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ORIGINAL ARTICLE

Grip and load force control and coordination in object manipulation during a night of sleep deprivation

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Abstract

Although sleep deprivation causes deficits in the performance of several sensorimotor tasks, its effects on object manipulation are underexplored. To investigate the possible effects of sleep deprivation on the control of object manipulation we assessed the relationship between the force components acting on the digits-object interaction (i.e. grip force [GF] and load force [LF]) during two simple manipulation tasks. Sixteen young adults performed two manipulation tasks five times along one night of sleep deprivation, at 23:00, 01:00, 03:00, 05:00, and 07:00 h. In the first task (i.e. holding), participants were asked to hold an instrumented object, as still as possible, during 12 s. In the second task (i.e. shaking), they were instructed to continuously oscillate the object upward and downward at two frequencies, 0.8 Hz and 1.2 Hz. The results revealed that individuals who remained sleep deprived decreased linearly the amount of GF exerted while holding the object still as the night progressed. Also, results revealed that during the shaking task the GF-LF coordination and GF control were negatively affected at 03:00. These results indicate that during the holding task GF control is strongly affected by time awake and that during the shaking, a dynamic task, circadian variations play a major role. These changes could be detrimental to work-related manipulation tasks.

Key words: circadian rhythm, hand function, motor performance, wakefulness.

INTRODUCTION

Sleep deprivation is a common phenomenon in modern society. The deleterious effects caused by such condition include alterations in judgment capability,[1] cognitive deficits,[2] and sensorimotor impairments.[3,4] Deficits in sensory integration have been suggested as responsible for decrements in performance in sensorimotor tasks following sleep deprivation[5,6] and the cortical areas that have its function temporarily affected by this condition[7,8] also suggest that sensorimotor processing is disrupted. Specifically, the decline in sensorimotor processing during object manipulation raises concerns since accidental slippage of an object, such as the wheel of a car or apparatus in the work place, can contribute to the alarming number of traffic and work-related accidents that occur due to sleepiness.[9,10]

The effects of sleep deprivation on human performance are based on a two-process model.[11] According to this model the interaction between two processes determines someone's propensity to enter in sleep state or remain alert: a homeostatic process, increasing sleep pressure as the time awake increases and a rhythmic process, increasing and decreasing alertness according to the circadian rhythm. Hence, performance in

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sensorimotor tasks is affected by the interaction of these two processes, being influenced by both time awake and time-of-day.[12,13]

One interesting manner to assess sensorimotor deficits caused by sleep deprivation, although not yet explored, is to use an elegant and simple experimental paradigm that investigates the control and coordination of forces acting on the digits-object interaction during object manipulation. The force component acting in parallel or tangentially to the object surface (load force – LF) tends to cause object slippage, which is avoided by the force component acting perpendicular to the object surface (grip force – GF).[14,15] Thus, to successfully manipulate a handheld object avoiding its slippage, the central nervous system (CNS) must control the exertion of GF based on the expectation of the changes in LF caused by the individual's own actions, establishing a strong coupling between GF and LF.[16,17]

It has been demonstrated that during object manipulation synaptic activity is increased in somatosensory and primary motor cortices.[18] In addition, Ehrsson *et al*.[19] have shown that the increase in activity of bilateral fronto-parietal cortical areas including premotor cortex, supplementary motor area, cingulate motor area, and posterior parietal cortex was also associated with GF-LF coordination during object manipulation. To date, no study has explored the combined effects of sleep deprivation and circadian rhythm on GF-LF coordination during object manipulation. Since performance decrements caused by sleep deprivation seem to be associated with altered activity in cortical areas similar[7,8,20,21] to the ones used in GF-LF coordination, one could expect deficits on those parameters during sleep deprivation. Therefore, the aim of this study was to examine variations in GF-LF coordination during the manipulation of a handheld object in static and dynamic conditions in adults throughout a night of sleep deprivation.

METHODS

Subjects

Sixteen healthy young adults (11 females and five males) voluntarily participated in this study. All participants reported no diagnosed sleep disturbances, although no polysomnography records were conducted. They were on average 25.06 (± 6.09) years-old and had 1.7 (± 0.07) m of stature and 71 (± 10.78) kg of body mass. Fourteen participants were right-handed and two were left-handed. All participants signed a written informed consent form approved by the research ethics committee of the University and all procedures were in accordance with the Declaration of Helsinki.

