The influence of task design on upper limb muscles fatigue during low-load repetitive work: A systematic review

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Abstract

Ergonomic interventions such as increased scheduled breaks or job rotation have been proposed to reduce upper limb muscle fatigue in repetitive low-load work. This review was performed to summarize and analyze the studies investigating the effect of job rotation and work-rest schemes, as well as, work pace, cycle time and duty cycle, on upper limb muscle fatigue. The effects of these work organization factors on subjective fatigue or discomfort were also analyzed. This review was based on relevant articles published in PubMed, Scopus and Web of Science. The studies included in this review were performed in humans and assessed muscle fatigue in upper limbs. 14 articles were included in the systematic review. Few studies were performed in a real work environment and the most common methods used to assess muscle fatigue were surface electromyography (EMG). No consistent results were found related to the effects of job rotation on muscle activity and subjective measurements of fatigue. Rest breaks had some positive effects, particularly in perceived discomfort. The increase in work pace reveals a higher muscular load in specific muscles. The duration of experiments and characteristics of participants appear to be the factors that most have influenced the results. Future research should be focused on the improvement of the experimental protocols and instrumentation, in order to the outcomes represent adequately the actual working conditions.

Relevance to industry

Introducing more physical workload variation in low-load repetitive work is considered an effective ergonomic intervention against muscle fatigue and musculoskeletal disorders in industry. Results will be useful to identify the need of future research, which will eventually lead to the adoption of best industrial work practices according to the workers capabilities.

Keywords

Fatigue; Repetitive work; Low-load work; Upper limbs

1. Introduction

Muscle fatigue is a complex phenomenon that has been suggested to be an important precursor for work-related upper-limb musculoskeletal disorders (Ding et al., 2000, Nussbaum et al., 2001 and Lomond and Cote, 2011). Several authors have reported that repetitive manual work is a risk factor associated with wrist and hand disorders, such as tendon-related disorders, carpal tunnel syndrome (CTS) and cramping of the hand and forearm (Muggleton et al., 1999, Viikari-Juntura and Silverstein, 1999 and Hansson et al., 2000). According to Thomsen et al. (2002), an increase duration of repetitive non-forceful work results in an increased risk of CTS. The effects of fatigue on functional capacity include reductions in maximal isometric force and power output (Vollestad, 1997, Blangsted et al., 2005, Enoka and Duchateau, 2008 and Fuller et al., 2009). Muscle fatigue can occur as a result of alterations in the central nervous system and/or neuromuscular junction (central fatigue) or in the muscle fiber (peripheral fatigue) (Willliams and Ratel, 2009). These mechanisms are dependent on the intensity, duration, the predominantly recruited muscle fiber type and type of contraction, as well as individual capacity and environmental conditions (McLean et al., 2000).

In the industrial environment, it is essential to reduce the occurrence of muscle fatigue because it has a great impact on task performance. Thus, the major challenge for ergonomics is to design the work in order to prevent work-musculoskeletal disorders (WMSD) and with no negative impact on production quality and productivity (Wells et al., 2007). At present, repetitiveness and monotonous work are common in industries with automated work processes. According to Eurofound (2010), more than 60% of workers currently report performing repetitive hand or arm movements at work. Assembly tasks are an example of work where the procedures are strictly standardized with short cycle times (less than 30 s), little task variation and reduced breaks or pauses. Furthermore, there is some evidence that upper limb WMSD risk factors are related to characteristics of the assembly task (van der Windt et al., 2000).

Despite numerous studies suggesting that muscle fatigue can be developed during highly repetitive low-load tasks (<20% maximal voluntary contraction (MVC)), there are several gaps in knowledge concerning the influence of task design, which includes work organization factors such as work duration (hours of work and shift work), duty cycle, cycle time, work pace and job rotation, on fatigue and musculoskeletal health. Changes in temporal organization of work (e.g. change in cycle time) or implementation of job rotation in workplaces may increase physical workload variation and has been proposed to minimize injury

risk and fatigue in jobs with repetitive tasks (Fallentin et al., 2001, Aptel et al., 2008 and Wells et al., 2010).
Thus, it is very important to study the risk factors associated with task design on the development of disorders in the wrists and hands in highly repetitive hand–arm work.

The purpose of this article is to review the scientific literature concerning the influence of the task design (related to temporal organization of work and job rotation) on muscle fatigue in low-load work development in workplaces or experimental settings.

2. Methods

2.1. Search strategy

The systematic search was focused on literature pertaining to the effect of task design on the development of muscle fatigue in upper limbs in workplaces or experimental settings (simulated occupational tasks). The search strategy consisted of a comprehensive search that could locate the widest spectrum of articles for consideration and was performed in selected electronic databases, namely: PubMed, Scopus and Web of Science, from the earliest date available in the database to 31st December 2013. Based on the electronic database used, the search terms were as follows: “muscle fatigue” combined with another term such as “upper limbs”, “forearm muscles”, “workload”, “work-related musculoskeletal disorders”, “repetitive movements”, “repetitive work”, “assembly work”, “low-force work”, “low-intensity work”, “low-load work“, “work cycle time”, “wrist”, “work rest pattern”, “rest breaks”, “work duration”, “work pace”, “job rotation” and “task design”. The Appendix A describe the search strategies in each database.

2.2. Screening criteria

Articles obtained by the systematic search were exported to EndNote library X4 (Thomson corporation) and duplicates were removed. Exclusion of irrelevant articles was performed using a three-step systematic approach: 1) titles were examined for relevance; 2) abstracts were then considered (in particular, objectives and methods); and 3) the full text article was retrieved and considered. If there was any uncertainty about content or if a title and abstract did not provide sufficient information to determine whether the inclusion/selection criteria were met, then the article proceeded to the next step.

