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RESEARCH ARTICLE

Physical and cognitive exertion do not influence feedforward activation of the trunk muscles: a randomized crossover trial

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Abstract

Fatigue arises during everyday activities, diminishes movement performance, and increases injury risk. Physical (PE) and cognitive exertion (CE) can induce similar feelings of fatigue, but it is not clear whether these also similarly affect movement performance. Therefore, this study examined the influence of PE and CE on anticipatory postural adjustments (APAs) of trunk muscles, which are feedforward mechanisms that contribute to motor control and controlled movement. Rapid arm movement tasks (RAM) were used to induce APAs of the trunk muscles prior and following three experimental conditions in 20 healthy adults: seated rest without exertion (NE), a combined isometric modified Biering–Sörensen and static abdominal curl to induce PE, and a modified incongruent Stroop colour-word task to induce CE. Fatigue was assessed using self-reported measures, and APA onset latencies of the trunk muscles with surface electromyography. Statistical analyses revealed that neither PE nor CE influence APAs of the trunk. Therefore, it is hypothesized that the influence of fatigue on movement performance might not be through altered motor control, but rather by reduced motivation. However, the possibility that fatigue might influence other mechanisms which contribute to trunk motor control, such as APA amplitude and variability, cannot be excluded and need further examination.

Keywords Sensorimotor control · Electromyography · Anticipatory postural adjustments · Exertion

Introduction

Anticipatory postural adjustments (APA) are feedforward muscle reflex activities aimed at maintaining whole-body balance which are programmed in the central nervous system and occur in preparation of predictable balance disturbances (Bouisset and Zattara 1987; Massion 1992; Allison and Henry 2002; Cavallari et al. 2016). These APAs are an essential part of the motor control system, and are needed to minimize the forces applied to the body and to attain controlled movements (Knox et al. 2018). For instance, when performing rapid arm movements, feedforward activation of several trunk muscles precedes the actual onset of the arm muscles and counteracts balance perturbation (van Dieen et al. 2018). When the feedforward activation of the trunk muscles is delayed, it ultimately increases injury risk (Cholewicki et al. 2005). This is the case in for instance low back pain (Knox et al. 2018; van Dieen et al. 2018) and ageing (Brauer and Burns 2002; Hwang et al. 2008; Kanekar and Aruin 2014). In addition, several other factors such as physical activity (Borghuis et al. 2011), posture (van der Fits et al. 1998), vision (Krishnan and Aruin 2011), and fatigue (Allison and Henry 2002; Mawston et al. 2007; Kanekar et al. 2008; Strang et al. 2008; Dupeyron et al. 2010) have been shown to affect the timing of APAs and might contribute to injuries.

Fatigue—a feeling of exhaustion arising from exertion—is a disabling symptom in which physical and psychophysiological function is limited by interactions between performance fatigability and perceived fatigability (Enoka

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and Duchateau 2016; Muller and Apps 2018). Importantly, fatigue can be induced through different tasks such as physical (PE) or cognitive exerting tasks (CE). Even though such different tasks induce highly similar perceptions of fatigue (Krupp et al. 1989; Enoka and Duchateau 2016), it is not yet clear whether they also have a similar effect on muscle function, as the underlying mechanisms for both are different. One important aspect of muscle function which could be affected by fatigue is the timing of APAs. As in everyday tasks, work, leisure, and sports fatigue can arise due to both PE and CE, it is important to assess their respective impact on APAs, because the paramount role APAs have in motor control, and consequently movement performance and injury risk.

PE is characterized by a decreased force production due to diminished neural excitation or due to failure of muscles to respond to neural excitation (Lorist et al. 2002; Corbeil et al. 2003; Bisson et al. 2011) caused by depletion of physiological energy resources of the body (Ament and Verkerke 2009). This can amount to feelings of fatigue and a decrease in physical performance (Macintosh et al. 2006; Abd-Elfattah et al. 2015). Fatigue induced by PE has only been associated with altered APAs in one pilot study. In healthy people APAs of abdominal and back muscles, measured during performance of a rapid arm movement task (RAM), occurred earlier after isometric PE of the trunk extensors, reflecting altered feedforward processes (Allison and Henry 2002). However, these results need to be replicated in a larger sample. Earlier trunk muscle onsets as a consequence of PE are hypothesized to be a neuromuscular compensation aimed at countering the decreasing muscle contractility which arises from fatigue.