Sleep deprivation procedures

Participants were instructed to keep regular sleep schedules 3 days before the experiment. On the day of the experiment, participants were instructed to wake up at their regular times and perform their routine activities during the day. They arrived in the lab at approximately 9:00 pm and were asked to remain awake over there until 8:00 am of the next day. Participants' awake state was monitored by the experimenters all the time. Upon participants' arrival a Portuguese version of the Pittsburgh Sleep Quality Index (PSQI)[22] as well as the Morningness-Eveningness Questionnaire (MEQ)[23] were administered. Participants were tested on object manipulation tasks five times during the night, every 2 h around 23:00 h, 01:00 h, 03:00 h, 05:00 h, and 07:00 h. At those times of the day they were on average 15, 17, 19, 21 and 23 h sleep-deprived. During the sleep deprivation period participants performed activities like playing cards, chatting, and reading. Light food was offered to participants each three hours, and the ingestion of alcohol and any stimulant beverage was forbidden.

Experimental apparatus

To perform the manipulation tasks of this study, participants used a customized instrumented object. The instrumented object (Fig. 1) has a parallelepiped shape (5 × 3 × 3 cm) and is formed by two same-sized horizontal aluminum plates (3 × 3 cm) connected with each other by a vertical aluminum plate (5 × 4 cm). A second vertical aluminum plate is connected to this vertical plate by a compression-tension load cell (Interface WMC Mini 10 lbf, Interface Inc) and not connected with the horizontal plates. On the bottom of this object we fixed a cylindrical mass to increase the total weight of the apparatus. On the top part of the object was fixed a multi-axis accelerometer (3D Inline, Noraxon). The total mass of this apparatus was 354 g (i.e. W = 3.47 N). The load cell was used to record the GF applied by the tip of the thumb against the object surfaces. The multiaxial accelerometer was used to record the acceleration of the object in order to calculate the tangential force component (i.e. LF) acting on the digits-object surface. The grasping surfaces of the object were covered with fine sandpaper (320 grit), which provided

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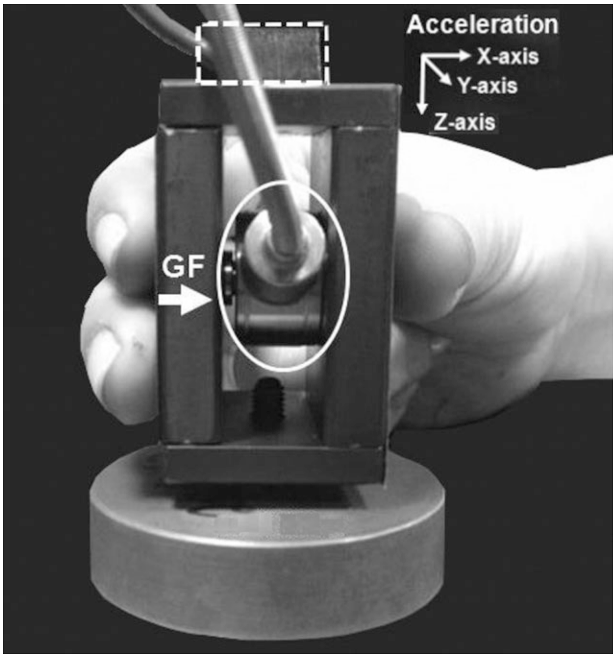

Figure 1 The instrumented object, containing uniaxial force sensor (ellipse) to measure grip force (GF) and a multiaxial accelerometer (dashed rectangle) to measure the object acceleration in three spatial dimensions (X-, Y-, and Z-axes).

a moderate coefficient of friction (COF) between the tip of the digits and the object surface.[24]

Experimental procedure

Before starting each test session participants were asked to clean the tip of their digits with alcohol swabs to remove natural and artificial substances that could affect the COF between the digits and the object surface. During each test session participants were requested to remain seated and to keep their arm internally rotated (≈60°) and vertically oriented and their forearm in horizontal orientation with the wrist in neutral position and digits flexed. This position was used while participants held the instrumented object with the tip of three digits (i.e. thumb, index and middle finger) of the dominant hand using a tripod grasp in order to perform two different manipulation tasks.