Studies were automatically excluded if one of these conditions were met: 1) studies not published in peer-reviewed journals written in English 2) studies reviewing literature; 3) studies where the intensity of the workload (maximal EMG activity) was higher than 30% MVC; 4) studies that did not apply an objective measuring method to assess the development of fatigue over time; 5) studies comparing different tools to assess muscle fatigue; 6) studies defining muscle fatigue models and/or acceptable limits; 7) studies assessing neuromuscular responses; and 8) studies investigating muscle fatigue caused by torque reaction forces.

2.3. Eligibility criteria

Studies were included in the review if the following conditions were met: (1) those that considered the development of muscle fatigue in upper limbs (including the forearm, arm and shoulder muscles) during repetitive low-load work; (3) those that only investigated the effect of temporal organization of work and job rotation schemes on upper limb muscle fatigue; and (4) those that assessed muscle fatigue in occupational activities performed in real work conditions and/or simulated occupational tasks. Two reviewers evaluated the eligibility of all articles, and disagreements were resolved by consulting a third reviewer.

2.4. Data extraction and risk of bias assessment

From the studies selected after eligibility, the following data (when available) were extracted: size (N) and characteristics of the sample (gender and age), muscle group under study, type of tasks, experimental conditions, methods and/or techniques used to assess fatigue, study design, main outcomes for objective and subjective measure of fatigue and statistical analysis. Data from each study were extracted by one of the reviewers and confirmed by the other. The information obtained from the included studies was organized descriptively in tables.

A quality assessment list was constructed using criteria from Greenhalgh et al. (2005) and from Von Elm et al. (2008), which were adapted to the specific aim of this review. To judge quality, information regarding participant's source (eligibility criteria), definition of variables and their methods of measurement/assessment, description of efforts to address potential sources of bias, outcome data, limitations and generalizability of each study, was collected. For all of these items, specific criteria assessment were defined (details are given in Appendix B). Two reviewers independently assessed the quality of each study by scoring each criteria as positive (+), negative (−), or unclear (?). Disagreements were resolved by consensus. The quality score for every study was calculated by summing the number of positive criteria.

3. Results and discussion

The search strategy identified a total of 1748 citations before duplicates removal. After confirming the duplicates (n = 779) and excluding the non-relevant ones (n = 895), 74 full-text articles were analyzed. After application of the eligibility criteria while considering the full text, another 60 articles were excluded. A total of 14 experimental studies conducted in the laboratory or in the field were considered for the final analysis. Fig. 1 displays the flowchart of the search strategy.