The contribution of cognitive function to the process of movement performance and the effect of fatigue on this process should be considered as well (Abd-Elfattah et al. 2015). Executive cognitive functions are recognized as a key factor in motor control (Abd-Elfattah et al. 2015). Hence, when these executive cognitive functions are affected by fatigue, alterations in movement performance can occur as a result. Indeed, the previous studies have found reductions in muscle activity (Mehta and Agnew 2011), force (Mehta and Agnew 2012; Budini et al. 2014), and endurance performance (Mehta and Agnew 2012) of peripheral muscles as a consequence of higher cognitive loads or CE. If and how CE affects the feedforward activation of the trunk muscles specifically has not been studied yet, but in knee muscles, neuromuscular function was not affected by CE in one study (Pageaux et al. 2013). However, the previous research did find reduced endurance times of physical tasks after CE (Marcora et al. 2009; Pageaux et al. 2013), which could indicate that CE can indeed affect movement performance and motor control. Furthermore, studies, which examined the cortical effects of PE and CE, showed that they both affect similar areas in the brain (Lim et al. 2010; Grinband et al. 2011; Asplund and Chee 2013). Based on these studies, it could be assumed that some of the central mechanisms underlying PE and CE entail similar processes. Therefore, a comparable hypothesis regarding CE effects on trunk motor control is formulated as with PE, i.e. earlier APAs after fatigue.

The main goal of this study is to examine the influence of PE and CE on mean onset times of APAs of the trunk muscles in healthy people and to compare effects of both types of exertion. It was hypothesized that PE and CE would lead to (1) earlier onset times of the APAs of the trunk muscles and that (2) both types of exertion would yield comparable results.

Methods

Participants

Healthy male and female participants between 18 and 45 years were recruited between September 2016 and December 2018 using advertisements. Healthy was defined as no history of/or current pain, severe pathologies, or traumata. In addition, people with colour blindness, professional athletes, women less than 1 year postnatal, or pregnant were not eligible. Participants had to refrain from alcohol and medication without prescription for at least 24 h, from prescribed medication at least two weeks, and from extreme physical activities 48 h prior to testing.

Procedure

This randomized within-participant crossover trial entailed participation to two sessions with minimally five days in-between. A medical background check, a general administrative, and a sociodemographic questionnaire were administered during session one. In addition, during each session, participants completed three validated questionnaires in Dutch (see 2.6 secondary outcome measures) to assess mental/cognitive functioning, physical activity and state fatigue levels, as well as visual analogue scales (VAS) to rate sleep quality and quantity during the prior night and week. To evaluate the APAs, EMG electrodes were placed on the trunk and the RAM was explained. APAs of the trunk muscles during RAM were evaluated in three conditions, i.e. a control condition with no exertion (NE) inducement, a condition during which CE was induced, and a condition during which PE was induced. To optimize task performance and familiarize the participants with the RAM extensive instructions, practice trials and feedback were provided prior to each condition. The NE condition was performed during session one, while the CE and PE conditions were performed during session two. The test order of the CE and PE conditions was randomized to prevent confounding and a 30-min rest phase was provided between these two conditions. The APAs during RAM were evaluated before (RAM1) and after (RAM2) each of these conditions. Before and after each RAM, participants rated their self-perceived state fatigue on a VAS. Furthermore, ratings of perceived exertion (RPE) of the RAM and condition-specific tasks were acquired using a Borg scale. An overview of the study protocol is provided in Fig. 1.

Fatigue-inducing conditions

No exertion

To control for possible effects due to repetition of the RAM, a control condition was performed during which participants spent 45 min sitting relaxed while watching an animated movie.

Physical exertion

To induce PE of the trunk muscles, both the Modified Biering–Sörensen and Static Abdominal Curl were performed. The Modified Biering–Sörensen is a validated PE task used to assess fatigue in the back extensors (Stevens et al. 2006; Coorevits et al. 2008) and was used to exert these muscles in the current study. Participants had to maintain a horizontal position of their upper body as long as possible, while they were positioned in a prone position with the legs strapped to a table and the upper body hanging unsupported over the edge of that table. Immediately afterwards, a Static Abdominal Curl was performed to exert the abdominal muscles (Van Damme et al. 2014). Participants had to maintain an unsupported 45° angle of trunk flexion while seated with their legs strapped to a table. Standardized motivational commands were given every 30 s, and the tasks were discontinued when the participant could no longer retain contact with a rope that indicated the required position, or had to stop due to pain or discomfort. Endurance times were measured using a chronometer.

Cognitive exertion

To induce CE, a 45-min modified incongruent Stroop task was performed identical as the protocol described by Pageaux et al. (Pageaux et al. 2015). During this task, font dominant tasks are alternated with word dominant tasks. The duration of the Stroop was increased to 45 min; as in 25% of the participants, 30 min was found to be insufficient to affect the RPE (Pageaux et al. 2015).

