforementioned criteria, we hypothesized that each tap should be adjusted to reduce the SE toward zero at the controlled and not the uncontrolled event.

Method

Participants

Nineteen adults (21.1 ± 1.3 years, 10 females) from the University of Maryland, College Park volunteered for this study. All participants were right handed, which was determined by a self-report questionnaire (Oldfield 1971) administered to the participants before the study began. A neurological health questionnaire was also given to each participant. No participants were excluded owing to neurological impairments or medical conditions that would affect motor performance. All participants signed the informed consent based on the procedures approved by the University of Maryland's Institutional Review Board (IRB) before starting the experiment. Upon completion of the study, participants received $10 monetary compensation.

Apparatus

The force data produced by the index, middle, ring, and little finger from the right hand were collected by four six-component force transducers (ATI Industrial Automation, Garner, NC, USA), and the force signals were routed to two synchronized 12-bit analog–digital converters (PCI-6031, National Instrument, Austin, TX, USA). The sensors were mounted on a flat wooden board that was fixed on a table with a Velcro strap. A custom software program created in LabVIEW (LabVIEW 7.1, National Instruments Corp.) produced metronome pulses (frequency 440 Hz, duration 30 ms) transmitted to the participants through a headphone. All force data were sampled at 200 Hz.

Procedure

Participants were seated comfortably in a chair facing a 19″ computer screen. The height of the chair was adjusted so that participants could reach the force sensor with the entire arm comfortably positioned and relaxed. The forearm rested on a wooden panel and was fixed by the Velcro straps to avoid forearm and wrist movements. Each of the four fingers including the index, middle, ring and little finger rested on individual force transducers before the experiment started. Through the whole experiment, participants were asked to tap only their index finger and lightly rest the other three fingers on the force transducers. Thus, the force transducer under the index finger recorded the tapping force and the data from the other three transducers revealed that participants did not also demonstrate overflow by tapping the middle, ring, and little fingers. Three practice trials were provided before the experimental trials. During the experimental trials, participants were asked to tap only their right index finger on the corresponding force sensor to match the external metronome in either: (1) the continuation task, in which participants tapped 11 times before the external metronome was turned off and were instructed to continue tapping at the same rate given by the metronome; or (2) the sensorimotor synchronization task in which participants tapped their index finger in synchrony with the external metronome throughout the entire trial. The interval between consecutive metronome pulses used in this experiment was 500 ms (30-ms duration + 470-ms delay), 1000 ms (30-ms duration + 970-ms delay), and 1500 ms (30-ms duration + 1470-ms delay). Timing control (at the initial contact) under these metronome intervals has been systematically examined (Madison 2001; Peters 1989; Repp and Doggett 2007; Sternad et al. 2000). We chose these interval lengths because they cover a wide range of tapping rates and do not exceed the rate limits of timing control (Repp 2005). We aimed to determine whether the timing is precisely controlled at the same event within this wide range of tapping rates. Each metronome condition consisted of 4 trials: 2 trials of synchronization and continuation tasks, respectively. Each trial lasted 31.5 s (500 ms condition), 63 s (1000 ms condition), or 94.5 s (1500 ms condition) resulting in 63 taps in each condition (the number of taps in the continuation task may vary). The first 11 taps in both tasks were excluded for data analysis. All the conditions were randomly assigned within subjects. Throughout the experiment, no visual feedback was provided.

Data analysis

All force data (i.e., the normal force component that is perpendicular to the tapping surface) were filtered by a low-pass filter (4th-order Butterworth with cut off frequency 50 Hz). We choose 50 Hz because it retained the details of tapping forces. In addition, the second phase of the force profile (see below) consisted of many spikes which had similar magnitudes. Using the cutoff frequency of 50 Hz helped reducing this noise and ensured a reliable estimation of the peak force time. A typical tapping force profile is shown in Fig. 1a. There were two force peaks during each tap (Vardy et al. 2009). The first peak corresponded to the finger impact on the force transducer, occurring about 10 ms after the initial contact[1]. The force then reached the second peak about 50 ms later, which was likely to result from fingertip pulp compression (Rempel et al. 1994). Given that the first peak was close to the initial contact and that our results demonstrated the same timing characteristics between the first peak and initial contact (i.e., for all variables and analyses described in the "Method" sections, the initial contact and the first force peak exhibited almost identical results), our primary goal was to compare timing control at the initial contact to that at the second force peak.

Custom-designed MATLAB programs derived the following variables from the force data of each experimental trial (Fig. 1b). The peak force magnitude was defined as the maximum force level of the second peak of each tap. The time-to-peak variable represented the time that force needs to arise to the second peak. This is the time elapsed from the time at initial contact (force onset) to the time at peak force. The force onset was marked at the time when force reached a threshold that was computed as the mean plus 5 standard deviations of the baseline force prior to the tap. We chose this threshold as it was a clear indicator of where the force initiated. In both continuation and synchronization tapping tasks, the inter-response interval at initial contact (IRIC) was defined as the time interval between two successive times of force onset when the finger initially touched the force sensor. The inter-response interval at peak force (IRIP; the second peak) was the time interval between two successive times of peak force. In the sensorimotor synchronization tapping task, the time difference between the time at initial contact and the onset of the 30-ms-long external metronome was defined as the synchronization error at initial contact (SEC). Similarly, the

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[1] Considering the short duration of about 10 ms where the finger impact on the force transducer occurred, the sample frequency of 200 Hz used in this study may underestimate the force magnitude of the first peak, but the time when the first peak force occurred was unlikely to be affected by the sampling frequency because the force arose sharply within a short duration.

