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Influence of an exhausting muscle exercise on bimanual coordination stability and attentional demands

Alexandre Murian [a], Thibault Deschamps [a,*], Jérôme Bourbousson [a,b], Jean Jacques Temprado [c]

[a] JE 2438 "Motricité, Interactions, Performance", Université de Nantes, Nantes Atlantique Universités, Faculté des Sciences du Sport, 25 bis boulevard Guy Mollet, BP 72206, 44322 Nantes Cedex 3, France
[b] Ecole Normale Supérieure de Cachan, Département EPS, France
[c] UMR 6152 "Mouvement & Perception", Université de la Méditerranée – Faculté des Sciences du Sport, Marseille, France

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Abstract

The present study investigated the influence of a bilateral exhaustive exercise on the stability of bimanual anti-phase coordination pattern and attentional demands. Eight subjects performed the anti-phase coordination pattern in two sessions: an Exhausting Session and a Control Session. During the Exhausting Session, subjects performed the bimanual coordination after exhaustion of forearms muscles (i.e. endurance time test). For the Control Session, no endurance time test was previously designed before the performance of anti-phase coordination. Within these experimental sessions, two levels of load (loaded and unload) and two frequencies (1.75 and 2.25 Hz) were also manipulated during the bimanual task. Attentional demands associated with performing the anti-phase coordination pattern was measured via a probe reaction time task (RT). The results showed that relative phase variability was higher for the fastest frequency after the exhaustive exercise. Moreover, as a result of the previous muscle exercise, the observed phase coupling was less accurate. No significant effect was found concerning the attentional demands as assessed through RT. The present findings suggest that the muscle exhaustion affects bimanual performance at a more peripheral level.

Keywords: Bimanual coordination; Attention; Exercise; Dual-task; Fatigue

Many studies suggested that the emergence of preferred bimanual coordination patterns results in a coalition of different constraints residing at the multiple levels of the motor system [19,24]. It is however widely recognized that among the influential constraints neuromuscular factors play a prominent role [2,6,7]. The present experiment addressed the role of neuromuscular constraints by investigating the effect of an exhausting bilateral muscle exercise on the stability of a bimanual anti-phase coordination mode and on attentional demands.

In bimanual coordination performed in the transverse plane of motion, there is considerable evidence that the coupling between the limbs is strongly influenced by neuromuscular factors. Specifically, patterns of bimanual coordination in which homologous muscles are simultaneously activated (in-phase) are more stable than those in which homologous muscles are engaged in an alternating fashion (anti-phase) [12]. This so-called "homologous coupling principle" [21] is supported by mechanisms of crossed interaction between central efferent output at different levels of motor pathways [3,6]. Other muscular factors such as force production capabilities of muscles engaged in the task are also involved in bimanual pattern stability. For instance, it has been showed that an increase of the muscular force capacity following resistance training enhanced the stability of sensory motor coordination [4]. Peripheral neuromuscular as well as central adaptations may account for this phenomenon [5]. Riek's findings [18] supported the hypothesis that the loss of rhythmic unimanual movement's stability resulting from a viscous loading condition involved complex interactions between the effects of muscular peripheral and neural/central activity [22].

Muscle fatigue defined as "any exercise-induced reduction in the capacity to generate force or power output" [26] is known to result (i) in alterations of the neuromuscular characteristics of the limb effectors and (ii) in an impairment of behavioural performance (temporal coordination between velocities of limb segments; see for details [9]) In this context, several studies have tested the effect of a localized muscle fatigue on the attentional demands associated with the voluntary control of movement

* Corresponding author. Tel.: +33 2 51 83 72 14; fax: +33 2 51 83 72 10.
E-mail address: thibault.deschamps@univ-nantes.fr (T. Deschamps).