Primary outcome measures

APA onset latencies of the trunk muscles in response to a RAM task

Surface EMG (sEMG) was performed to assess APA onset latencies of the trunk muscles. sEMG signals were captured using a wireless 16-channel EMG system (Telemyo Desktop DTS, Noraxon Inc., USA). Skin preparations were performed to reduce electrode-signal impedance to < 5 kΩ (Impedance checker, Noraxon Inc., USA). Circular surface electrodes with an electrical surface contact of 1 cm^2 and a maximal inter-electrode distance of 25 mm (Ag/AgCl, Ambu® Blue Sensor N, 30 × 22 mm, Ballerup, Denmark)

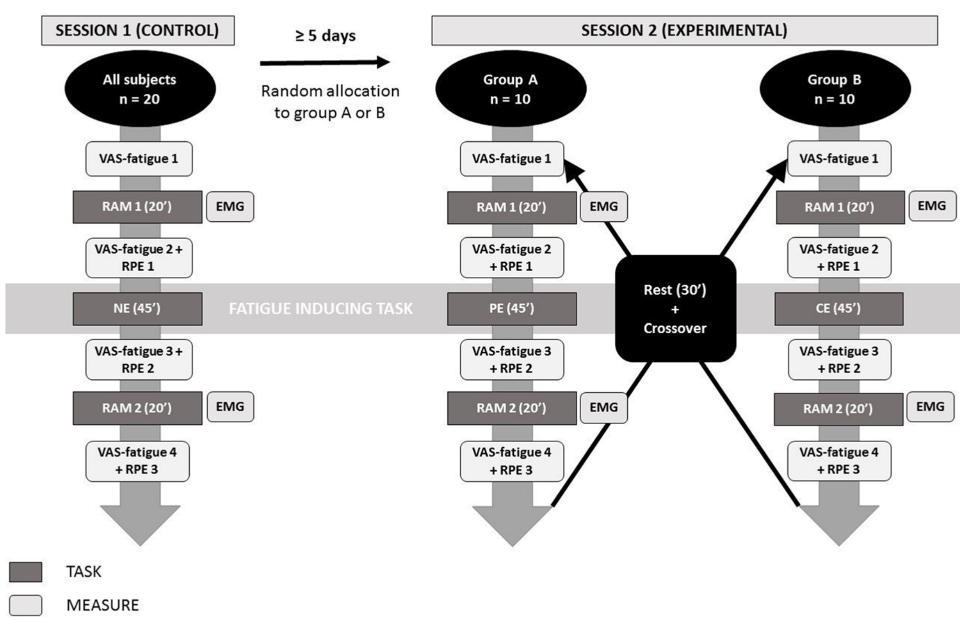

Fig. 1 Flowchart of the study protocol. *CE* cognitive exertion, *n* number of, *NE* no exertion, *PE* physical exertion, *RAM* rapid arm movement task, *RPE* rating of perceived exertion, *VAS-fatigue* visual analogue scale for fatigue

were positioned bilaterally over the Internal Oblique/Transversus Abdominis (IO/TrA) (Stevens et al. 2008), External Oblique (EO) (Ng et al. 1998), Multifidus (MF) (Danneels et al. 2001a, 2002), the Iliocostalis Lumborum pars Thoracis (ILT) (Macintosh and Bogduk 1987), and unilateral over the anterior deltoid (AD) of the dominant arm. EMG signals were analogue bandpass-filtered between 10 and 500 Hz, pre-amplified (CMRR > 100 dB, overall gain 500, noise < 1 µV RMS), and AD-converted (16-bit) at a sampling rate of 1500 Hz.

The EMG signals were recorded during the RAM, which was first described by Hodges et al. (Hodges and Richardson 1997) and is a frequently used, valid and reliable task for assessing APAs of the trunk muscles related to arm movements (Marshall and Murphy 2003). Participants stood barefoot with the feet at shoulder width and the arms hanging relaxed alongside the body (Park et al. 2014). A visual warning cue (white cross) appeared on a screen 2 m in front of the participant, followed in a jittered interval of 1000–1500 ms by a second direction-specific cue (arrow) instructing participants to move their dominant arm to the indicated direction and back to neutral as fast as possible with extended elbow (Jacobs et al. 2009, 2010). One of the two possible direction-specific cues was presented: an upright green arrow indicating shoulder flexion to 90° (Hedayati et al. 2010), or a downward red arrow indicating shoulder extension to 30°. The interval between two consecutive trials was 12 s with the command to relax the trunk muscles and to breathe normally (Marshall and Murphy 2008; Jacobs et al. 2009, 2010; Marshall et al. 2014). A familiarization session with feedback concerning relaxation of the abdominal muscles, performance and velocity of the arm movement was performed at the start of session one and each session was preceded by a training phase. The experimental RAM consisted of 80 trials, i.e. 40 per movement direction presented in a randomized order. Every 5 min a short feedback with regard to maintaining maximal velocity and correct amplitude of the arm movements, and sufficiently relaxing trunk muscles after movement was implemented to ensure optimal task performance. Performance of all the RAM trials took 20 min.