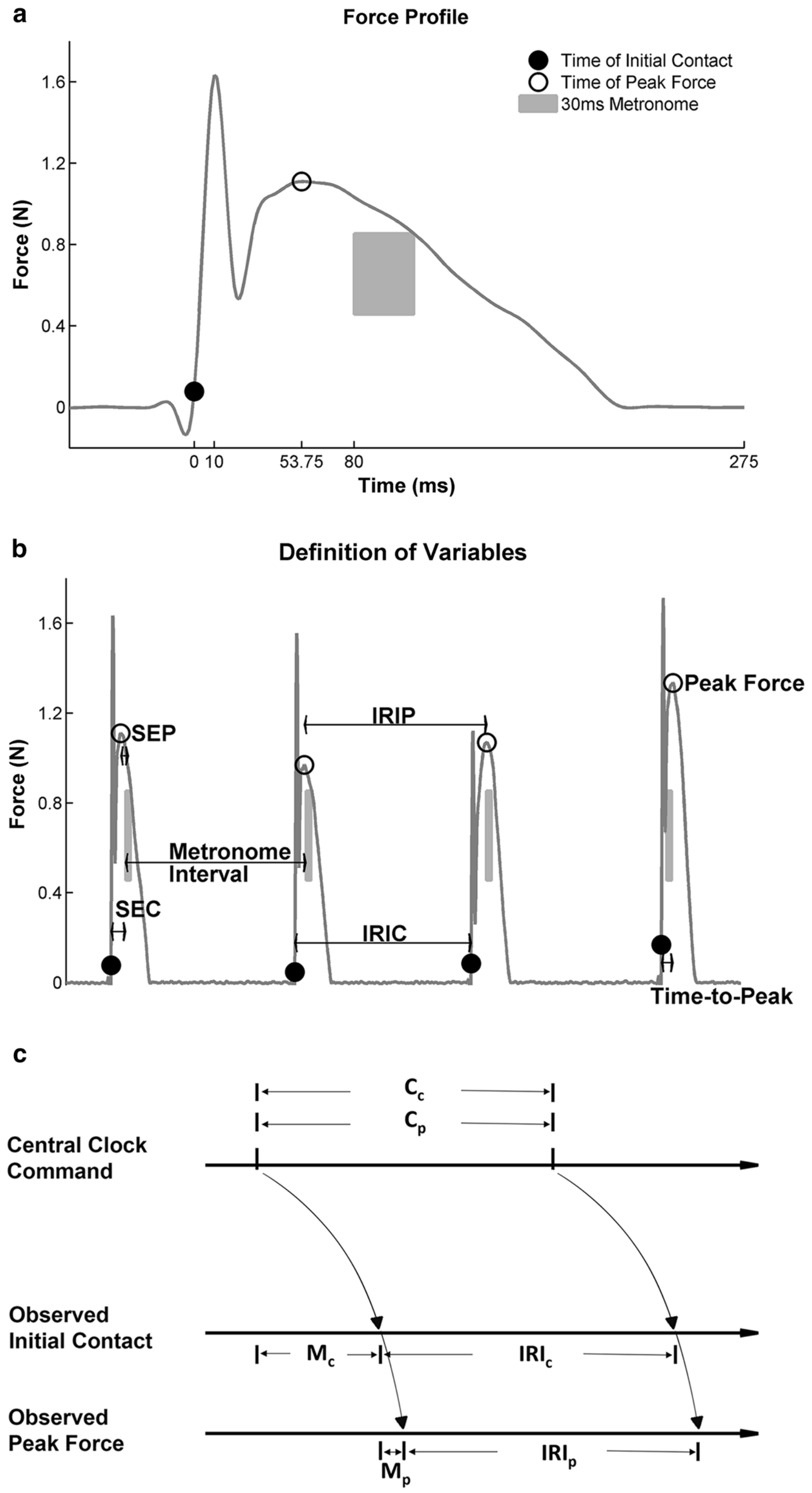

Fig. 1 The force profile for a single tap and its measurements. **a** There were two force peaks during each tap. Our primarily goal was to compare timing control at the initial contact to that at the second peak (see "Method" section). **b** The peak force magnitude was defined as the maximum force level of the second peak of each tap. The time-to-peak variable represented the time that force needs to arise to the second peak. Inter-response interval at the initial contact (IRIC) or peak force (IRIP) was defined as the time interval between two successive times of force onset when the finger initially touches the force sensor or between two successive times of peak force. Synchronization error at initial contact (SEC) or peak force (SEP) was the time difference between the time at initial contact or peak force and the onset of the 30-ms-long external metronome. **c** The central clock C_p (when the force peak is the target event of each response) or C_c (when the initial contact is the target event of each response) was assumed to generate an event that triggered the motor response. The motor response was observed after a motor delay $M_c + M_p$ (when the force peak is the target event of each response) or M_c (when the initial contact is the target event of each response)

difference between the time at peak force and the onset of the metronome was the synchronization error of peak force (SEP). A negative value of SEC/SEP means that the initial contact or the point of peak force precedes the external metronome onset.

To investigate whether the timing at peak force is the primary target controlled in continuation and synchronization finger tapping, we employed three criteria to compare IRIC and IRIP. First, it is apparent that the primary target is more likely to demonstrate a higher timing accuracy.

We thus calculated the mean IRIC and IRIP (i.e., averaged across all taps without the first 11 taps within each trial) and subsequently computed the IRIC and IRIP accuracy as the difference between the mean IRIC/IRIP and the given metronome interval. Second, given a notable attribute of the event point in timing control is its minimized variability (Vorberg and Wing 1996), we compared the variability of IRIC and IRIP computed as the standard deviation of IRIC and IRIP within each trial. In addition, the observed IRI variability is attributed to two components according to the Wing and Kristofferson two-level model (Wing and Kristofferson 1973): the central clock that provides an estimation of the stimulus interval and the motor implementation that translates the timing signal into a movement. In the original two-level model, there was a single central clock and only one motor delay component. Thus, extensions of the original two-level model were needed when there were multiple central clocks and motor components (Wing 1980; Wing et al. 1989). Here, we assumed two central clocks, C_p and C_c, responsible to the timing of finger responses that targeted at the peak force and the initial contact, respectively, and we hypothesized that the primary timing target would show lower central clock variability. The central clock C_p or C_c generated an event triggering the motor response that was observed after a motor delay $M_c + M_p$ (when the force peak is the target event of each response) or M_c (when the initial contact is the target event of each response; see Fig. 1c). Following Wing and Kristofferson's assumption that the events generated by the central clock and the motor implementation delay are independent random variables (Wing and Kristofferson 1973), the variability of IRIC, $\sigma^2(\text{IRIC})$, can then be represented as $\sigma^2(C_c)+2\sigma^2(M_c)$ and the variability of IRIP, $\sigma^2(\text{IRIP})$, was calculated as $\sigma^2(C_p)+2\sigma^2(M_c)+2\sigma^2(M_p)$ (assuming that M_c and M_p were independent). Wing and Kristofferson (1973) used the first equation of observed IRI variability and the lag-one autocorrelation function of IRI to calculate the central clock variability. However, their method could not be implemented here as the autocorrelation magnitudes observed under the 1000- and 1500-ms metronome interval conditions violated the two-level model that assumes the autocorrelation to fall between −0.5 and 0 (see "Results" section). Instead of using the autocorrelations, we approximated the central clock variability by subtracting the variability explained by the motor implementation from the total observed IRI variability. That is, we approximated the central clock variability as $\sigma^2(C_c) = \sigma^2(\text{IRIC}) - 2\sigma^2(M_c)$ and $\sigma^2(C_p) = \sigma^2(\text{IRIP}) - 2\sigma^2(M_c) - 2\sigma^2(M_p)$. This required us to determine the proportion of total IRIC/IRIP variability that arises from the motor delay M_c and M_p. The motor delay M_c from the movement initiation to initial contact would be related to the peak force magnitude as a large force may shorten the preceding IRIC while lengthen the following IRIC (Billon et al. 1996; Keele et al. 1987). Meanwhile, the motor delay M_p from the contact to the force peak was more likely to depend on time-to-peak. For example, a longer time-to-peak of the second tap would lead to a longer IRIP. Thus, we examined the correlation between the variability of IRIC/IRIP and that of peak force as well as between the variability of IRIC/IRIP and time-to-peak variability. As shown in Fig. 1c, M_c was identical despite the controlled target, and so was $\sigma^2(M_c)$, which suggests that the correlation between the peak force variability and IRIC variability would be comparable to that between the peak force variability and IRIP variability. In contrast, since M_p contributed only to the variability of IRIP, we expected a significant correlation between the IRIP variability and time-to-peak variability and not between the IRIC variability and time-to-peak variability. One note to emphasize is that peak force, time-to-peak, and IRIC/IRIP were all affected by the metronome interval and tapping task (see results), so the correlation between the variability of IRIC/IRIP and peak force variability as well as between the variability of IRIC/IRIP and time-to-peak variability may be byproducts of the mediating effects of metronome interval and tapping task. To circumvent this problem, we used partial correlation, rather than simple correlation analysis, to remove the effects of the metronome interval and tapping task. After this, the proportion of total IRIC/IRIP variability that results from the motor implementation delay was determined. It was subsequently subtracted from the total IRIC/IRIP variability to approximate the central clock variation. Finally, we expected that the primary timing target would exhibit greater trial-by-trial statistical dependence, reflected by the lag-one autocorrelation within IRI (Wing and Kristofferson 1973). We compared the lag-one autocorrelations of the de-trended IRIC and IRIP time series within each trial. We also investigated whether the lag-one autocorrelation within IRIC and IRIP was attributed to the dynamics of force production by examining the cross-correlations between IRIC/IRIP and peak force as well as between IRIC/IRIP and time-to-peak.