In the first manipulation task, named holding, the participants were instructed to grasp, lift and hold the instrumented object vertically and keep it positioned in front of the umbilical scar (as if they were holding a small cup of coffee), as still as possible, during 12 s, not tilting it in any circumstance. The data collection of each trial started as soon as the participants were able to keep the object still and were feeling comfortable. Participants repeated this task three times in each test session.

In the second task, named shaking, the participants, keeping the above described position, were asked to hold the instrumented object with the same tripod grasp and perform continuous oscillatory movements in vertical direction during 12 s. The peak-to-peak amplitude of each movement was approximately 20 cm, generated by a combination of shoulder and elbow flexion and extension. To complete the task within this amplitude, participants had to move the object in a vertical line to match the position of two targets localized in front of them, which were horizontal red stripes 20 cm distant from each other in the vertical. The accurate movement execution was monitored by an experimenter. A metronome dictated the rhythm of the oscillatory forearm movements, which were performed in two distinct frequencies, 0.8 Hz and 1.2 Hz, with the metronome set at 96 bpm and 144 bpm, respectively, which provided a beep to the upper and other to the lower target. Participants performed three trials at each frequency. Half of the participants began the shaking task at 0.8 Hz, and the other half started at 1.2 Hz. No instruction was given regarding the exertion of GF.

A familiarization period with the instrumented object was provided before the first test session so participants could get used to the object weight and surface roughness, as well as with the amplitude and frequency of the movements of the shaking task.

Data processing

Two customized LabView (Version 2010, National Instruments, Austin, TX, USA) routines were used for data acquisition and processing. Force and acceleration components signals were low-pass filtered with a fourth-order (zero-phase lag) Butterworth filter with a cut-off frequency of 20 Hz. Data from the first and the last 1 s of each trial were not considered and removed after filtering processing. Therefore, only the data between the 1st and 11th s were analyzed.

The GF exerted against the object surface was the force value recorded from the object's imbedded load cell. LF was calculated taking into consideration the object mass and the acceleration due to gravity and due to the object's oscillatory movement recorded by the accelerometer ($LF = m \times \text{sqrt}([[g + AccV]^2 + AccH^2])$, where, m is the object mass, AccV is the object's vertical acceleration, and AccH is the object's horizontal acceleration directed tangentially to the object surface).

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For the holding task, GF and LF stability was assessed by the coefficient of variation (CV) shown in percentage of averaged GF and LF, respectively. GF scaling, which represents the CNS ability to scale GF with respect to LF, was assessed by GF-LF ratio, calculated as the averaged GF divided by the averaged LF.[25–27] For the shaking task, GF scaling was also assessed by GF-LF ratio and GF-LF coupling was accessed by the maximum cross-correlation coefficient (r_{max}) observed between GF and LF time-series, and the respective time lag. The r_{max} observed between GF and LF and its respective time lag were obtained from a linear cross-correlation function to assess, respectively, the directional and temporal coupling between LF and GF. Negative (positive) time lag values indicate that changes in GF occurred before (after) changes in LF. The predominant LF frequency, which indicates the frequency of the arm movement, was also calculated from a power spectrum density function obtained after a spectral analysis to assure that participants executed the shaking task within the required frequencies.

Statistical analyses

Two groups of analyses were conducted, one for each task. For the holding task, to examine the effects of time-of-day (23:00 h, 01:00 h, 03:00 h, 05:00 h, and 07:00 h) on GF-LF ratio, CV of LF and CV of GF three one-way repeated measures (RM) analyses of variance (ANOVA) were performed. For the shaking task, three two-way RM ANOVAs were conducted to test the effect of time-of-day (23:00 h, 01:00 h, 03:00 h, 05:00 h, and 07:00 h) and shaking frequency (0.8 Hz and 1.2 Hz) on GF-LF ratio, Fisher's z transformed of r_{max} values, and time lag. When the main effect of time-of-day was significant, polynomial contrasts were performed. Alpha level was set at 0.05.