The latencies between the EMG onset of the trunk muscles and that of the AD during the forward arm movement were analysed in Matlab version 9.1 (Mathworks Inc., US). Backward movements were performed to increase unpredictability of the movement direction and were not analysed. The EMG data were cut into segments − 3000 to + 3000 ms around the movement onset that was determined by a light sensor. Information regarding participant, condition, side, trial, and muscle was removed to blind the assessor. Subsequently, the raw, non-rectified, and rectified 30 Hz high-pass filtered signals of each segment were presented to the assessor, with the possibility to zoom in and out. After onset determination of the AD muscle, the assessor visually picked (Hodges and Bui 1996) the onset of the trunk muscles in a time window of − 1500 to + 1500 ms around AD onset, as this technique has been shown to be reliable. Furthermore, a time frame of − 150 to + 400 ms around AD was visually presented with dotted lines to indicate the possible time frame wherein the onset could occur (Fig. 2). All 40 forward arm movement trials per RAM were analysed. Trials were excluded whenever the muscle onset could not be visually determined due to excessive baseline muscle activity, electromagnetic artefacts or interference, ECG signals coinciding with muscle onset, EMG-signal loss, or non-optimal movement execution. Furthermore, onset times occurring more than 100 ms before the prime mover were also excluded, as EMG activity before that time point is unlikely to be related to the RAM. At least five trials without artefacts, but more if possible, per muscle

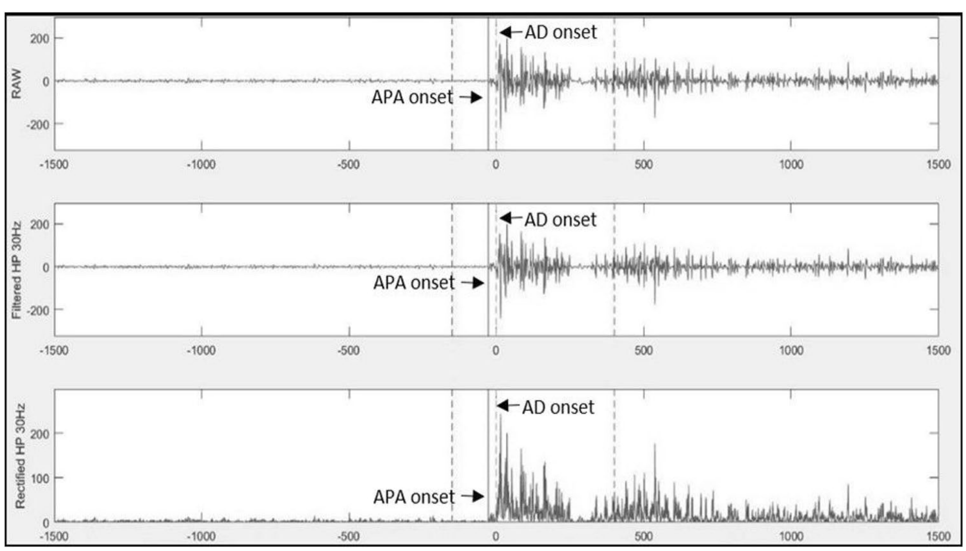

Fig. 2 Example of visual picking an APA onset. *x*-axis indicates time in ms, *y*-axis indicates amplitude in microvolts, *HP* high pass; The visual picked APA onset determination for the trunk muscle that is under analysis is represented by a full line. The time frame for visual picking is indicated by the outermost dotted lines − 150 ms to + 400 ms around the 0-point. The dotted line at time zero represents the onset of the anterior deltoid muscle

were needed for reliable assessment (Marshall and Murphy 2003). Afterwards, an overlay graph with all analysed trials per muscle was controlled for outliers. Trunk APAs of > 100 ms before AD onset were excluded, as they were unlikely to represent RAM-related feedforward activation of the trunk muscles (Strang and Berg 2007).

Secondary outcome measures

The Profile Of Mood State Short Form (POMS-SF) was used to evaluate mood states (Wald 1884; Wald and Mellenbergh 1990). It measures affective disturbances along five dimensions, namely, depression, anger, fatigue, tension, and vigour. Furthermore, a total score can be calculated. Higher scores reflect higher presence of the related moods. The POMS-SF has sufficient consistency, reliability, and a high validity (Wald 1884; de Groot 1992).

The International Physical Activity Questionnaire (IPAQ) estimates physical activity levels based on the reported activities during the last seven days (Booth 2000; The IPAQ Group November 2005). Metabolic equivalents were calculated by multiplying the amount of minutes/week spent on work, transport, household, and leisure tasks, with a factor that represents the strenuousness of the activities. The IPAQ has a fair validity and acceptable reliability (Craig et al. 2003; van Poppel et al. 2004).