In addition to IRI, the synchronization error (i.e., SE) is an evident sign of timing control in sensorimotor synchronization tapping (see Repp 2005, for a review). Thus, we compared SEC and SEP regarding the accuracy, variability, and trial-by-trial statistical dependence. We hypothesized that the primary timing target would show a higher accuracy, lower variability, and greater trial-by-trial statistical dependence in SE. In addition, given the correction mechanism employed when an individual taps the finger to synchronize external metronomes (Semjen et al. 2000; Vorberg and Schulze 2002; Vorberg and Wing 1996), each tap might be expected to be adjusted to correct the SE toward zero at the controlled event. One circumstance that could allow us to determine whether the SEC or SEP is corrected

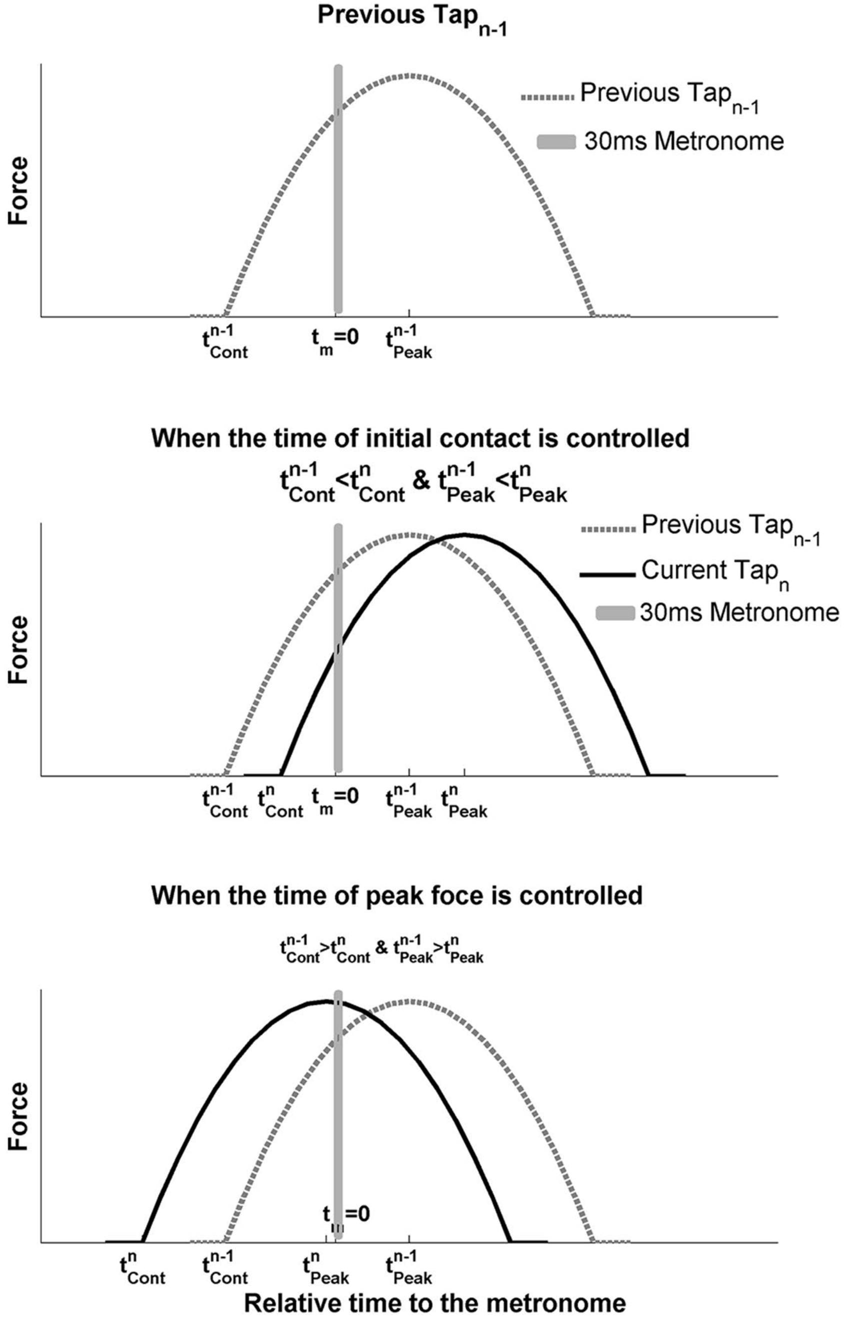

Fig. 2 The schema for how the current tap is adjusted based on the previous SEC and SEP when the previous tap (the *dashed curve*) has a negative synchronization error of initial contact (SEC) and a positive synchronization error of peak force (SEP)

is when the previous tap (i.e., tap $n-1$) has a negative SEC but a positive SEP (Fig. 2). That is to say, the initial contact (t^{n-1}_{Cont}) precedes the metronome ($t_{\mathrm{m}}=0$), while the peak force (t^{n-1}_{Peak}) is after the metronome. Specifically, if the time of initial contact is controlled, SEC should be reduced. Thus, the current tap (i.e., tap n) should be delayed so that the initial contact (t^{n}_{Cont}) becomes closer to the metronome ($t_{\mathrm{m}}=0$), resulting in a smaller SEC. This adjustment yields $t^{n-1}_{\mathrm{Cont}} < t^{n}_{\mathrm{Cont}}$ and $t^{n-1}_{\mathrm{Peak}} < t^{n}_{\mathrm{Peak}}$. Equivalently, $t^{n}_{\mathrm{Cont}} - t^{n-1}_{\mathrm{Cont}} > 0$ and $t^{n}_{\mathrm{Peak}} - t^{n-1}_{\mathrm{Peak}} > 0$. In contrast, considering the assumption that time of peak force is controlled, SEP should be reduced. Thus, the current tap should be implemented earlier so that the peak force (t^{n}_{Peak}) becomes closer to the metronome ($t_{\mathrm{m}}=0$), leading to a smaller SEP while producing a larger SEC. This adjustment yields $t^{n-1}_{\mathrm{Cont}} > t^{n}_{\mathrm{Cont}}$ and $t^{n-1}_{\mathrm{Peak}} > t^{n}_{\mathrm{Peak}}$, namely, $t^{n}_{\mathrm{Cont}} - t^{n-1}_{\mathrm{Cont}} < 0$ and $t^{n}_{\mathrm{Peak}} - t^{n-1}_{\mathrm{Peak}} < 0$. Another circumstance of previous taps (not shown) is that SEC and SEP are both negative. Pertaining to the negative SEC and SEP, the current tap should be delayed, resulting in $t^{n}_{\mathrm{Cont}} - t^{n-1}_{\mathrm{Cont}} > 0$ and $t^{n}_{\mathrm{Peak}} - t^{n-1}_{\mathrm{Peak}} > 0$ regardless of whether the time at initial contact or the time at peak force is controlled. Thus, this circumstance could not be used to determine the control point and we did not further analyze it. Similarly, when both SEC and SEP are positive, the control point could not be identified as $t^{n}_{\mathrm{Cont}} - t^{n-1}_{\mathrm{Cont}} < 0$ and $t^{n}_{\mathrm{Peak}} - t^{n-1}_{\mathrm{Peak}} < 0$ regardless of whether the time at initial contact or the time at peak force is controlled.