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in different motor tasks. These studies suggested that muscle fatigue increased the associated attentional cost (e.g. [9,27]). However, even if some studies support the hypothesis that fatigue affects high-level cognitive processes (e.g. [14]), the question remains whether these alterations have their origins in the central and/or in a more peripheral level. Recent studies have investigated the influence of trial duration (300 s) [16] and resistance to motion [17] on the stability of bimanual coordination patterns and simultaneous probe reaction times. The results demonstrated that the progressive degradation in the motor task was not paralleled by an increase in attentional demands. The observed drop in performance with time-on-task was then hypothesized to result from muscle fatigue rather than from a depletion in attentional resources [16,17]. Thus, in the present study, to further investigate this hypothesis, attentional demands (assessed in a double task design), reflecting the *central cost* associated with the performance of pattern coordination [24], was assessed as a function of the motor fatigue. More specifically, we tested the influence of an exhausting fatigue protocol on a bimanual anti-phase coordination and on the concomitant attentional cost (RT) in two load conditions, loaded and unload. If a contribution of central processes is involved in the loss of pattern stability because of muscle fatigue, a concomitant increase of attentional demands should be observed particularly in the loaded condition.

Eight healthy right-handed male volunteers (aged from 19 to 32 years old), presenting no motor or perceptual deficits, participated in this experiment. They had no previous experience with the experimental bimanual task and were clearly informed the purpose of the study before their written consents were obtained. This study was conducted according to the Helsinki Statement (1964). Participants had to execute periodic forearm pronation-supination movements while responding simultaneously as fast as possible to auditory signals (100 ms at 450 Hz) by releasing a switch placed under their right heel (sampling at 1000 Hz). Reaction time was considered as the time elapsed between the apparition of the signal and the releasing onset of the switch, and was recorded via a specific computer program. Seated participants had to execute an anti-phase coordination pattern (180° of relative phase) in which non-homologous muscles were simultaneously activated, by manipulating a pair of customized joysticks. The resisting load acting against oscillatory movements was manipulated by means of two rotary pneumatic jacks (Festo (Bry sur Marne, France), DSR-40-180-P). Moreover, target marks (placed at 45° from the vertical joystick position) were provided for setting movement amplitude of 90° for a half cycle. The participants were instructed to attain these target marks by moving the joysticks. The output signals of the potentiometers (Radiospares (Beauvais, France), 10-kΩ resistance and 15% linearity) connected to joysticks signals were sampled at 128 Hz. Oscillation frequency was imposed by an auditory metronome (200 ms at 1900 Hz).

After practise trials to bimanual task (four 1-min in-phase trials and four 1-min anti-phase trials at 1 Hz of frequency) and simple discrete RT task (20 s trials), subjects took part in two experimental sessions (see Fig. 1): an Exhausting Session (ES) and a Control Session (CS). Each session was composed of either an endurance time test ($T1_{ES}$) or a control task (CT) followed by a bimanual coordination task and an endurance time test ($T2_{ES}$ or $T2_{CS}$). $T1_{ES}$ aimed to induce peripheral fatigue specifically localized to the bimanual limbs. The volunteers had to produce constant oscillations with both hands in a symmetrical fashion (in-phase mode) in a loaded condition while following a 1.5 Hz frequency. They were instructed and encouraged to respect the frequency and to cover the required amplitude (90° for each half cycle) as long as possible. Such endurance time test is assumed to induce fatigue whatever the underlying mechanisms [26]. The participants were considered as fatigued, when they were unable to keep the required frequency or amplitude for at least three consecutive cycles. The control task consisted in producing in-phase movements, in the unloaded condition for 3 min. This duration was approximately equivalent to that of endurance times previously estimated during pre-experimentations. During the experimental sessions, two load conditions (loaded and unload) and two frequencies (1.75 and 2.25 Hz) were manipulated. The order of experimental sessions (ES and CS) as well as load and frequency conditions within the sessions was counterbalanced between participants. Two trials were performed at each frequency level for each load condition. Hence an experimental session was made up of eight anti-phase coordination trials of 40 s. During a trial, the metronome was turned off after the first 10 s in order to avoid interference between RT signals and metronome. Thus, only the remaining 30 s of the trials were analysed. Subjects were asked to give priority to the bimanual task without giving up the secondary RT task (e.g. [24]). In sum, the participants performed anti-phase patterns while responding to auditory signals (50 ms) by releasing a foot-switch placed under their right heel that was sampled at 1000 Hz. RT was measured by the time elapsed between the signal and the onset of releasing of the switch. It was calculated by a specific computer program and stored for further treatment. The inter-trial interval varied randomly between 1 and 6 s. The position time series were filtered with a dual pass, second-order Butterworth filter, with a cut-off frequency of 10 Hz. For each movement cycle, the position (x) and velocity (dx/dt) data were rescaled to the interval [−1, 1] for the calculation of point-estimates of relative phase relation between limbs. A peak-picking algorithm was used to locate the reversal points of the movement. Cycle frequency (in Hertz) was defined as the inverse of the time between two successive right reversals.