The Checklist Individual Strength (CIS) evaluates behavioural aspects related to trait fatigue in the past two weeks (Vercoulen et al. 1999; Enoka and Duchateau 2016). Four fatigue-related aspects are evaluated by the following subscales: subjective fatigue (8–56 score range), concentration (5–35 score range), motivation (4–28 score range), and physical activity (3–21 score range). In addition, a total score reflecting the general amount of fatigue severity can be calculated (20–140 score range). High scores indicated more fatigue and less concentration, motivation, and physical activity. For total fatigue severity, scores of < 27, 27–35, and > 35, respectively, represent low, moderate, and high fatigue rates (Vercoulen et al. 1999). The CIS has an excellent validity and reliability (Vercoulen et al. 1994, 1999).

A visual analogue scale for fatigue (VAS-fatigue) was used to rate state fatigue (Enoka and Duchateau 2016) prior and following each RAM. A VAS is a continuous scale consisting of a 10 cm horizontal line with the left and right outer ends, respectively, labelled as no fatigue at all and worst imaginable fatigue ever.

The rating of perceived exertion (RPE) scale ranging from 6 (very, very light) to 20 (maximal exertion) was used to rate the subjective exertion of the RAM and fatigue-inducing conditions (Borg 1982, 1998; Achttien et al. 2011).

Statistical analysis

Data were analysed using IBM SPSS Statistics 25 (IBM Corp., Armonk, N.Y., USA) with the significance level set at .05. Descriptives were calculated and normality of data distribution was assessed with the Shapiro–Wilk test. As this report is part of a larger study, a priori sample size calculations were based on articles describing the influence of fatigue on feedforward timing of paraspinal muscles (Strang et al. 2009) and describing the influence of fatigue on EMG amplitude and on movement-related cortical potentials (Johnston et al. 2001) (results not included in the current manuscript) and resulted in a minimum of 20 participants to attain a power of 0.80 with significance level .05.

To assess the strenuousness of the fatigue-inducing tasks, RPE ratings were compared between conditions (NE–PE–CE) with a Friedman test and post-hoc Wilcoxon signed-rank tests with Bonferroni correction. Furthermore, VAS-fatigue ratings prior and following to the RAM performances and fatiguing tasks were compared within and between conditions (NE–PE–CE) with a linear mixed model analysis. In this model, VAS fatigue was the dependent outcome, and fixed factors condition (NE–PE–CE), task (RAM1—fatiguing task—RAM2; with RAM1 and RAM2, respectively, representing the RAM performed before and after the fatiguing task), and time to task (pre-task—post-task; i.e. whether the outcome variable was measured prior to or following the examined task), and random intercept on subject level with a variance components covariance type was implemented.

To examine whether fatigue would influence the APAs, and whether the type of fatigue-inducing task would influence the effects, a linear mixed model analysis was performed with the mean onset of the APAs per muscle from each side as the dependent outcome, factors condition (NE–PE–CE) and RAM task (RAM1–RAM2), and random intercept on subject level with a variance components covariance type. These analyses were performed separately for eight muscles, i.e. IO, EO, MF, and ILT of both the ipsilateral and contralateral side in relation to the dominant arm. Furthermore, Cohen's d effect sizes were calculated for each muscle in each condition comparing the difference in APA latencies from RAM1 to RAM2. Cohen's d effect sizes can range from very small (0.10), small (0.20), medium (0.50), and large (0.80) up to huge (2.0) (Cohen 1988).

For all linear mixed models performed in this study, possible confounders were assessed, i.e. age, sex, handedness, BMI, IPAQ total scores, hours of sport/week, hours of sleep/week, VAS sleep quality the night and week preceding testing, hours of sleep the night prior to testing, CIS subscale and total scores, and POMS subscale and total scores. Confounders were retained in the model if they lowered the Akaike's information criterion with minimally 10 points and had a significant influence on the model, which was deemed a significant better model fit. In this regard, for the linear mixed models examining the influence of NE, PE, and CE on the APA onset times of the ipsilateral MF and the ipsilateral ILT muscle, respectively, hours of sleep/week (week before testing) and sex were retained as a significant confounder, whereas for all other models, no significant confounders were retained. Post-hoc comparisons for linear mixed model analyses were always made using Bonferroni corrections.

Results

Participants

Twenty-two participants were recruited. As one participant fainted during data collection and EMG data of another participant was corrupted, the data of 20 participants (11 male, 9 female) were analysed. Participants had a mean age of 22.3 years (SD 1.23), mean height of 174.5 cm (SD 8.37), and mean weight of 66 kg (SD 10.37). Ninety percent of participants were right-hand dominant. Furthermore, mean hours of sport performance per week and mean hours of sleep per night were, respectively, 3.5 h (SD 2.95) and 7.6 h (SD 0.76). The mean endurance time for the modified Biering–Sörensen and abdominal Endurance task was, respectively, 121.2 s (SD 49.40) and 340.8 s (SD 368.10).