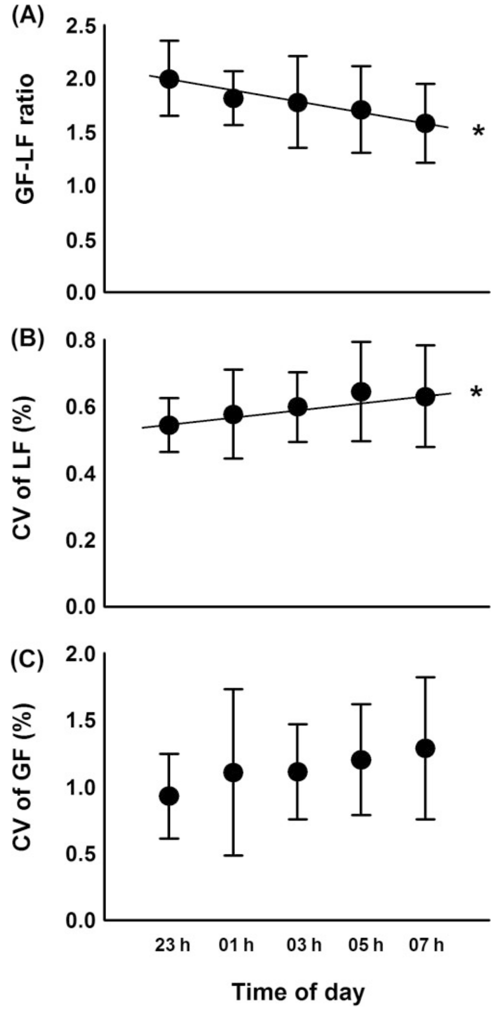

Figure 2 Grip force and load force (GF-LF) ratio (A), coefficient of variation (CV) of LF (B) and CV of GF (C) values for the holding task during all five test sessions. Error bars represent standard deviation. (*) significant linear trend.

RESULTS

Sleep diary data confirmed that participants followed the instructions to keep regular sleep schedules three days before the experiment. They slept in average 6.74 (± 1.54) hours in the first day, 7.14 (± 1.42) hours in the second day, and 7.90 (± 1.94) hours in the third day. Sleep diaries showed that participants' habitual sleep hours per day is on average 7.26 (± 1.32) hours. Participants' scores on the PSQI were on average 5.88 (± 2.28) points; scores range from 0 (better) to 21 (worse), with values lower than or equal to 5 considered as good sleep quality and higher than 5 poor sleep quality.[28] MEQ showed that four participants were moderate morning type, one participant was defined as morning type, and 11 participants were neither type.

Holding task

Results demonstrated that participants were able to maintain the object still in the holding task, as evidenced by CV of LF values smaller than 1% in all test sessions. Figure 2 depicts group average and respective standard deviation of GF-LF ratio, CV of LF and CV of GF at each one of the five test sessions. ANOVA revealed a significant effect of time-of-day on GF-LF ratio

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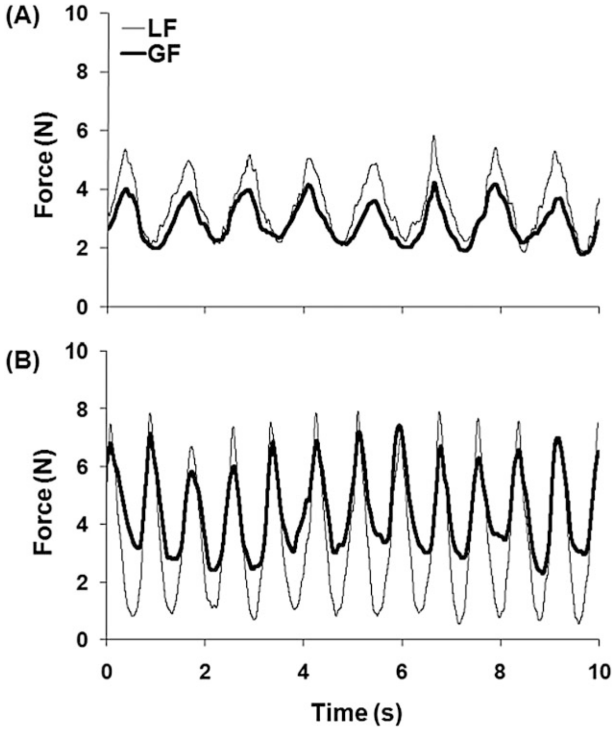

Figure 3 Force time-series (load force [LF] – thin line, and grip force [GF] – bold line) obtained from a representative participant around 3:00 am during the exertion of the shaking task, which was performed in 0.8 Hz (A) and 1.2 Hz (B).