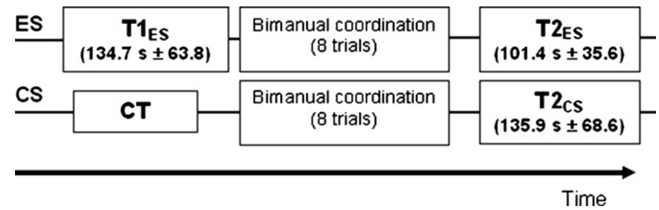

Fig. 1. Experimental design for the Exhausting Session (ES) and the Control Session (CS) ($T1_{ES}$ or $T2_{ES}$: endurance time test; CT: control task).

The dependent behavioural variables were (1) the standard deviation (S.D.) of the relative phase (an index of the coordination stability), (2) the absolute difference between the actual relative phase and the intended phasing coupling named the absolute constant error (ACE) (an index of subjects' accuracy related to the required 180° of relative phase), (3) the difference between the intended frequency and the observed frequency (Dif_{fq}) and (4) the movement amplitude (AMP). The two lasts variables allowed examining whether task criterions were respected. For all these variables (as the average of the two trials), ANOVAs with repeated measures were carried out with session, load and frequency as within subject factors. The attentional demand associated with the maintenance of coordination was assessed via RT (ms). For each trial, the minimum and the maximum RT as well as all RT values below 100 ms (considered as anticipated) were removed of the data set. Considering all participants and all conditions, nine of 576 RT (1.56%) were discarded because anticipated. All variables were then averaged for each 30-s period of a trial.

RTs were submitted to an ANOVA with repeated measures with session, load and frequency as factors. The statistical significance was set at $p < .05$ and LSD comparisons were used for post hoc tests when significant effects were identified. In the following section, only the significant results are presented.

Paired Student *t*-test was used to evaluate differences between the endurance time tests ($T1_{ES}$, $T2_{ES}$ and $T2_{CS}$). As expected, $T2_{ES}$ (101.44 ± 35.61 s) was found to be significantly shorter than the $T1_{ES}$ (134.72 ± 63.82 s), evidencing the fatiguing influence of the first endurance time test on the subject's capacity to reproduce the same performance. This result is reinforced by a $T2_{CS}$ (135.94 ± 68.56 s) significantly longer than the $T2_{ES}$. Moreover, no significant difference was found between $T1_{ES}$ and $T2_{CS}$ ($p = .92$).

The magnitude of the Dif_{fq} was small across all conditions (about .18 Hz on average) revealing that participants moved at the required frequency. The analysis of variance failed to reveal significant effects. Considering the movement amplitude (half cycle), the analysis indicated that the AMP was shorter in the loaded condition (177.09 ± 14.44°) compared to the AMP in the unloaded condition (208.38 ± 21.11°) ($F(1, 7) = 45.92, p < .001$) (Fig. 2).

The analysis of the S.D. of relative phase revealed only a two-way interaction between session and frequency ($F(1, 7) = 8.11$, $p < .05$). The post hoc analysis showed that the variability of the coordination in the Exhausting Session was higher than during the Control Session, but only at the highest frequency (Fig. 3).

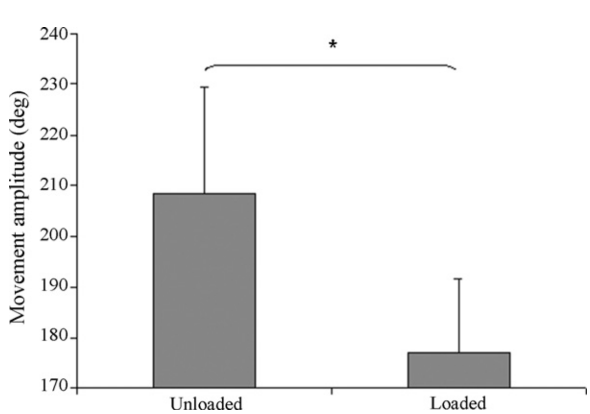

Fig. 2. Movement amplitude as a function of the load condition (unloaded vs. loaded).