Fatigue induction

Median RPE scores for the NE, PE, and CE conditions were, respectively, 6.5 (range 6–12), 16.0 (range 11–18), and 12.0 (range 7–16). Thus, NE was generally considered to induce no exertion, PE was considered as a very high exertion, and CE as somewhat high. There were significant between condition differences in RPE scores ($\chi^2(2) = 32.141$, $p < 0.001$). The NE condition was less exerting than the PE ($Z = -1.861$, $p < 0.01$) and CE ($Z = -1.139$, $p < 0.01$) condition, whereas no significant differences were found between PE and CE ($Z = 0.722$, $p = 0.91$).

The VAS-fatigue mixed model analysis showed a significant three-way interaction of condition × task × time to task [$F(4;322.011) = 4.666$, $p = 0.001$]. Post-hoc analyses revealed that before RAM1 and prior to the fatigue-inducing conditions, VAS-fatigue did not significantly differ between conditions, nor did RAM1 influence VAS-fatigue significantly. Thus, participants commenced these experiments with similar levels of fatigue. Immediately after performing the fatiguing task, VAS-fatigue ratings were significantly increased in response to PE ($p = 0.044$), but not in response to NE ($p = 0.095$) or CE ($p = 0.156$). VAS-fatigue ratings in response to RAM2, after the fatiguing task, were significantly higher than those prior to that RAM in the NE ($p = 0.026$) and PE ($p = 0.049$) conditions.

Effects of PE and CE on APA onset latencies

For none of the examined muscles, a significant condition × time interaction was found, i.e. IO/TrA [ipsilateral: $F(2;63.776) = 0.324$, $p = 0.725$; contralateral: $F(2;36.671) = 0.770$, $p = 0.470$], EO [ipsilateral: $F(2;77.632) = 2.490$, $p = 0.090$; contralateral: $F(2;74.428) = 0.110$, $p = 0.896$], MF [ipsilateral: $F(2;29.183) = 0.290$, $p = 0.750$; contralateral: $F(2;33.433) = 1.106$, $p = 0.343$], and the ILT [ipsilateral: $F(2;70.350) = 0.643$, $p = 0.529$; contralateral: $F(2;92.968) = 0.044$, $p = 0.957$].

However, a main effect of condition was found for the ipsilateral ILT muscle, with later APAs in the CE compared to the PE condition (+ 7.6 ms, SE 2.82 ms, $p = 0.027$).

Estimated mean APA onset times and effect sizes of these analyses are depicted in Table 1.

Discussion

This study found no effects of PE and CE on mean APA onset latencies of the trunk muscles during RAM in healthy people.

As the current study did not find evidence that PE influences the mean APAs of trunk muscles, it does not fully support previous findings of a pilot study (Allison and Henry 2002) which on the one hand also found no effect on APAs of the IO/TrA, but on the other hand indicated earlier APAs of the EO following a fatiguing isometric trunk extensor task. However, the latter study was only performed on a sample of four participants.

Importantly, this is the first study that examined effects on the MF with surface EMG. However, as depicted in Table 1. Rather low effective sample sizes for this muscle were attained, as high baseline activity of the MF and possibly cross-talk of more superficial muscles in several participants often made it impossible to detect a clear onset. Hence, future studies are necessary to confirm that the MF mean APAs are not affected by PE. Especially, because the MF has a primordial role in segmental control and trunk stabilisation (Panjabi 1992; Goel et al. 1993; Kaigle et al. 1995; Danneels et al. 2001b). As APAs of the deep, but not the superficial, parts of the MF are often delayed in low back pain patients (MacDonald et al. 2009), and fatigue complaints have also been described in this population (Feuerstein et al. 1987; Perry et al. 2016), further research regarding the fatigability of the MF and whether it affects APAs could be interesting from a clinical point of view. It would be advisable for future studies to use fine-wire EMG, which specifically allows to