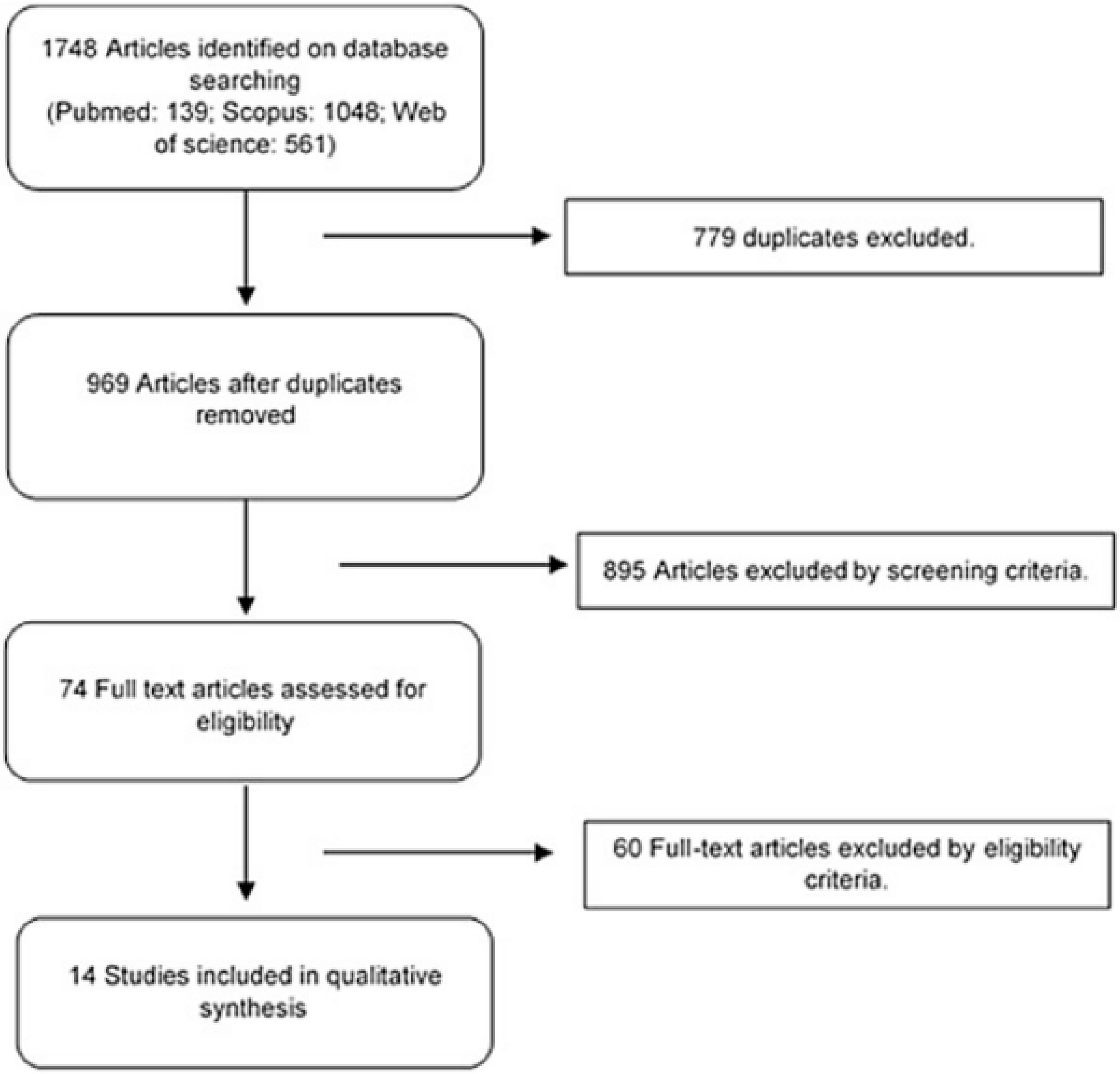

Fig. 1.
Article screening process.

The 14 articles included a total of 246 participants, of which 45.1% were females. Our search identified 12 studies on tasks that were simulated in the laboratory (Horton et al., 2012, Gooyers and Stevenson, 2012, Bosch et al., 2011, Keir et al., 2011, Wells et al., 2010, Raina and Dickerson, 2009, Iridiastadi and Nussbaum, 2006, Balci and Aghazadeh, 2004, Gerard et al., 2002, McLean et al., 2001, Mathiassen and Winkel, 1996 and Sundelin, 1993) and 2 studies on real-life occupational settings (Bosch et al., 2007 and Christensen et al., 2000). In general, the laboratory studies had small-sized sample groups.

The task characteristics included job rotation in 4 studies (Horton et al., 2012, Gooyers and Stevenson, 2012, Keir et al., 2011, Wells et al., 2010 and Raina and Dickerson, 2009) work-rest schemes (or pauses or breaks) schedules in 4 studies (Balci and Aghazadeh, 2004, McLean et al., 2001, Christensen et al., 2000 and Sundelin, 1993) and 6 studies investigating the effects of work pace, cycle time, duty cycle and work duration (Gooyers and Stevenson, 2012, Bosch et al., 2011, Bosch et al., 2007, Iridiastadi and Nussbaum, 2006, Gerard et al., 2002 and Mathiassen and Winkel, 1996). Only one study did not use electromyography (EMG) as an objective measuring method to assess the development of fatigue (Wells et al., 2010). All tasks included in this review were considered to be repetitive work categorized in dynamic (e.g., assembly work) or intermittent static work (e.g. handgrip exercise) (Kilbom, 1994). Forearm muscles were studied in eight articles.

The resulting 14 articles are presented in Table 1 (effects of job rotation), Table 2 (effects of work/rest schemes) and Table 3 (effects of work pace, cycle time and duty cycle). In each article analyzed, the experimental conditions were identified with a “C” letter and followed by a number. Regarding the main outcomes of the parameters for each experimental condition they are presented in descending order (e.g., C2 > C1 > C3).

Table 1
Overview of results of "effects of rotation".

Reference	Sample	Muscle group	Task	Conditions	Fatigue measure	Response variables and main outcomes	
						Objective Fatigue	Subjective fatigue
Horton et al. (2012)	General population $N = 12$ (6M, age: 22.5 ± 1.9 years). (6F, age: 23.0 ± 1.97 years).	Middle deltoid muscle	Repetitive static shoulder abduction tasks (60 min).	**Two exertion levels:** 15% MVC – "L" lower exertion task. 30% MVC – "H" higher exertion task. C1: No rotation LLLL C2: No rotation HHHH C3: One rotation LH C4: One rotation HL C5: Three rotation LHLH C6: Three rotation HLHL	EMG RPD	**EMG amplitude (% RVE):** C3–C6 > C1 ($p < 0.001$) C2 > C3–C6 ($p < 0.001$) C2 > C1 ($p < 0.001$) C3 > C4 ($p = 0.39$) C5 = C6 ($p = 0.88$) **EMG MPF (%RVE):** C1 > C3–C6 ($p < 0.001$) C3–C6 > C2 (n.d) C1 > C2 (*n.d*) C3 = C4 (*n.d*) C5 > C6 (*n.d*) **DSI (%RVE):** C3–C6 > C1 ($p < 0.001$) C2 > C3–C6 ($p < 0.001$) C2 > C1 ($p = 0.0005$) C3 > C4 ($p = 0.25$) C6 > C5 ($p = 0.096$)	**Mean RPD:** C3–C6 > C1 ($p = 0.0038$) (shoulder) C3–C6 > C1 ($p = 0.038$) (upper arm) C2 > C3–C6 ($p = 0.001$) (shoulder) C2 > C3–C6 ($p = 0.0006$) (upper arm) C2 > C1 ($p < 0.0001$) (shoulder) C2 > C1 ($p < 0.0001$) (upper arm) C3 > C4 ($p = 0.82$) (shoulder) C3 < C4 ($p = 0.39$) (upper arm) C6 > C5 ($p = 0.091$) (shoulder) C6 > C5 < ($p = 0.076$) (upper arm) **Peak RPD:** C3–C6 > C1 ($p < 0.0001$) (shoulder) C3–C6 > C1 ($p = 0.0003$) (upper arm) C2 > C3–C6 ($p = 0.007$) (shoulder) C2 > C3–C6 ($p = 0.0004$) (upper arm) C2 > C1 ($p < 0.0001$) (shoulder) C2 > C1 ($p < 0.0001$) (upper arm) C4 > C3 ($p = 0.54$) (shoulder) C4 > C3 ($p = 0.34$) (upper arm) C5 > C6 ($p = 0.56$) (shoulder) C6 > C5 < ($p = 0.51$) (upper arm)
Keir et al. (2011)	University population $N = 10$ (10M, age: 21.8 ± 2.2 years)	Upper erector spinae (UE); lower erector *spinae* (LE); trapezius (TR); anterior deltoid (AD); extensor *carpi radialis* (ECR); flexor *carpi radialis* (FCR); flexor *digitorum superficialis* (FDS) and extensor *digitorum communis* (ED).	Lifting/Lowering task (L) – 12 kg box (handles 0.50 m apart), at a rate 6 per minute, 10 s cycle (5 s for task with 5 s for rest); gripping task (G) at 20%, at a rate 6 per minute, 10 s cycle (5 s for task with 5 s for rest).	C1: No rotation: LL (30 min) C2: No rotation: GG (30 min) C3: Rotation: L (15 min) and G (15 min) C4: Rotation: G (15 min) and L (15 min)	EMG RPE	**EMG APDF10th%:** C2 (ECR) > C1 (ECR) and C3 (ECR) ($p = 0.011$) C2 (ED) > C1 (ED) and C3 (ED) ($p = 0.001$) **EMG APDF50th%:** C2 (ECR) > C1 (ECR) and C3 (ECR) ($p = 0.030$) C2 (ED) > C1 (ED) and C3 (ED) ($p = 0.030$) C2 (FDS) > C1 (FDS) and C3 (FDS) ($p = 0.030$) C1(ECR) > C4 (ECR) ($p = 0.030$) C1(ED) > C4 (ED) ($p = 0.030$) **EMG APDF90th%:** C1, C3 and C4 > C2	**RPE:** C1 > C2 (n.s.) C3 > C4 (n.s)