Statistical analysis

A mixed-effect ANOVA (the MIXED Procedure, SAS, version 9.3) was used to determine the effect of metronome intervals and tasks on IRIC or IRIP accuracy and variability. To determine whether the magnitudes or variability of IRIC and IRIP were the same, the ratio between the magnitudes or variability under each interval was compared to 1 through a Student's *t* test. In sensorimotor synchronization tapping, a mixed-effect ANOVA was employed to examine the effect of metronome intervals on SEC, SEP, and their variability. The ratio between variability of SEC and SEP under each metronome interval conditions was compared to 1 with a Student's *t* test. Similarly, Student's *t* tests were used to examine whether the magnitudes of SEC and SEP under all metronome interval conditions were different from zero. In addition, paired *t* tests were employed to compare the magnitudes between SEC and SEP under all metronome interval conditions. To further examine whether SEC or SEP was corrected toward zero, Student's t tests were performed on $t^{n}_{\mathrm{Cont}} - t^{n-1}_{\mathrm{Cont}}$ and $t^{n}_{\mathrm{Peak}} - t^{n-1}_{\mathrm{Peak}}$ to compare their magnitudes to zero (Fig. 2). Since the above Student's *t* tests examined means for multiple metronome intervals and/or tasks simultaneously, the Bonferroni correction was employed to control the familywise error rate. For all mixed-effect ANOVA used in this study, the covariance structure was determined by the Akaike's Information Criterion (AIC) and Bonferroni-corrected *post hoc* analyses were used to decompose any significant effect. Partial correlations were employed to control the metronome interval and task effects when we examined the correlation between timing (i.e., IRIC/IRIP and SEC/SEP) and force variability (i.e., peak force and time-to-peak). In autocorrelation and cross-correlation analyses, the cutoff value of significant correlation was approximated by $\frac{1.96}{\sqrt{n}} = 0.27$ ($n = 52$ taps). The significance level $p < 0.05$ was used for all effects.

Results

Peak force and time-to-peak

We found no effects of metronome interval, tapping task, and their interaction on peak force magnitude. The mean force magnitudes across all individuals were between 0.61 N and 0.90 N (the force magnitude for individuals ranged from 0.1 N to 6.43 N). These magnitudes were comparable with a previous study (Inui et al. 1998), while they were much smaller compared to another study (Experiment 1 in Sternad et al. 2000), in both of which tapping force magnitudes were not specified to participants. It is unknown whether these two previous studies used the first or second force peak of tapping. Unlike the magnitude of peak force, force variability was affected by the metronome interval ($F(2,36) = 4.66$, $p < 0.05$). Specifically, the force variability was smaller under the 500-ms interval than the 1000-ms and 1500-ms intervals (both $p < 0.05$). Time-to-peak magnitude was significantly affected by the metronome interval ($F(2,36) = 3.41$, $p < 0.05$) and its interaction with task ($F(2,36) = 4.3$, $p < 0.05$). *Post hoc* analyses revealed that time-to-peak was shorter under the 500-ms metronome interval than the 1000-ms ($p = 0.07$) and 1500-ms intervals ($p < 0.05$) in the continuation tapping. Time-to-peak variability significantly depended on the metronome interval ($F(2,36) = 2.88$, $p = 0.06$) only. Specifically, time-to-peak variability was the lowest when the metronome interval was 500 ms and increased when the metronome interval was 1000 ms ($p = 0.09$) and 1500 ms ($p = 0.07$).

Inter-response-interval accuracy

Our analyses revealed significant effects of metronome interval ($F(2,36) = 107.58$, $p < 0.001$), tapping task ($F(1,18) = 113.91$, $p < 0.001$), and their interaction ($F(2,36) = 27.03$, $p < 0.001$) on IRIC accuracy (Fig. 3a). The IRIC accuracy was the highest when the metronome interval was 500 ms, followed by 1000 ms ($p < 0.001$) and then 1500 ms ($p < 0.001$). Despite the metronome interval, the IRIC accuracy was higher in the synchronization compared to continuation tapping (all $p < 0.05$), perhaps because the external metronomes in the synchronization task assisted participants to accurately maintain the IRIC (Semjen et al. 2000). The same results were found on IRIP (Fig. 3a) with significant effects of metronome interval ($F(2, 36) = 101.72$, $p < 0.001$), tapping task ($F(1,18) = 98.74$, $p < 0.001$), and their interaction ($F(2,36) = 25.44$, $p < 0.001$). The IRIP accuracy was higher when the metronome was 500 ms compared to 1000 ms ($p < 0.005$) which had a higher IRIP accuracy than 1500 ms ($p < 0.001$). Similarly to IRIC, IRIP was more accurate in the synchronization than continuation tapping regardless of metronome intervals (all $p < 0.05$).

One of our primary interests was to compare the magnitude between IRIC and IRIP. We found no effects of metronome interval and tapping task on the accuracy ratio between IRIC and IRIP. Furthermore, Student's *t* tests revealed that the ratios were not significantly different from one for all metronome and task conditions. These results