Table 1 Estimated means of APA onset latencies

Muscle	Condition	Task	EM (ms)	SD (ms)	*N*	Difference RAM1-2 (ms)	*P* value	ES
IO/TrAi	NE	RAM 1	1.3	17.84	14	0.2	0.952	0.011
		RAM 2	1.5	18.24	15			
	PE	RAM 1	2.8	19.11	17	3.3	0.308	0.186
		RAM 2	− 0.5	16.89	12			
	CE	RAM 1	5.1	18.29	15	2.4	0.459	0.132
		RAM 2	2.7	17.84	14			
IO/TrAc	NE	RAM 1	− 26.8	19.95	6	6.8	0.234	0.300
		RAM 2	− 20.0	23.92	10			
	PE	RAM 1	− 23.4	24.77	11	1.3	0.797	0.055
		RAM 2	− 22.1	22.03	8			
	CE	RAM 1	− 16.2	22.96	9	2.7	0.609	0.115
		RAM 2	− 18.9	23.81	10			
EOi	NE	RAM 1	− 7.0	26.46	16	7.2	0.100	0.266
		RAM 2	0.2	27.61	18			
	PE	RAM 1	− 5.4	28.18	19	2.0	0.643	0.072
		RAM 2	− 3.4	26.47	16			
	CE	RAM 1	0.9	26.44	16	6.4	0.141	0.239
		RAM 2	− 5.5	27.62	18			
EOc	NE	RAM 1	− 14.2	22.67	15	0.4	0.930	0.017
		RAM 2	− 13.8	24.03	18			
	PE	RAM 1	− 17.9	24.03	18	1.9	0.687	0.082
		RAM 2	− 19.8	21.70	13			
	CE	RAM 1	− 14.2	23.11	16	1.0	0.814	0.044
		RAM 2	− 13.2	23.99	18			
MFi	NE	RAM 1	− 24.7	18.02	9	4.6	0.298	0.261
		RAM 2	− 20.1	17.36	8			
	PE	RAM 1	− 20.5	17.36	8	0.7	0.868	0.044
		RAM 2	− 19.8	17.31	8			
	CE	RAM 1	− 24.1	15.82	6	5.8	0.316	0.365
		RAM 2	− 18.3	15.83	6			
MFc	NE	RAM 1	− 20.8	16.51	10	5.5	0.112	0.347
		RAM 2	− 15.3	15.21	8			
	PE	RAM 1	− 18.3	17.19	11	6.2	0.099	0.384
		RAM 2	− 12.1	13.73	6			
	CE	RAM 1	− 16.5	14.53	7	0.6	0.865	0.037
		RAM 2	− 17.1	16.59	10			
ILTi	NE	RAM 1	.5	16.46	17	1.5	0.704	0.087
		RAM 2	− 1.0	16.49	17			
	PE	RAM 1	− 6.2	4.15	15	3.6	0.367	0.227
		RAM 2	− 2.6	4.22	14			
	CE	RAM 1	4.4	4.07	16	2.4	0.548	0.149
		RAM 2	2.0	4.22	14			
ILTc	NE	RAM 1	− 15.7	17.84	19	0.4	0.876	0.020
		RAM 2	− 15.3	18.21	20			
	PE	RAM 1	− 15.1	18.21	20	0.1	0.990	0.001
		RAM 2	− 15.2	18.21	20			
	CE	RAM 1	− 15.5	18.21	20	0.6	0.792	0.033
		RAM 2	− 16.1	17.84	19			

c contralateral, *CE* cognitive exertion, *EM* estimated mean, *EO* external oblique, *ES* effect size (Cohen's *d*), *i* ipsilateral, *ILT* Iliocostalis Lumborum pars Thoracis, *IO/TrA* Internal Oblique/Abdominal Transverse, *N* sample number, *NE* no exertion, *PE* physical exertion, *RAM* rapid arm movement task, *SD* standard deviation, *MF* Multifidus study the superficial and deep fibres of the MF. Furthermore, this technique could diminish drop-out based on cross-talk.

The previous studies have described earlier APAs for the Erector Spinae muscles following PE (Strang and Berg 2007; Strang et al. 2008, 2009; Monjo and Forestier 2015), which is not in line with the non-significant findings for the ILT in the current study. However, there were important methodological differences between these studies and the current study, making comparability difficult. For instance, other PE tasks [i.e. concentric dead-lifts (Strang and Berg 2007), aerobe exertion (Strang et al. 2008), isokinetic lower limb exercises (Strang et al. 2009), or electrically induced fatigue of the AD (Monjo and Forestier 2015)], and other types of APA-eliciting movement tasks [i.e. bilateral reach (Strang and Berg 2007; Strang et al. 2008, 2009) or loaded arm movements (Monjo and Forestier 2015)] were performed. Furthermore, none of these studies exerted both the abdominal and paravertebral muscles.

This was also the first study to examine effects of fatigue induced by CE on APAs of the trunk muscles, and analogue to the PE results no effects were found. Similarly, the previous research in knee muscles also found unaltered neuromuscular function after CE (Pageaux et al. 2013).

In conclusion, based on the current study no indications for altered APAs due to fatigue, either induced by PE or CE, were found. In contrast, previous research did find reduced endurance times of physical tasks after CE (Marcora et al. 2009; Pageaux et al. 2013), which could indicate that CE can indeed affect movement performance, even though APAs are unaffected. Therefore, it is hypothesized that the influence of CE on movement performance is not through physiological adaptions in motor control, but rather by reduced motivation induced by CE (Pageaux et al. 2015; Muller and Apps 2018). A similar hypothesis can be made for fatigue induced by PE as diminished movement performance was also described after PE in the past (Enoka and Stuart 1992; Gandevia 2001; Morrison et al. 2005). While in the current study, effects of PE and CE on feedforward activation of the trunk muscles were studied, which is one of the mechanisms of the motor control system, and no effects were found, this does not exclude the possibility that fatigue might influence other mechanisms which contribute to trunk motor control. For instance, amplitude properties or variability of APAs could be examined in the future to examine whether these are altered after PE and CE.