Table 1 (*continued*)

Reference	Sample	Muscle group	Task	Conditions	Fatigue measure	Response variables and main outcomes	
						Objective Fatigue	Subjective fatigue
						(ED) ($p = 0.028$) C1, C3 and C4 > C2 (FCR) ($p = 0.028$) **EMG gaps:** C1 and C3 > C4 > C2 (ED) (n.s.) C1 > C3 > C4 > C2 (ECR) (n.s.) C3 > C4 > C1 > C2 (FDS) (n.s.) C3 > C1 > C4 > C2 (FCR) (n.s.)	
Wells et al. (2010)	University population $N = 25$ (age: 20–34 years)	Forearm muscles	**Three handgrips:** power grip (PG); two finger pulp pinch (PP); lateral pinch (LP) at 30% MVC during 55 s each, followed by a 5 s maximum test task. (sequence: first work task → first test task → second work task → second test task)	**15 combinations (2 min duration):** C1. PG, PG, PG, PG C2. PP, PG, PG, PG C3. LP, PG, PG, PG C4. PG, PG, PP, PG C5. PG, PG, LP, PG C6. PP, PP, PP, PP C7. LP, PP, PP, PP C8. PG, PP, PP, PP C9. PP, PP, LP, PP C10. PP, PP, PG, PP C11. LP, LP, LP, LP C12. PP, LP, LP, LP C13. PG, LP, LP, LP C14. LP, LP, PG, LP C15. LP, LP, PG, LP	Hand grip dynamometer	**Grip strength:** C3, C4, C5, C9, C10 and C15 > C1, C6 and C11 ($p < 0.05$) **Functional similarity (%):** PG/PP = 75.7 PG/LP = 33.5 LP/PP = 66.3	n.a.
Raina and Dickerson (2009)	University population $N = 10$ (6 M and 4 F, age: 25.7 ± 5.4 years)	Anterior deltoid muscle (AD), middle deltoid muscle (MD) and posterior deltoid muscle (PD)	Two repetitive, unilateral (right side), unloaded arm movements, repeated at a frequency of 0.5 Hz. **Task combinations:** a forward shoulder flexion movement in the sagittal plane (A) and a shoulder abduction movement in the frontal plane (B).	C1: 4 continuous minutes of task A (forward flexion) - AA. C2: 2 min of task A (forward flexion), followed by 2 min of task B (abduction in the frontal plane) - AB. C3: 2 min of task B (abduction in the frontal plane), followed by 2 min of task A (forward flexion) – BA. C4: 4 min of task B (abduction in the frontal plane) - BB.	EMG Force cube RPE	**Adjusted means of mEMG (%MVC):** C3 > C4 (AD) (n.s.) C4 > C3 = C2 > C1 (MD) (n.s.) C4 > C3 > C2 > C1 (PD) ($p < 0.05$) **iEMG (%MVC):** AD: n.s. between conditions C4 > C1–C3(MD) ($p = 0.001$) C4 > C1–C3 (PD) ($p = 0.001$) **EMG MPF:** C2 > C4 (AD) ($p < 0.05$) C2 > C4 (PD) ($p < 0.05$) **Maximum elevation force (MVF):** n.s between conditions	**RPE:** C4 = C3 > C2 = C1 ($p < 0.0003$)

Abbreviations: M, male; F, female; s, seconds; MVC, maximum voluntary contraction; RVE, sub-maximal reference contraction; MPF, mean power frequency; DSI, Dimitrov spectral index; RPD, rating of perceived discomfort; APDF, amplitude probability distribution function; RPE, rating of perceived exertion; iEMG, integrated amplitude; mEMG, windowed amplitude; n.a., not applicable; n.d., not defined; n.s., not significant.

Table 2
Overview of results of "effects of work breaks".