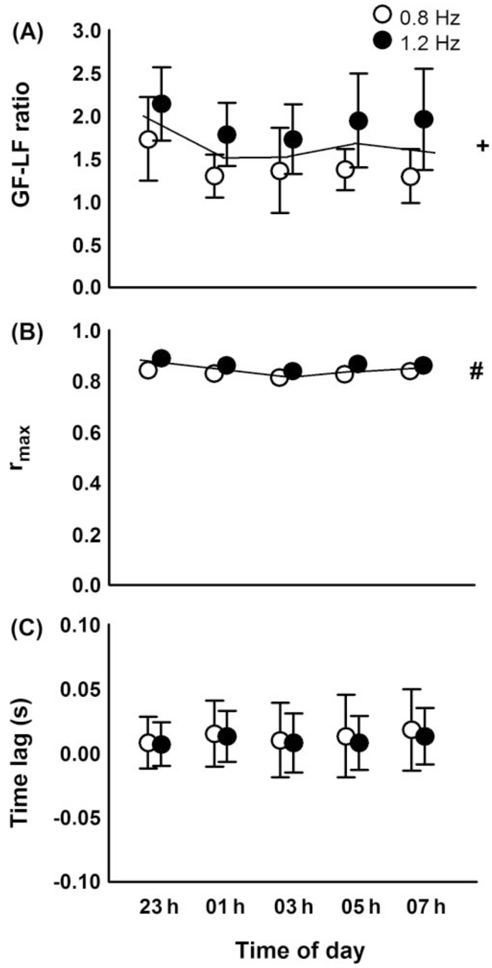

Figure 4 Grip force and load force (GF-LF) ratio (A), r_{max} (B), and time lag (C) values for the shaking task in 0.8 and 1.2 Hz frequency and across all five test sessions. Error bars represent standard deviation. (+) significant cubic trend. (#) significant quadratic trend.

($F[2.53, 37.94] = 5.23$, $P < 0.01$, Greenhouse-Geisser corrected) and CV of LF ($F[4, 60] = 3.1$, $P < 0.05$), but not on CV of GF ($F[4, 60] = 1.72$, $P > 0.05$). Polynomial contrasts confirmed a negative linear trend between GF-LF ratio and time of the day ($F[1, 15] = 10.3$, $P < 0.005$), indicating that GF-LF ratio decreased as time-of-day progressed. In addition, the polynomial contrasts revealed a positive linear trend for CV of LF, indicating that the variability of LF increased as time-of-day progressed ($F[1, 15] = 20.44$, $P < 0.001$).

Shaking task

Overall, results showed that participants performed the shaking task within the required frequencies. Mean values of predominant LF frequency during 0.8 and 1.2 Hz were in average 0.8 (± 0.001) Hz and 1.2 (± 0.001) Hz, respectively. In addition, forearm movements performed at 0.8 Hz generated peaks of LF that were in average 4.89 (± 0.05) N and movements at 1.2 Hz generated peaks of LF of 6.78 (± 0.12) N. Figure 3 depicts GF and LF profiles of a representative subject (at 3:00 h) during the shaking task performed at 0.8 (Fig. 3A) and 1.2 Hz (Fig. 3B).

Figure 4 depicts GF-LF ratio and time lag averaged values as well as r_{max} median values for all test sessions during 0.8 and 1.2 Hz shaking frequencies. ANOVA revealed an effect of time-of-day on GF-LF ratio ($F[2.12, 31.8] = 4.3$, $P < 0.05$, Greenhouse-Geisser corrected) and r_{max} Fisher's z transformed values ($F[4, 60] = 2.64$, $P < 0.05$), but not on time-lag ($F[4, 60] = 1.76$, $P > 0.05$). Also, RM ANOVA revealed a main effect of frequency on GF-LF ratio ($F[1, 15] = 121.3$, $P < 0.001$) and r_{max} Fisher's z transformed values ($F[1, 15] = 13$, $P < 0.005$), but not on time-lag ($F[1, 15] = 0.44$, $P > 0.05$). Specifically, GF-LF ratio and r_{max} were higher

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at 1.2 Hz than at 0.8 Hz. In addition, RM ANOVA revealed no interaction between time-of-day and frequency for any variable ($P > 0.05$).