Two manipulation checks were examined before addressing the main research questions. First, it was ascertained whether the fatigue-inducing condition indeed had a sufficient fatiguing effect. Based on the previous literature, the tasks chosen to induce PE (Coorevits et al. 2008; Morris and Allison 2011) and CE (Pageaux et al. 2015) were valid for this purpose. Furthermore, in the current study, the participants considered these tasks as heavily exerting, whereas the NE condition was considered not exerting. Self-reported state fatigue increased following both PE and CE, but the difference was only significant for PE. Even though self-reports are the only measures considered to be able to really assess fatigue (Enoka and Duchateau 2016), other measures such as EMG median frequency (Sparto et al. 1999; Allison and Henry 2001; Coorevits et al. 2008; Morris and Allison 2011) or wavelet analysis (Bartuzi and Roman-Liu 2014) could be valuable in future research to objectify the performance fatigability of the PE used to induce fatigue. Furthermore, even though no participants in this study reported pain as a main reason for discontinuation of the PE tasks, pain was not explicitly assessed in this study. This is recommended for future research as pain and effort might confound the fatigue effects of these tasks. In addition, analysis of Stroop scores could be useful as well to obtain more objective assessment of CE. Although these analyses were not possible in the current study, they are recommended for future studies. In this study, the duration of the fatigue-inducing tasks was standardized to 45 min to neutralize differences due to time between conditions. Based on the previous studies, the performance of the PE until exhaustion would last 3–5 min on average (Van Damme et al. 2014). Therefore, the PE was commenced after 40 min of rest and was performed until exhaustion, whereas the CE had a fixed duration of 45 min. The fatigue experience is dependent on the cost–benefit balance of the exertion (Boksem and Tops 2008). The costs for a PE until exhaustion possibly weighed more than that of the 45-min CE task. This might explain why self-reported state fatigue after the CE task was not increased to the same extent as following the PE task.

Second, although APAs are consistent patterns that should be present in healthy adults, there is often an acquisition phase for the specific task used to evoke APAs. This might lead to differences in mean APA onsets between subsequent RAM performances (Liu et al. 2015). However, the current study showed that repeated performance of the RAM without exertion in-between (NE condition) did not alter the means of APAs of the trunk muscles, because sufficient practice trials were performed beforehand to counter these possible acquisition effects. This implies that APAs can be assessed multiple times during one session while remaining consistent.

An important consideration of these results is the decrease in the effective sample remaining for statistical analysis after visual picking, mainly regarding the bilateral MF and the contralateral IO/TrA APAs. Due to high baseline activity in these muscles, the required minimum of five trials with a clear onset detection to attain a reliable APA measure was often not acquired during visual picking, explaining these diminished samples. This highlights an important challenge for future research in this matter to further look for ways to diminish baseline activity in these muscles during RAM to avoid losing trials for analysis. Especially, since effect sizes of APA differences due to fatigue in the current study were small, which already indicates that for future research, larger samples should be included. However, this could not be anticipated, as the included sample in this study amply met the required a priori sample size calculations. Furthermore, a high between-trial variability in APAs is often reported (Hodges and Richardson 1998; Hedayati et al. 2010; Boucher et al. 2018) and might explain the considerably large standard deviations seen in this data. As only healthy, young adults were examined in this study, to rule out ageing effects, the findings might not be generalizable to older or clinical populations, which might have less recuperation after fatigue. For future research, it would be interesting to examine fatigue in other populations to see whether the results of this study are generalizable. Older adults, for example, or people with (chronic) pain complaints are thought to have less recuperation capacity after fatigue than a healthy, young adult group. Furthermore, exploration of the influence of fatigue on the brain and central factors related to movement preparation might be valuable for future research as well.

Conclusion

This was the first study conducting an integrative analysis and comparison of fatigue induced by both PE and CE on the APAs of multiple trunk muscles which have an important role in trunk motor control. As no fatigue effects were found, it is hypothesized that the influence of fatigue on impaired movement performance might not be through physiological adaptions in motor control, but rather by reduced motivation. However, even though the PE and CE tasks used here were deemed valid for inducing fatigue, effect sizes of these results were small and thus need further confirmation. Furthermore, future research is recommended to examine amplitude properties and variability of APAs, as well as studying other populations such as older adults or (chronic) pain sufferers in relation to PE and CE.

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Compliance with ethical standards

Ethical approval All procedures performed in this study were in accordance with the ethical standards of the institutional research committee (University Hospital Ghent/Ghent University) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent All participants provided signed informed consent.

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