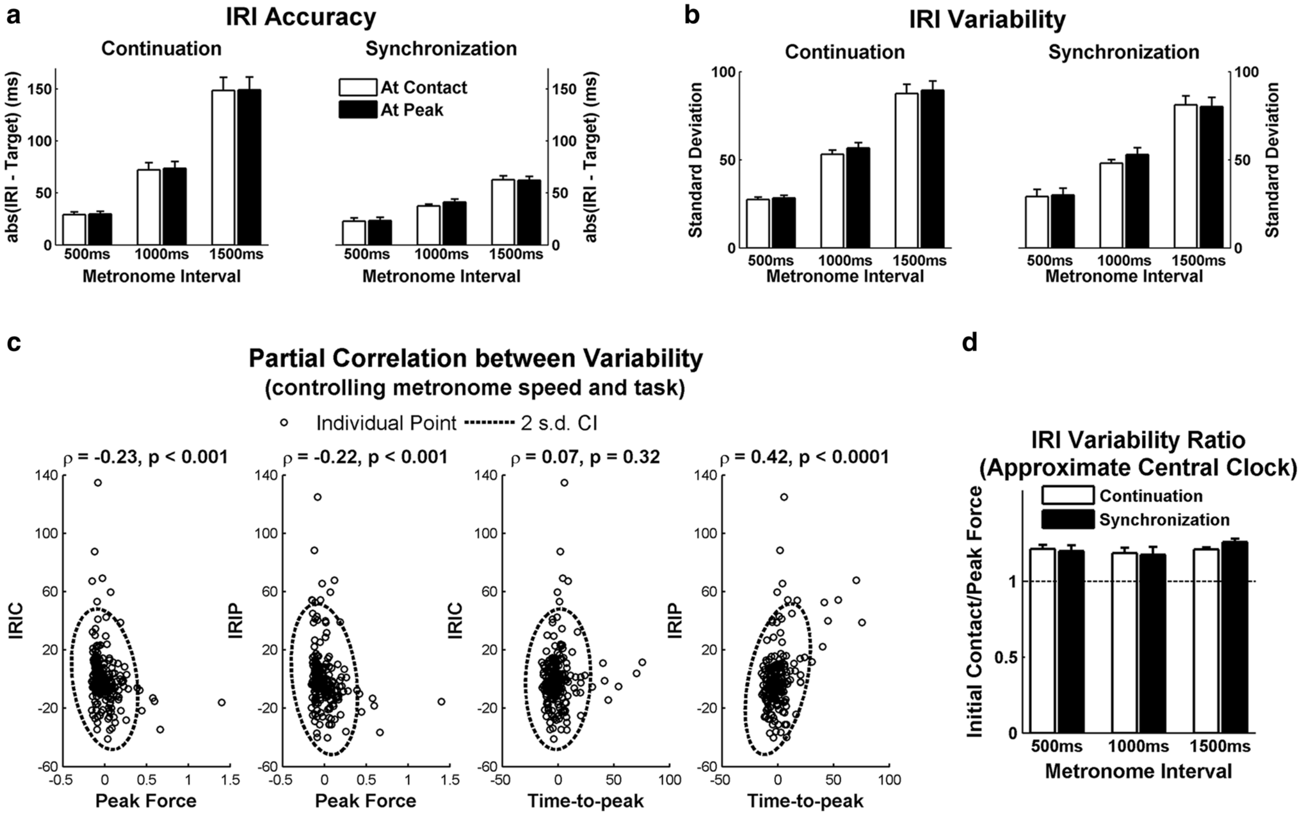

Fig. 3 Inter-response interval (IRI) in continuation tapping. **a** IRI accuracy decreased as metronome interval lengthened for both IRI measured at the peak force (IRIP) and initial contact (IRIC). The IRIC accuracy was comparable between the peak force and the initial contact. **b** IRI variability decreased with shorter metronome interval for both IRIC and IRIP. The IRIC variability was comparable between the peak force and the initial contact. **c** IRIC variability was correlated to peak force variability while there was no correlation between IRIC variability and time-to-peak variability. However, IRIP variability was correlated to both peak force and time-to-peak variability. **d** The ratio in the approximated central clock variability between IRIC and IRIP was larger than 1 for all metronome intervals and tasks. *Error bars* represent standard errors

suggest that IRI at peak force was as accurate as the IRI at the initial contact in both continuation and synchronization tapping tasks.

Inter-response-interval variability

Regarding the IRIC variability (Fig. 3b), there was a significant effect of metronome interval only ($F(2,36) = 161.71$, $p < 0.001$). Specifically, as the metronome interval became longer, the variability increased, suggesting it was more difficult to maintain the target interval for slower tapping (all $p < 0.001$). When IRIP variability was examined, the main effect of metronome interval was also significant ($F(2,36) = 128.77$, $p < 0.001$; Fig. 3b). *Post hoc* analyses found that the variability of IRIP increased with the metronome interval (all $p < 0.001$). However, the ratio between IRIC and IRIP variability was not subjected to the effects of metronome interval, tapping task, and their interaction. In addition, Student's t tests revealed that the ratios were not significantly different from one for all metronome and task conditions.

The comparable total IRI variations between the force peak and the initial contact may arise from the central clock and motor implementation variability. There were two sources of motor implementation variability: peak force magnitude and time-to-peak that were not correlated to each other ($\rho = -0.07$, $p = 0.48$), which was consistent with our assumption that M_c and M_p were independent. Partial correlation analyses found that both IRIC ($\rho = -0.23$, $p < 0.001$; Fig. 3c) and IRIP ($\rho = -0.22$, $p < 0.001$) variability were negatively correlated to the variability of peak force. However, the correlation between IRIC and time-to-peak variability was not significant ($\rho = 0.07$, $p = 0.32$). In contrast, IRIP variability was found to be significantly correlated to the variability of time-to-peak ($\rho = 0.42$, $p < 0.001$). These correlation results were consistent with our hypotheses (see "Method" section) and imply that peak force variability accounted for only about 5% (i.e., $0.23^2 \times 100$)

of the total IRIC variations, while peak force and time-to-peak variability accounted for about 23% (i.e., $0.22^2 \times 100 + 0.42^2 \times 100$) of the total IRIP variations. Thus, the approximated central clock variability would be lower in IRIP compared to IRIC. Student's *t* tests confirmed that the ratios in the approximated central clock variability between IRIC and IRIP were significantly larger than one for all metronome and task conditions (all $p < 0.001$; Fig. 3d). These results suggest that the central clock may be more stable at the force peak than the initial contact.

Trial-by-trial statistical dependence in inter-response interval

The mean lag-one autocorrelations (i.e., averaged across participants) in IRIC (i.e., 0.12 ± 0.03 for 1500 ms; 0.04 ± 0.03 for 1000 ms; −0.16 ± 0.03 for 500 ms)[2] and IRIP (i.e., 0.08 ± 0.03 for 1500 ms; 0.01 ± 0.04 for 1000 ms; −0.15 ± 0.03 for 500 ms) in the continuation task were not significant for all metronome intervals. Across all individuals, there were only 25 trials (out of 114 trials) in IRIC and 30 trials (out of 114 trials) in IRIP that showed a significant lag-one autocorrelation. Therefore, there was no systematic lag-one autocorrelation pattern shown in our data. In the synchronization task, both IRIC (i.e., −0.37 ± 0.03 for 1500 ms; −0.34 ± 0.03 for 1000 ms; −0.29 ± 0.02 for 500 ms) and IRIP (i.e., −0.36 ± 0.03 for 1500 ms; −0.34 ± 0.03 for 1000 ms; −0.30 ± 0.02 for 500 ms) exhibited significantly negative lag-one autocorrelations under all metronome intervals. However, as it can be seen, the autocorrelations between IRIC and IRIP were identical. Across all individuals, there were 81 trials (out of 114 trials) in IRIC and 85 trials (out of 114 trials) in IRIP that showed a significant lag-one autocorrelation. In addition, we did not find significant lag-one cross-correlations between peak force and IRIC/IRIP (i.e., less than 20 trials out of 228 trials exhibited significant cross-correlations in both IRIC and IRIP) as well as between time-to-peak and IRIC/IRIP (i.e., less than 30 trials out of 228 trials exhibited significant cross-correlations in both IRIC and IRIP) across the metronome interval and task. Taken together, IRIC and IRIP demonstrated similar trial-by-trial dynamics.

Synchronization error in sensorimotor synchronization tapping

We examined the magnitude of sensorimotor synchronization error measured at the time of peak force (SEP) and initial contact (SEC). One participant's data were excluded for the metronome interval 500 ms as the mean synchronization error was larger than 250 ms, indicating that the participant tapped the finger off-beat.