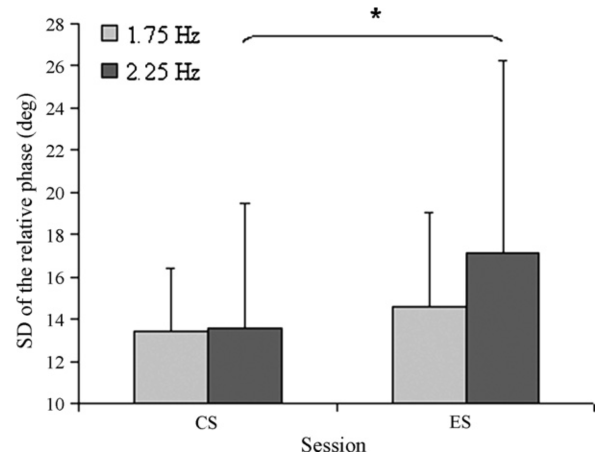

Fig. 3. Coordination variability (S.D. of relative phase) as a function of the session (Exhausting Session: ES; Control Session: CS) and the frequency (1.75 and 2.25 Hz).

Concerning the accuracy, the analysis revealed only a main effect of session ($F(1, 7) = 14.09, p < .01$). The ACE was greater during the Exhausting Session (8.61 ± 6.43) compared to the ACE for the Control Session (6.41 ± 5.22) (Fig. 4). For the RT, no significant difference was found, suggesting that all conditions required similar attentional demand (effect of session: $F(1, 7) = .685$, $p = .435$; load: ($F(1, 7) = .123$, $p = .736$; frequency: ($F(1, 7) = 1.054$, $p = .339$). For example, the RT values for the Exhausting Session (mean RT: 185,941 ± 38,329) were reliably equivalent to the RT observed during the Control Session (mean RT: 179,711 ± 24,899) (effect size = .193).

The first aim of this study was to investigate the adaptation of the neuro-musculo-skeletal system during a bimanual task in response to fatigue induced by an exhausting bilateral movement. Muscular fatigability is usually assessed by the magnitude of the decline in force production capacity (i.e. fatigue) over the time to exhaustion (endurance time) [10,26]. In the present study, the analysis of the endurance times showed a significant drop of 24.7% in performance from $T1_{ES}$ to $T2_{ES}$, providing

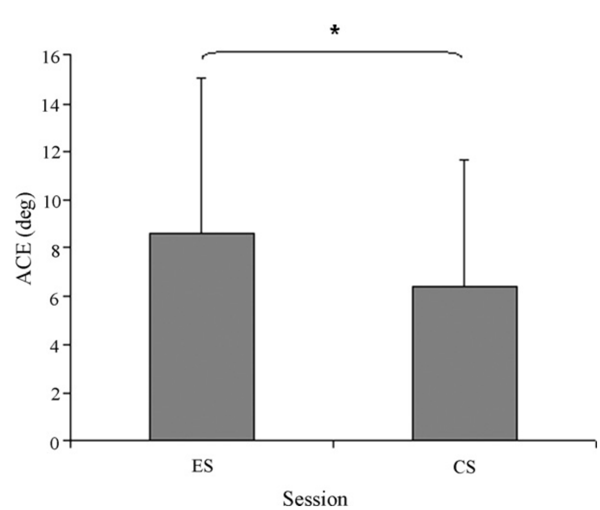

Fig. 4. Absolute constant error as a function of the session (Exhausting Session: ES; Control Session: CS) averaged across all subjects.

information on changes in capacity to generate force or power because of prior exercise. This observed incapability of participants to produce the "muscle force" required for maintaining the given target amplitude and driven frequency, as a notable index of impaired muscle efficiency, is a prerequisite to discuss the stability of bimanual coordination and the concomitant attentional cost as a function of exhaustion. Moreover, it is worth noting that these changes in the fatigue development cannot be attributed to the bimanual coordination trials as evidenced by the significant difference between $T2_{ES}$ and $T2_{CS}$ and the absence of difference between $T1_{ES}$ and $T2_{CS}$ ($p = .92$). Thus, the force production involved to perform experimental bimanual task did not influence the level of muscular fatigability.