Reference	Sample	Muscle group	Task	Conditions	Fatigue measure	Response variables and main outcomes	
						Objective fatigue	Subjective fatigue
Balci and Aghazadeh (2004)	Students $N = 10$ (10M)	Right upper trapezius (UT) and right arm flexor *carpi radialis* (FCR).	Video display terminal (VDT) work	C1:15 min.work/ microbreaks – cognitive task C2: 30 min.work./ 5 min.rest – cognitive task C3: 60 min work/ 10 min rest – cognitive task C4:15 min.work/ microbreaks – data entry task C5: 30 min.work./ 5 min.rest – data entry task C6: 60 min work/ 10 min rest – data entry task	EMG Speed Accuracy RPD	**Performance (speed and accuracy):** C1 and C4 > C3 and C6 (n.d) **Muscular Load:** C6 > C5 > C4 (UT) (n.d.) C3 > C1 > C2 (UT) (n.d.) C3 > C1 > C2 (FCR) (n.d.)	**RPD:** C6 > C1–C5 for upper extremities (n.d.)
McLean et al. (2001)	Office workers $N = 15$ (15F, age: 23–50 years)	Cervical paraspinal extensors (CPE), lumbar erector spinae (LES), upper trapezius(UT) and wrist extensors (WE)	Computer terminal work (4 weeks)	C1: "No break protocol" C2: "Microbreak protocol" – microbreaks at their own discretion (control) C3: "Microbreak protocol" – microbreaks at 20 min intervals C4: "Microbreak protocol" – microbreaks at 40 min intervals	MES activity VAS score (discomfort) Productivity	**Mean of MNF cycles:** UT: no protocol effect C3 > C1 (WE) (n.d.) C2 and C4 > C3 (WE) (n.d.) **Productivity (number of words typed):** C1 > C2 (n.s.) n.s. effect of C3 and C4	**VAS score:** n.s. between C1 and C2–C4 (shoulder) C1, C2, C4 > C3 (forearm) (n.d.)
Christensen et al. (2000)	Meat cutters $N = 48$ (48M, age: 33.7 years)	Extensor *carpi radialis* muscle; flexor *carpi radialis* muscle	**Three work tasks:** Deboning belly pork – 59.6 s; Deboning shoulders – 111.0 s; Deboning ham – 133.0 s.	C1: "Fast" group (6 M) 68.4–85.5% of the mean of work time (higher rest periods). C2: "Slow" group (6M) 121.0–138.9% of the mean of work time (lowest rest periods).	Heart rate (HR) Blood pressure Hand dynamometer EMG	**HR:** n.s. between C1 and C2 **Blood pressure:** n.s. between C1 and C2 **Muscular load (Maximal EMG activity %):** n.s. between C1 and C2 **EMG RMS:** n.s. between C1 and C2 **EMG MPF:** n.s. between C1 and C2 **EMG power spectrum:** n.s. between C1 and C2 **EMG APDF:** n.s. between C1 and C2	n.a.
Sundelin (1993)	Students $N = 12$ (12F, age: 25.5 ± 4.14 years)	Cervical portion of the descending trapezius muscle (TC), lateral portion of the descending trapezius muscle (TL), *infraspinatus* muscle (IS)	Grasping a small cylinder with the right hand, releasing it through a hole in the table; Subject was seated with 90° of flexion in the hips and in the knees; work pace: MTM-132. 41 work cycle per minute with a cycle time of 1.22s	**Repetitive work was performed:** C1: without pauses during 60 min and; C2: with 1 min of pause every sixth min. – 50 min of work and 10 min of pause.	EMG RPE	**EMG MPF:** C1 (TL): decrease (8 subjects) (n.d.) C2 (TL): decrease (8 subjects) (n.d.) C1 (TC): decrease (8 subjects) (n.d.) C2 (TC): decrease (3 subjects) (n.d.) C1 (IS): decrease (3 subjects) (n.d.) C2 (IS): none subjects (n.d.) **EMG RMS:** C1 (TL): increase (8 subjects) (n.d.) C2 (TL): increase (8 subjects) (n.d.) C1 (TC): increase (8 subjects) (n.d.) C2 (TC): increase (3 subjects) (n.d.) C1 (IS): increase (3 subjects) (n.d.) C2 (IS): none subjects (n.d.)	**RPE:** n.s. between C1 and C2 ($p < 0.053$)

Abbreviations: M, male; F, female; s, seconds; MPF, mean power frequency; RPD, rating of perceived discomfort; RPE, rating of perceived exertion; n.a., not applicable; n.d., not defined; n.s., not significant; MES, myoelectric signal; MNF, mean frequency; VAS, visual analogue scale; RMS, root mean square.

Table 3
Overview of results of "effects of work pace, duty cycle and cycle time".