Mixed-effects ANOVAs found that neither SEC nor SEP were affected by the metronome interval. Student's *t* tests showed that the negative mean SECs under all metronome interval conditions were significantly different from 0 ms (all $p < 0.001$; Fig. 4a). Paired *t* tests revealed that the magnitudes of SEPs were smaller (i.e., closer to zero) than SECs (all $p < 0.001$). Moreover, Student's *t* tests revealed that SEPs were not statistically different from 0 ms for all metronome intervals (1500 ms: $p = 0.22$; 1000 ms: $p = 0.9$; 500 ms, $p = 0.97$), suggesting that mean SEPs could be non-negative (Fig. 4a).

Because SE demonstrates large individual differences (Repp 2005) as illustrated in Fig. 4a, we further analyzed individuals' SEPs. Figure 4b depicts distributions of individuals' SEPs from two participants (see Supplementary Figures for all individuals' data). We compared each individual's SEP to 0 ms using student's *t* tests. We found that 44% (500 ms), 58% (1000 ms), and 50% (1500 ms) of all trials (2 trial × 19 participants) exhibited non-negative mean SEPs. These results demonstrate that about half the participants exhibited non-negative synchronization errors at the time of peak force. Unlike the SEP, most individuals' SECs were negative (see also Fig. 4a).

The SEP variability, as well as SEC variability (Repp 2005), was reduced as the metronome interval length decreased (SEP: $F(2,18) = 46.06$, $p < 0.001$; SEC: $F(2,18) = 31.61$, $p < 0.001$; Fig. 5a). By comparing variability of SEC to that of SEP, Student's *t* tests revealed that the ratio was not significantly different from 1 across all metronome intervals. However, we subsequently found that both SEC ($\rho = -0.21$, $p < 0.05$; Fig. 5b) and SEP ($\rho = -0.21$, $p < 0.05$) variability were negatively correlated to the variability of peak force. The correlation between SEC and time-to-peak variability was not significant ($\rho = 0.12$, $p = 0.21$). In contrast, SEP variability was significantly correlated to that of time-to-peak ($\rho = 0.42$, $p < 0.001$). Thus, peak force variability accounted for only about 4% (i.e., $0.21^2 \times 100$) of the total SEC variations, while peak force and time-to-peak variability (peak force and time-to-peak variability were not correlated to each other ($\rho = -0.01$, $p = 0.88$)) accounted for about 22% (i.e., $0.21^2 \times 100 + 0.42^2 \times 100$) of the total SEP variations. The approximated central clock variability was expected to be lower in SEP than SEC. Student's *t* tests confirmed that the ratios in the approximated

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[2] For the two longer metronome intervals, the autocorrelation was positive that violated with the Wing–Kristofferson two-level model prediction. This perhaps is because the original level-two model was developed under fast finger tapping with the metronome interval shorter than 600 ms (Wing 2002). The autocorrelation under the 500 ms metronome interval was consistent with the prediction of the Wing-Kristofferson two-level model.

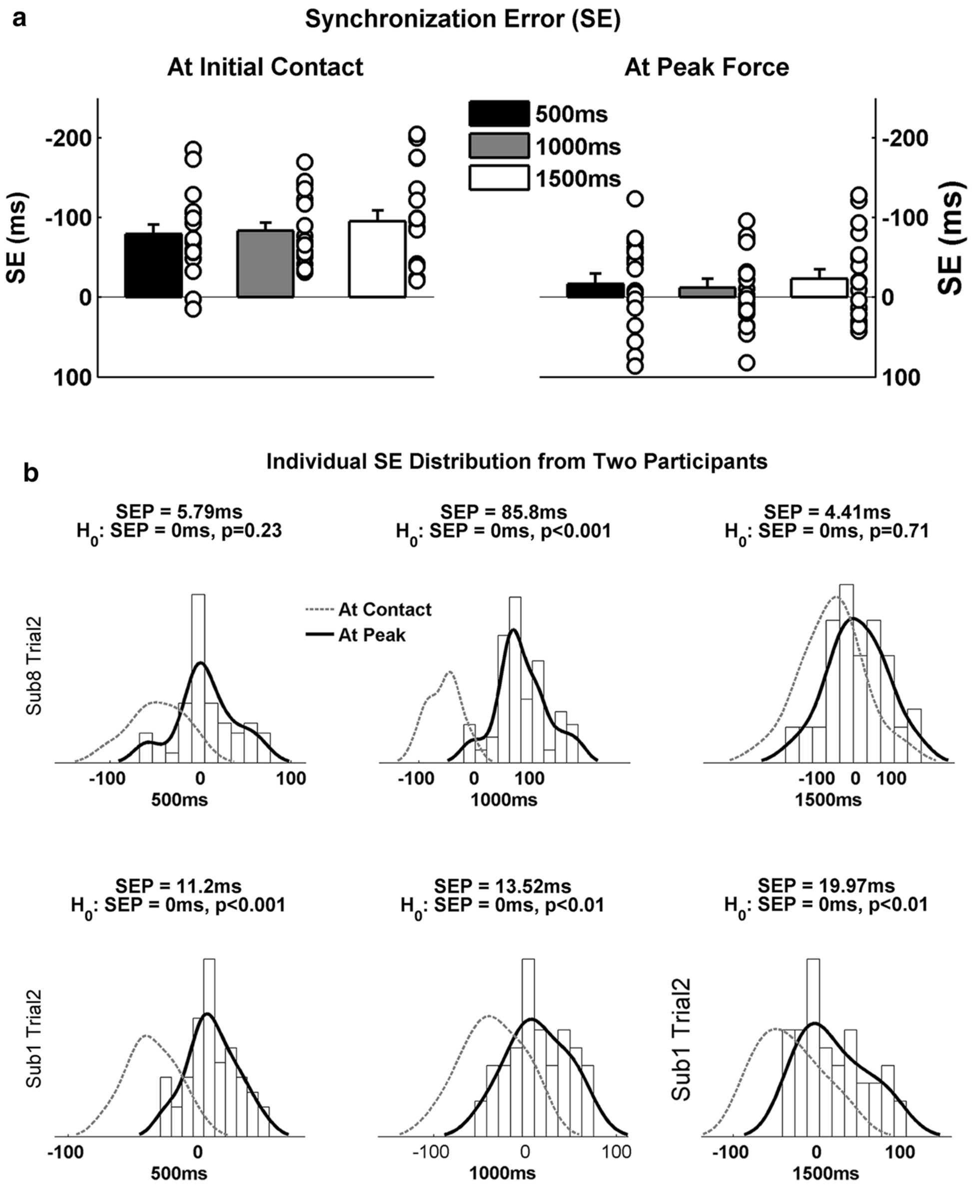

Fig. 4 The magnitude of synchronization error (SE). **a** SE at the initial contact (SEC) were all negative as demonstrated in the literature. SEP was not negative for all metronome intervals. *Circles* represent individual data. **b** Samples of individuals' SEP and SEC distributions. One participant showed zero mean SEP (when the metronome interval was 500 and 1500 ms) while the other produced positive mean SEP (around 10–20 ms) under all metronome intervals. See Supplementary Figures for all individuals' SEP and SEC distributions. *Error bars* represent standard errors

central clock variance between SEC and SEP were significantly larger than one for all metronome and task conditions (all $p < 0.001$; Fig. 5c). These results suggest that the central clock was likely to be more stable at the force peak than the initial contact.