Analysis showed that the participants were able to follow the requested frequency throughout the trials, in all experimental conditions. A significant effect of load was observed on movement amplitude: amplitude was shorter in the loaded condition than in the unloaded condition. This result suggests that both muscle fatigue and the level of force production influenced bimanual movement kinematics [8,9]. Since participant's strategy was to reduce the movement amplitude in order to compensate for the peripheral loading effects, the question then arises whether such a decrease in movement amplitude may have change the difficulty of the task, allowing participants to preserve pattern stability and the central cost (RT). According to the results of previous comparable studies, it is however unlikely that the decrease in movement amplitude might be the prominent cause of equivalent stability and central cost in the two conditions of load. Indeed, it has been shown that gradually increasing movement frequency results in an increase in relative phase variability paralleled by a decrease in movement amplitude due to the nature of non-linear oscillators involved in human bimanual task [11]. Thus, decreasing movement amplitude did not allow to maintain pattern stability. Moreover, it has been repeatedly shown that change in central cost (RT) was associated to change in pattern stability, irrespective of movement amplitude (see Monno et al. [15]). Taken together, these findings make our results interpretable. Indeed, if loading destabilized the bimanual coordination pattern, one would observe an increase in relative phase variability even when movement amplitude decreased. Thus, an increase in RT would also be observed, irrespective of movement amplitude (Monno et al. [15]).

The analysis of the relative phase variability revealed that the anti-phase pattern was less stable after the specific exhausting muscle exercise ($T1_{ES}$) only at the highest frequency, suggesting an additive effect of movement velocity and the previously performed muscle activity. A main effect of session was shown on the accuracy of coordination (ACE) suggesting that bimanual performance decreased when the involved muscles were previously exhausted. Both results (S.D. of relative phase and ACE) are consistent with those observed by Temprado et al. [22], who showed the influence of neuromuscular factors (such as the inertial loading of the end effectors) on alterations of the interlimb coupling and consequently on bimanual performance. At a neurophysiological level, possible, though speculative, explanation would be that fatigue increased contralateral motor irradiation [6] then leading to a greater difficulty to maintain the anti-phase pattern after the exhausting exercise. Besides, as a decline in contralateral irradiation has also been observed after fatigue, interesting insight has to be gained from further studying the relation between muscle fatigue and such contralateral interactions [28].

A second aim of the present study was to determine whether this increase of instability was paralleled by a change in attentional demands. The results reveal neither main effect nor interaction on the probe reaction time task. These results are not consistent with the findings that the attentional demands for maintaining a stable discrete movement increase with fatigue [27]. Although it has been shown that the CNS participates for a non-negligible part to voluntary force production [13] as well as for the performance of preferred bimanual coordination modes [24], our results (similar to [22]) suggest that the fatigue-induced anti-phase degradation may not involve allocation of supplementary attentional resources. The fact that exhaustion did not affect RT seems to stress different evolutions between the central attentional activity and the peripheral muscular processes, as previously supported by studies on motor learning/control and attentional demands [16,23]. The increase of the anti-phase coordination variability as a function of fatigue development seems not to be associated with an increase of the attentional cost, as assessed through a reaction time task, as if central and peripheral dynamics with different adapting inertias could be emphasized. Peripheral neuromuscular constraints would primarily degrade the coordination dynamics while the functional alterations associated with the central attentional cost would be effective later in time.

In summary, the present findings (see also Ref. [16]) suggest that neuromuscular factors (i.e. muscular fatigue) have to be taken into account in the exploration of bimanual coordination dynamics. However, we did not observe any significant modification of attentional cost as assessed via reaction time. In this respect and according to recent studies demonstrating changes in cortical activation after fatiguing protocols [1,25], important insight would be gained from the observation of bimanual performance on longer time scales [16] as well as from the exploration of relationship between neural activity, neuromuscular and behavioural dynamics [20].

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