Polynomial contrasts were performed for GF-LF ratio and r_{max} Fisher's z transformed values. Results indicated a cubic trend for GF-LF ratio ($F[1, 15] = 8.87$, $P < 0.01$), indicating a drop in GF-LF ratio values from 23:00 h to 01:00 h and 03:00 h, and subsequent increase at 05:00 h followed by a slight decreased at 07:00 h. For r_{max} Fisher's z transformed values polynomial contrasts indicated a quadratic trend ($F[1, 15] = 10.58$, $P < 0.01$), indicating that r_{max} Fisher's *z* transformed values decreased in the first three test session reaching its lowest value at 03:00 h and then increased again in the following test sessions.

DISCUSSION

The aim of this study was to examine variations in GF and LF control and coordination during the manipulation of an instrumented handheld object in static and dynamic conditions in healthy adults throughout a night of sleep deprivation. Our results demonstrated that LF stability (CV of LF), GF scaling (GF-LF ratio), and GF-LF directional coupling (r_{max}) change throughout a night of sleep deprivation in both static and dynamic manipulation tasks. However, these changes depend on the type of task performed. Namely, while in the holding task LF stability and GF scaling impaired progressively throughout the night as the individuals increase their time awake, in the shaking task GF scaling and GF-LF directional coupling present a circadian pattern, being negatively affected around 03:00 h. Next, we will discuss the results obtained in each task separately, beginning with the holding task.

Holding task

In the holding task participants linearly increased the variability of the object position and, at the same time, reduced the amount of GF applied to the object progressively along the night. The increased variation in the object position as the night progressed, could be a sign that the processes involved in sending neural commands to the muscles involved in maintaining a stable forearm and hand position become slightly compromised after prolonged wakefulness, even in a task as simple as holding an object. Patel *et al*.[5] suggested that sleep deprivation could lead to slower sensory integration, which would result in the selection of inappropriate motor responses produced by the CNS after prolonged wakefulness. Also, other studies have shown that sleep deprivation is associated with diminished neural activity in certain encephalic areas related to sensorimotor processing.[7,8] Both could be the origin of this increase in variability of the object position.

Besides keeping the stability of the object position, a successful object manipulation requires a proper control of GF. To maintain a handheld object one needs to apply GF not too high to damage a fragile object or spend unnecessary energy, but not too low that could put someone at risk of dropping the object.[29,30] Therefore, the linear reduction of GF and increase of LF variability in the situation of sleep deprivation could have detrimental consequences such as an accidental slip of a hand-held object in situations with external perturbations (e.g. unexpected increase in LF) or a slip of the hand off a handle while manipulating an externally fixed object (e.g. steering wheel).

In terms of the cause of the linear decrease of GF with time awake, some speculations could be made. As far as we know, there is no evidence that sleep deprivation disrupts the functioning of the peripheral afferent neurons. Thus, it is plausible that sleep deprivation affects the functioning of the central controller. It has been demonstrated that decrease in cognitive and motor performance was related to reduction in activity in thalamus, cerebellum, and especially in the regions of motor and posterior parietal cortices after sleep deprivation.[7,8,20,21] Interestingly, some of those sites are also related to GF control and GF-LF coordination.[18,31] Thus, the reduction in GF magnitude as the pressure for sleep increases could be caused by the reduction of neural activity in those sites responsible for GF control.

However, someone could argue that the reduction of GF over time could be related to a learning effect of the task as well. Based on our results we could not exclude this possibility, but due to the fact that this is a very simple task that does not require many repetitions for "learning" (i.e. creation of an internal representation based upon feedback information) and, also, due to the observed increase in the variation of LF (CV of LF) over time we assume that the learning effect in this specific task is unlikely. In addition, in Jasper and Hermsdörfer (2007) study, GF-LF ratio was assessed before individuals went to bed and just after they woke up during a "shaking task" and they found a higher r_{max} in the morning (30 min and 1 h after waking) than before sleeping (around 22:00), strengthening the notion that reduction in GF in the present study was not due to "learning", but due to sleep deprivation.