Trial-by-trial statistical dependence in SE

The mean lag-one autocorrelations (i.e., averaged across participants) in SEC (i.e., 0.16 ± 0.03 for 1500 ms; 0.26 ± 0.04 for 1000 ms; 0.46 ± 0.04 for 500 ms) and SEP (i.e., 0.17 ± 0.04 for 1500 ms; 0.25 ± 0.04 for 1000 ms; 0.44 ± 0.05 for 500 ms) were significant for the metronome intervals of 500 and 1000 ms and the autocorrelation became stronger as the metronome interval shortened, which is consistent with the literature (Semjen et al. 2000). As the data show, the autocorrelation between SEC and SEP were identical for each metronome interval. Across all individuals, there were only 30 trials (out of 114 trials) in SEC and 29 trials (out of 114 trials) in SEP that showed a significant lag-one autocorrelation, which was also comparable between SEC and SEP. In addition, we did not find significant lag-one cross-correlations between peak force and SEC/SEP (i.e., less than 20 trials out of 114 trials exhibited significant cross-correlations in both SEC and SEP) as well as between time-to-peak and SEC/SEP (i.e., less than 15 trials out of 114 trials exhibited significant cross-correlations in both SEC and SEP) across all metronome intervals. Therefore, SEC and SEP exhibited similar trial-by-trial statistical dependence.

Finally, we examined how the current tap was corrected given the preceding SEC_{n-1} and SEP_{n-1}. When the SEC_{n-1}

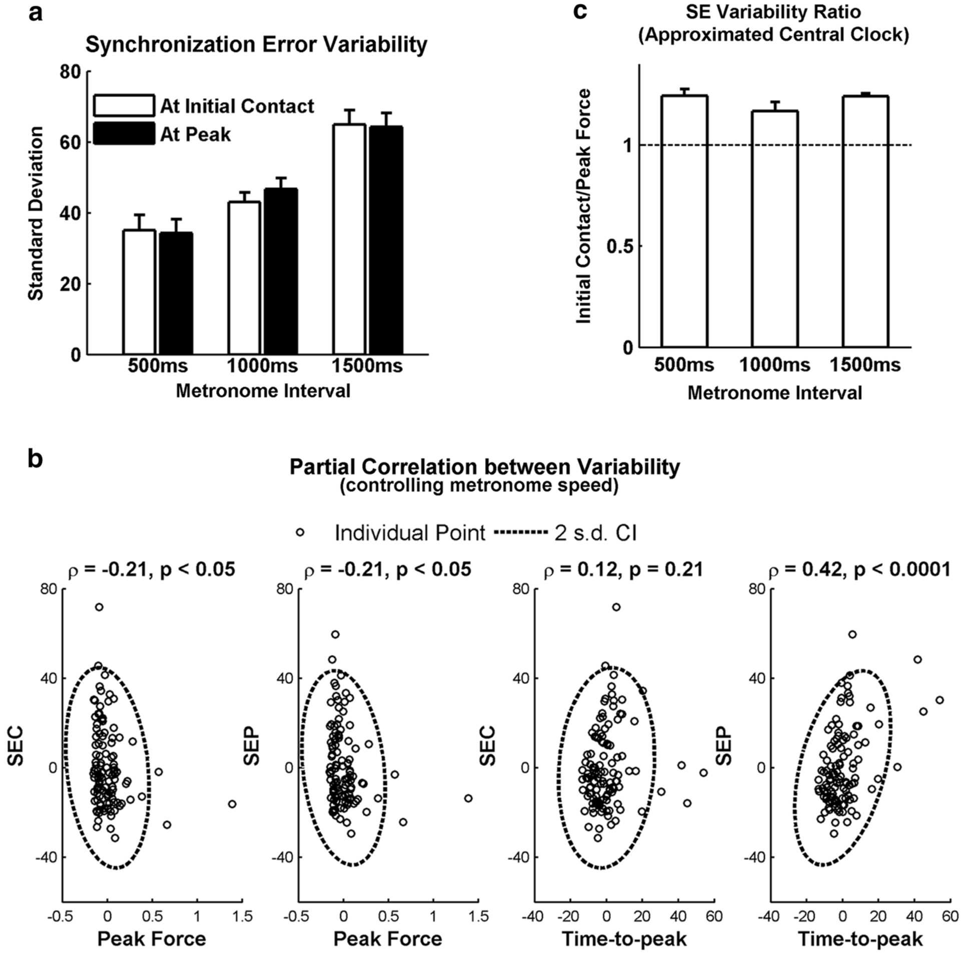

Fig. 5 Variability of synchronization error. **a** Synchronization error variability at the initial contact (SEC) and the peak force (SEP) reduced as the metronome interval decreased. **b** SEC variability was correlated to peak force variability while there was no correlation between SEC variability and time-to-peak variability. However, SEP variability was correlated to both peak force and time-to-peak variability. **c** When the peak force and time-to-peak variances were taken into consideration, the ratio in the approximated central clock variability between SEC and SEP was larger than 1 for all metronome intervals. *Error bars* represent standard errors

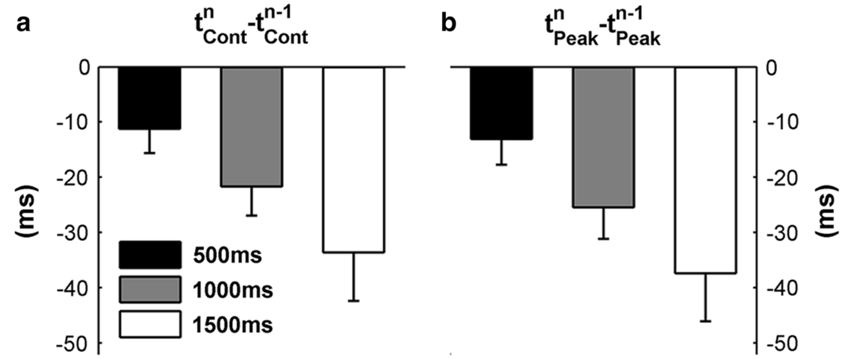

Fig. 6 Experimental observations of $t^{n}_{\mathrm{Cont}} - t^{n-1}_{\mathrm{Cont}}$ and $t^{n}_{\mathrm{Peak}} - t^{n-1}_{\mathrm{Peak}}$. **a** $t^{n}_{\mathrm{Cont}} - t^{n-1}_{\mathrm{Cont}} < 0$. **b** $t^{n}_{\mathrm{Peak}} - t^{n-1}_{\mathrm{Peak}} < 0$, suggesting that timing at peak force rather than timing at initial contact is controlled in synchronization tapping. *Error bars* represent standard errors

was negative and SEP_{n-1} was positive (Fig. 2), Student's *t* tests found $t^{n}_{\mathrm{Cont}} - t^{n-1}_{\mathrm{Cont}} < 0$ (1500 ms: −33.59 ± 8.77 ms (mean ± standard error), $p < 0.005$; 1000 ms: −21.68 ± 5.21 ms, $p < 0.005$; 500 ms: −11.83 ± 4.17 ms, $p < 0.05$; Fig. 6a) and $t^{n}_{\mathrm{Peak}} - t^{n-1}_{\mathrm{Peak}} < 0$ (1500 ms: −37.34 ±8.70 ms (mean ± standard error), $p < 0.005$; 1000 ms: −25.39 ± 5.72, $p < 0.005$; 500 ms: −13.6 ± 4.41, $p < 0.05$; Fig. 6b). These results violated the hypothesis that the time of initial contact is the target controlled, while they were consistent with the alternative hypothesis that the time of force peak is the controlled target in sensorimotor synchronization (Fig. 2).