Reference	Sample	Muscle group	Task	Conditions	Fatigue measure	Response variables and main outcomes	
						Objective fatigue	Subjective fatigue
Bosch et al. (2011)	General population $N = 8$ (8F, age: 20.5 ± 1.8 years)	Upper trapezius (Trap), deltoid anterior (Delt) and extensor *digitorum* (ExtD)	**Simulate industrial assembly:** 2-h to pick, place and remove three pins, three collars and three washers in a fixed order with the left and right hand simultaneously – sitting, knee angle of 90°, placing the table surface 5 cm below the position of the wrist when the elbow was 90°flexed	C1: "low" work pace (LWP) - cycle time of 48 s. C2: "high" work pace (HWP) - cycle time of 38 s.	Kinematic data EMG Force transducer Performance Perceived fatigue Pressure pain threshold (PPT)	**Average EMG activity levels (%MVE):** C2 > C1 (Trap) (n.s.) C1 > C2 (Delt) (n.s.) C1 > C2 (ExtD) (n.s.) **Average cycle-to-cycle variability (EMG amplitude and EMG MPF):** n.s. between C1 and C2 (Trap. - $p = 0.58$ and Delt. - $p = 0.48$) C2 > C1 (ExtD) ($p = 0.012$) **Distance covered (m):** C1 > C2 (wrist) ($p = 0.012$) C1 > C2 (elbow relative to wrist) ($p = 0.012$) C1 > C2 (elbow relative to shoulder) ($p = 0.017$) **Speed (cm/s):** C2 (wrist) > C1 (wrist) ($p = 0.012$) **Acceleration (mm/s^2):** C2 (wrist) > C1 (wrist) ($p = 0.017$) **Maximum shoulder force:** n.s. between C1 and C2 ($p = 0.86$) **PPT:** n.s. between C1 and C2 (Trap, Delt) ($p = 0.9$) **Performance (errors per work cycle):** C2 > C1 ($p = 0.017$)	**Level of fatigue:** n.s. between C1 and C2 ($p = 0.307$)
Iridiastadi and Nussbaum (2006)	University population $N = 48$ (24M and 24F, age: 21.8 ± 2.1 years)	Middle deltoid muscle	**Intermittent static arm abductions:** secured in a supine posture, with the right arm abducted at 90° – performed no fatiguing shoulder abductions, followed by a measurement of the individual's abduction MVE. (20 –60 min)	C1: 28%MVE (CL), 0.75 (DC), 166 s (CT) – HHH C2: 28%MVE (CL), 0.75 (DC), 34 s (CT) – HHL C3: 28%MVE (CL), 0.25 (DC), 166 s (CT) – HLH C4: 28%MVE (CL), 0.25 (DC), 34 s (CT) – HLL C5: 12%MVE (CL), 0.75 (DC), 166 s (CT) – LHH C6: 12%MVE (CL), 0.75 (DC), 34 s (CT) – LHL C7: 12%MVE (CL), 0.25 (DC), 166 s (CT) – LLH C8: 12%MVE (CL), 0,25 (DC), 34 s (CT) – LLL	EMG RPD	**Endurance Times (min.):** C5–C8 > C4 > C3 > C2 > C1 *(Main and interactive effects: CL ($p < 0.001$); DC ($p < 0.001$); CL x DC ($p < 0.001$))* **Strength (%/min.):** C8 > C5 and C7 > C6 > C3 > C4 > C1 and C2 *(Main and interactive effects: CL ($p < 0.001$))* **EMG RMS (%/min.):** C1 > C2 > C8 > C3 and C4 > C6 and C7 > C5 (n.s) **EMG MPF(%/min.):** C7 > C4 and C6 > C3 > C8 > C5 > C2 > C1 *(Main and interactive effects: CL ($p < 0.001$); DC ($p < 0.001$); CT ($p = 0.029$); CL x DC ($p = 0.033$))* **EMG MF(%/min.):** C8 > C4 > C3 and C6 > C7 > C5 > C2 > C1 *(Main and interactive effects: CL ($p = 0.004$); DC ($p < 0.001$); CT ($p = 0.006$); CL x DC ($p = 0.003$))*	**RPD:** C1 > C2 > C4 > C3 > C5 > C6 > C8 and C7 *(Main and interactive effects: CL ($p < 0.001$); DC ($p = 0.002$))*
Mathiassen and Winkel (1996)	General population N = 8 (8F, age: 22–32 years)	Right upper trapezius muscle	**Assembling starters for power saws:** components (six parts and five screws) weighed up to 90 g and the complete starter 220 g.	C1: 2 h of work at 120 MTM C2: 4 h of work at 120 MTM C3: 6 h of work at 120 MTM C4: 4 h of work at 100 MTM C5: 6 h of work at 100 MTM C6: 4 h of work at 120 MTM with 20 min of active breaks C7: 4 h of work at 120 MTM with 20 min of passive breaks	EMG Heart rate (HR) Pressure pain threshold (PPT) Perceived fatigue	**EMG APDF (%RVE):** Higher at 120 MTM than 100 MTM (interaction of pace and hour: $p = 0.03$ at 10th percentile level and $p = 0.06$ at 50th percentile level). **EMG EVA:** Higher at 120 MTM than 100 MTM (interaction of pace and hour: $p = 0.09$). **HR:** Higher at 120 MTM than 100 MTM (n.d.) n.s. between C6 and C7 (n.d.) **PPT:** Higher at 120 MTM than 100 MTM (only for the first 4 h of work) (n.d.)	**Perceived fatigue:** Higher at 120 MTM than 100 MTM (n.d.) No conclusive effects for C6 and C7
Gerard et al. (2002)	Typists N = 18 (16F and 2M, age: 34 ± 10 years)	Flexor digitorum superficialis and extensor digitorum communis.	Typing for three 30 min trials.	C1: self-pace; C2: 50% of the participant's 1-min. maximum typing speed; C3: 100% of the participant's1-min. maximum typing speed	EMG Force Subjective discomfort	**Typing speed (WPM):** C3 > C1 > C2 (n.d.) **Typing force (10th, 50th and 90th APDF percentiles):** C3 and C1 > C2 ($p < 0.01$) **EMG (50th APDF percentile):** C3 > C1 > C2 ($p < 0.01$) (finger flexor) **EMG (90th APDF percentile):** C1 > C2 ($p < 0.01$) (finger flexor) C3 > C1 and C2 ($p < 0.01$) (finger flexor) **EMG (10th, 50th and 90th APDF percentiles):** C1 > C2 ($p < 0.01$) (finger extensor) C3 > C1 and C2 ($p < 0.05$) (finger extensor)	**Subjective discomfort:** C3 > C1 and C2 ($p < 0.01$) (fingers) C3 > C1 and C2 ($p < 0.01$) (lower arm) C3 > C1 and C2 ($p < 0.01$) (overall task)
Gooyers and Stevenson (2012)	Students $N = 12$ (12F, age: 23.6 ± 1.8 years)	Flexor *carpi radialis* (FR), extensor *carpi radialis longus* (ER), biceps brachii (BC), triceps brachii (TC), anterior deltoid (AD), and the	Simulated Speed Fastening (SF) task – using a pneumatic, powered, pistol-grip hand tool, to broach a 4.76 mm stainless-steel fastener at waist and shoulder height into perforated Masonite pegboard (hole diameter = 6.35 mm).	C1: 7 fasteners per minute C2: 14 fasteners per minute C3: 21 fasteners per minute	EMG Kinematic data	**50th muscle activity (% MVC):** C3 > C2 (ER) ($p < 0.0001$; 3% MVC) C3 > C1 (ER) ($p < 0.0001$; 7% MVC) C3 > C1 (BC) ($p < 0.0573$; 2% MVC) **Integrate EMG muscle activity (total muscular**	n.a.