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Shaking task

In the shaking task, contrary to holding, GF control was affected at 03:00 h. At this time-of-day there was a reduction in GF exertion, evidenced by a lower GF-LF ratio which could be a sign of altered GF control. Regarding the GF-LF coupling, we observed no change in GF-LF temporal coupling. Time-lags were around zero, independently of the shaking frequency. These results indicate that sleep-deprived individuals are able to anticipate changes in LF caused by arm motion, changing GF accordingly to maintain a relatively stable relationship between GF and LF. Thus, this finding indicates that neither sleep deprivation nor circadian rhythm affect the ability of the central controller to predict the consequences of the upper-limb motion on the digits-object surface interaction. However, despite being able to keep a proper temporal coupling between GF and LF, individuals present a slight reduction in the directional GF-LF coupling on the middle of the night, around 3:00 h.

To successfully perform the shaking task GF and LF should change in parallel with minimum delay between them and this is achieved by a complex interaction between feedforward and feedback control mechanisms. Specifically, when physical characteristics of the manipulated object (i.e. weight and surface roughness), and self-induced changes in LF are known in advance, the central controller coordinates the actions of muscle groups responsible for exerting GF in a predictive way (i.e. feedforward control). Namely, the magnitude of GF exerted against the object surface varies according to the changes in LF, increasing when LF increases and reducing when LF decreases.[17,29,32] This elaborate coupling between GF and LF is known to be related to activity of specific brain regions such as somatosensory and primary motor cortices and the cerebellum.[18,31] As already mentioned, these regions have their function altered (i.e. reduction in neural activity) by sleep deprivation[7,8] and, also by circadian variations,[33] which could explain the slight reduction in GF-LF directional coupling around the circadian minimum. These findings are consistent with several others that show that individuals have their worst performance in several sensorimotor tasks by around 3:00 h, which is known as the time of day in which alertness and other biological functions reach its minimum within the circadian clock.[4,34–36] Nevertheless, such conclusions should be taken with caution since specific circadian measures were not used in this study, which could assure that changes in control and coordination in shaking task occurred during the circadian nadir.

Closing remarks

Our results demonstrated that while in one task (i.e. static holding) GF control and object stability are progressively affected by the increase of the individuals' time awake, in the other (i.e. shaking task) GF control and the directional coupling between GF and LF presented a circadian pattern with a reduction about 3:00 h A possible explanation for this difference is in the nature of the manipulation tasks performed. The holding task in which the individual simply has to maintain the position of the object for a few seconds could be considered an easy task with little attentional demands. Conversely, the shaking task requires a high level of attention so the individual can successfully perform the oscillatory arm movement in a specific frequency and amplitude. Task requirements and, especially the sound of the metronome could influence one's level of arousal, diminishing the negative effects of sleep deprivation. Therefore, the level of attentional demands to perform the task could explain the different results observed. This observation is in accordance with previous findings, showing that only aspects of the Sustained Attention to Response Test (SART) that required more cognitive or attentional resources showed a time-of-day effect, while automatic processes seemed not be affected by time-of-day.[37] In addition, tasks requiring motion accuracy, such as placing pegs in holes[35] or handwriting,[4] as well as tasks requiring visuomotor accuracy (i.e. adjusting the force produced to reach a moving target force),[34] which require high levels of attention and alertness were also affected by time-of-day.

Important limitations of the present study include the lack of measures of sleepiness. Subjective measures such as Karolinska Sleepiness Scale or Visual Analog Scale, as well as objective measures such as the Psychomotor Vigilance Task (PVT) could furnish relevant information about participants' sleepiness level further validating the sleep deprivation protocol. Besides sleepiness measures, circadian measures were also absent, which could include melatonin and core body temperature. Finally, additional measures on electrodermal activity such as skin potential and skin conductance levels could also be useful to confirm that changes in GF were caused by sleep deprivation rather than perspiration of the tip of the fingers, although this seems less likely since besides the fact that participants had their fingers cleaned with alcohol before every test session, it has been demonstrated that sleep deprivation did not alter sweating threshold in women.[38] We suggest future studies address such limitations improving the sleep deprivation

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protocol and, therefore, strengthening the conclusions regarding performance changes in object manipulation due to sleep deprivation and circadian variations.

In sum, our results demonstrated that individuals who remained sleep-deprived for one night decreased control of the handheld object during manipulation tasks progressively according to their time awake for static conditions and with circadian variations for dynamic conditions. This is the first study to examine variations in control and coordination of forces acting on the digits-object interaction during object manipulation throughout a night of sleep deprivation, which could be important for the proposition of a simple test with reliable outcomes to detect sleepiness.

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