Discussion

The primary purpose of this study was to identify the target of timing control when participants tap their finger at a given rate without a simultaneous signal (continuation tapping) or synchronize their tapping to an external metronome (sensorimotor synchronization tapping). In the continuation tapping task, we found that the timing at peak force and initial contact between finger and tapping surface showed comparable accuracy and trial-by-trial statistical dependence, while central timing variability was lower at peak force than initial contact, possibly suggesting that the event at peak force may be the primary timing target. In the synchronization tapping task, we demonstrated that the timing at peak force, rather than the timing at initial contact, was more likely to be the primary target being controlled because the tapping force reaches its peak in time with the external metronome, yielding a mean magnitude in errors around 0 ms. Furthermore, the central clock at peak force (SEP) is more stable compared to that at initial contact (SEC), and the time of finger tapping is flexibly modulated in order to correct SEP rather than SEC.

Although we failed to observe distinguishable accuracy and trial-by-trial statistical dependence of the two timing targets in the continuation task, and only supported our hypothesis that time of peak force is controlled by a lower variability, we speculate that incorporating a requirement of force control in future continuation studies could allow us to differentiate the corresponding properties of IRIC and IRIP. In our study, we found that the force production (i.e., time-to-peak and peak force) did not influence the dynamics of IRIC and IRIP, and thus participants did not regulate force to adjust IRIC and IRIP (e.g., increasing time-to-peak would lengthen the IRIP). Hence, when an individual continuously tapped a finger without being required to noticeably change the force profile of taps, IRIC and IRIP may be very similar as contacting the surface earlier or with a delay would concurrently push force to reach its peak earlier or with a delay, which yields the same accuracy and trial-by-trial statistical dependence between IRIC and IRIP. However, when a force requirement is present, for example, a tap with little force followed by a tap with more force, the force profiles of these two taps must differ and subsequently may affect IRIC or IRIP. If the timing at peak force is controlled, the more forceful tap would need to contact the surface earlier in order to produce an accurate IRIP, which yields a shorter IRIC. Such an effect of an accentuated tap would not take place if timing at initial contact is the controlled target. Little attention has been paid to timing control under force constraints, but two previous studies have demonstrated a shortened IRIC prior to an accentuated tap (Billon et al. 1996; Keele et al. 1987), supporting the hypothesis that the timing of peak force is the target being controlled in continuation tapping.

Our findings demonstrate that timing of peak force rather than timing of initial contact appears to be controlled when an individual attempts to tap a finger in synchrony with an external metronome (i.e., sensorimotor synchronization). Regarding our criteria, we observed more stable central timing control at peak force compared to that at initial contact. In addition, the synchronization error at peak force (SEP) was smaller than the synchronization error at initial contact (SEC). Importantly, the magnitude of mean SEP was zero, indicating a precise synchronization to the external metronome. The zero SEP was systematically reported in this study but can be observed elsewhere (Fig. 9.2, 9.3, Vaughan et al. 1998). The zero SEP may not allow us to conclude that the timing of peak force is better controlled than the timing of initial contact, because the zero SEP could be a by-product of the negative SEC. That is, the SEC is controlled so that the time of peak force coincidently synchronizes to the metronome. However, more evidence showing the time of peak force as the control target comes from the observation that the time of finger tapping was adjusted to regulate SEP rather than SEC. Synchronization error correction is learned through experience (Whitall et al. 2008) and is assumed to be a well-learned ability by adulthood (Repp and Moseley 2012; Semjen et al. 1998, 2000). It might be argued, therefore, that participants would minimize synchronization error at the event point that requires precise timing control. Our results show that when initial contact of the preceding tap took place prior to the metronome while force arrived at the peak later than metronome (SEC was negative and SEP was positive), participants subsequently made an earlier contact of finger to surface and produced peak force earlier, enlarging SEC but reducing SEP, suggesting that the time of finger tapping is adjusted to correct SEP instead of SEC. The attempt to correct SEP rather than SEC also implies that the trial-by-trial statistical dependence within SEC was a by-product of that within SEP although their lag-one autocorrelations were identical. This converging evidence suggests that timing of peak force is the primary target controlled in sensorimotor synchronization.

The finding that participants subliminally control the timing of peak force in sensorimotor synchronization could provide insights into understanding the property of negativity regarding SE measured at initial contact of finger tapping. The initial contact usually precedes an external metronome, which results in a negative SEC with a magnitude from −20 to −80 ms (Dunlap 1910; Hary and Moore 1987; Johnson 1899; Mates et al. 1994; Peters 1989; Stenneken et al. 2006). This anticipatory property has been assumed to be the result of feedforward processing (Miyake et al. 2004; Van Der Steen and Keller 2013), sensory accumulation (Aschersleben 2002), p-center perception (Morton et al. 1976), as well as others (see, Repp 2005, for a review). Unlike other explanations of negative synchronization error that mainly focus on central neural systems, an alternative could be that the initial contact to the tapping surface has to precede an external metronome in order to allow force to be produced and the point of peak force to be synchronized with the metronome (Repp 2005). The negative SE measured at the initial contact is never reduced to zero even in participants who received excessive training on the tapping task (Aschersleben 2003) as force needs time to rise. Consistent with previous studies (Inui et al. 1998; Keele et al. 1987; Sternad et al. 2000; Therrien and Balasubramaniam 2010; Vaughan et al. 1998), this interpretation emphasizes the important roles of force (or more generally movement control) in timing control of finger-tapping tasks. For example, participants with musical expertise (Aschersleben 2002) usually produced smaller negative SEC compared to non-musicians. However, this superior ability in musicians was observed only when movements were involved (Manning and Schutz 2015). In addition, musicians showed even smaller synchronization error when playing their own instruments compared to tapping to an external metronome (Stoklasa et al. 2012) with which they do not have extensive practice, confirming the critical role of force or movement production in sensorimotor synchronization. It seems that rapid force production in musicians (especially of movements they have extensive practice on) requires less time for force to reach its peak and thus reduces SE measured at the initial contact. Taken together, we suggest that the negative synchronization error at the initial contact could be a result of precisely synchronizing the timing of peak force.

In summary, we found that in the continuation tapping task, the timing at peak force may be better controlled than the timing at initial contact, as revealed by the smaller central clock variability. Timing at peak force is likely to be the primary target controlled in the sensorimotor synchronization task. Supporting evidence comes from the observation that sensorimotor synchronization is more stable and accurate at peak force compared to initial contact, and that movements were modulated to correct sensorimotor synchronization error at peak force instead of initial contact. This finding provides a window into understanding the mechanisms underlying the negativity of synchronization error that has been widely reported in previous studies of sensorimotor synchronization.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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