(*continued on next page*)

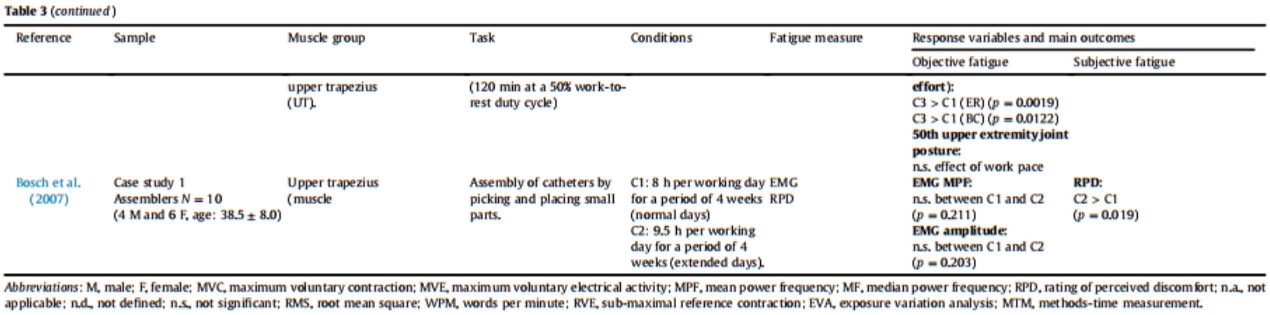

Table 3 (*continued*)

Reference	Sample	Muscle group	Task	Conditions	Fatigue measure	Response variables and main outcomes	
						Objective fatigue	Subjective fatigue
		upper trapezius (UT).	(120 min at a 50% work-to-rest duty cycle)			**effort):** C3 > C1 (ER) ($p = 0.0019$) C3 > C1 (BC) ($p = 0.0122$) **50th upper extremity joint posture:** n.s. effect of work pace	
Bosch et al. (2007)	Case study 1 Assemblers $N = 10$ (4 M and 6 F, age: 38.5 ± 8.0)	Upper trapezius (muscle	Assembly of catheters by picking and placing small parts.	C1: 8 h per working day for a period of 4 weeks (normal days) C2: 9.5 h per working day for a period of 4 weeks (extended days).	EMG RPD	**EMG MPF:** n.s. between C1 and C2 ($p = 0.211$) **EMG amplitude:** n.s. between C1 and C2 ($p = 0.203$)	**RPD:** C2 > C1 ($p = 0.019$)

Abbreviations: M, male; F, female; MVC, maximum voluntary contraction; MVE, maximum voluntary electrical activity; MPF, mean power frequency; MF, median power frequency; RPD, rating of perceived discomfort; n.a., not applicable; n.d., not defined; n.s., not significant; RMS, root mean square; WPM, words per minute; RVE, sub-maximal reference contraction; EVA, exposure variation analysis; MTM, methods-time measurement.

3.1. Effects of job rotation

None of the rotation studies (see Table 1) showed that the increase in task variation had a significant effect on the objective and subjective manifestation of muscle fatigue.Horton et al. (2012) found that rotation frequency and task order at higher exertion levels presented an increase in EMG amplitude and a decrease in EMG mean power frequency (EMG MPF). However, at lower exertion tasks, the results were opposite to the expected. For low-load tasks, Yung et al. (2012) suggested that time-varying force may be a useful intervention to reduce local fatigue.

Keir et al. (2011) demonstrated that only the anterior deltoid, trapezius and lower erector*spinae* benefited from rotating lifting and gripping tasks. However, forearm extensor muscles benefited from the task order, because they presented significantly higher levels of activity (10th (static level) and 50th (median level) percentile activity levels) for gripping–gripping compared to lifting-gripping, while for lifting–lifting, they presented a significantly lower activity compared to the griping-lifting condition. Indeed, these muscles are required for both tasks, which contrasts with the principle of job rotation, which intends to promote alternating tasks to provide rest periods to muscle groups and to reduce overall muscle activity, thereby reducing muscular overload (Mathiassen, 2006). A potential determinant of these results in both articles could be the variation of intensity of work tasks across conditions. Raina and Dickerson (2009) demonstrated that performing continuous shoulder abduction (BB) was more fatiguing than rotation between shoulder abduction and flexion. In this case, integrated EMG for shoulder abduction alone was significantly higher than for all other task combinations and EMG MPF values were lower. Wells et al. (2010) presented positive results of an increase in grip strength as a consequence of prehensile activity variation despite the high functional similarity of tasks (both tasks utilized a common group of musculoskeletal tissues), particularly between power grip/pulp pinch grip (75.7%) and lateral pinch/pulp pinch (66.3%). Interestingly, only this job rotation study did not implement a subjective measurement of fatigue.

In general, the subjective rate of fatigue increases across time in three of the reviewed studies. The effect of change intensity in the subjective feelings was reported by Horton et al. (2012), and these results showed that during the task with more muscular demand (30% MVC), the rating of perceived exertion (RPE) increases. In contrast, for the lowest exertion task (15%), the RPE decrease. Thus, the variation between tasks with different physical exposures reduces the risk of fatigue and consequently WMSD, as recommended by Mathiassen (2006). However, currently with the intensive production systems, which are characterized by short-cycle tasks and standardized processes (Neumann et al., 2002), it is challenging to identify work tasks that overload different muscle groups. The findings of Keir et al. (2011) and Raina and Dickerson (2009) were similar because the RPE was lower when the participants started with the less strenuous task.

3.2. Effects of work/rest schemes

In the four studies examined (see Table 2), two of the studies were related to tasks analyzed during computer work. According to Balci and Aghazadeh (2004), the introduction of microbreaks (every 15 min–30 min of work) contributed to a reduction in discomfort and increased performance. Similar results were confirmed by van den Heuvel et al. (2003) in an office work field study. For EMG measurements, the study byBalci and Aghazadeh (2004) showed that a 60/10 schedule (60 min work/10 min rest) caused the highest load increase in the upper trapezius. McLean et al. (2001) also demonstrated that microbreak protocols had a positive effect on subjective discomfort and did not affect worker productivity. Previous research conducted by Dababneh et al. (2001) revealed that two experimental rest break schedules did not have a negative effect on production. In the study by McLean et al. (2001), wrist extensors presented a higher frequency of mean frequency (MNF) of the myoelectric signal (MES) when “microbreaks” were introduced in 20-min intervals. These results were consistent with those obtained from McLean et al. (2000), who found a higher median value of mean frequency for the “break” compared to the “no break” protocol regarding cervical extensors.

In the other two studies, the results of objective manifestation of muscle fatigue in the EMG signals were not consistent. Christensen et al. (2000) found no differences in RMS values, EMG power spectrum and EMG mean power frequency (MPF) between groups with longer and faster breaks. In addition, heart rate and blood pressure did not present significant differences in these two groups. This type of field research has some confounding variables that may have influenced the results, such as duration of tasks and variation of products, but field studies have the advantage of not requiring extrapolation to practice. Sundelin (1993) found objective evidence of muscle fatigue with a decrease in MPF and an increase in RMS amplitude during work with and without breaks in some participants. Furthermore, no differences in ratings of perceived exertion and discomfort between groups were found.

3.3. Effects of work pace, duty cycle and cycle time

In the seven studies reviewed (see Table 3), one analyzed only the influence of work duration (Bosch et al., 2007) and three studies investigated only the effect of work pace on muscle fatigue and/or muscle activity (Gooyers and Stevenson, 2012, Bosch et al., 2011 and Gerard et al., 2002). The remaining articles tested experimental protocols with variation of contraction level (CL), duty cycle (DC), cycle time (Iridiastadi and Nussbaum, 2006) and with variation of working time and work pace simultaneously (Mathiassen and Winkel, 1996).

Gooyers and Stevenson (2012) showed that the increase in work rate (7 fasteners per minute to 21 fasteners per minute) contributed to a significant increase in muscle activity (50th percentile muscle activity) for the *extensor carpi radialis longus* (ER) and a significant increase in average integrated EMG (total muscular effort) for the ER and *biceps brachii* (BC). These results indicated that 21 fasteners per minute were more fatiguing than 7 fasteners per minute. However, only two of the six muscles examined were significantly affected by an increase in work rate. Importantly, the collection of EMG data in forearm muscles could be influenced by a phenomenon known as EMG crosstalk. This phenomenon occurs as a result of the proximity of various muscles included in the forearm and a relatively small surface area of the overlying skin to place recording electrodes (Mogk and Keir, 2003). The Bosch et al. (2011) study did not observe a significant effect of work pace on EMG manifestations of muscle fatigue. As expected, the distance covered by wrist and elbow (relative to wrist and to shoulder) was significantly shorter in “high” work pace (HWP). Speed and acceleration were significantly higher during the same condition. Performance was affected by work pace because participants made more errors per cycle during the HWP. Gerard et al. (2002) showed that the increase in typing pace resulted in a linear increase in finger flexor and extensor EMG activity and typing force.

The field study of Bosch et al. (2007) was performed under realistic working conditions and no differences were found in EMG MPF and amplitude between normal (8 h) and extended working days (9.5 h).

Mathiassen and Winkel (1996) confirmed that daily duration might be more effective in reducing acute fatigue than reducing work pace or increasing breaks.

Indeed, for 4 h of work at a pace of 100–120 methods-time measurement system (MTM), a complete recovery of EMG variables, maximal strength, heart rate, blood pressure sensitivity, and tenderness was observed. As expected, the heart rate (HR) was higher with 120 MTM than with 100 MTM. Iridiastadi and Nussbaum (2006) found that CL and DC significantly affected endurance time and muscle fatigue. However, EMG spectral measures did not always present a typical pattern.

In the six studies analyzed, five of them evaluated perceived discomfort or fatigue. The increase in work pace negatively affected perceived fatigue or discomfort in studies performed by Gerard et al. (2002) and the Mathiassen and Winkel (1996). However, in the last study mentioned, the implementation of active or passive breaks did not have a significant effect on subjective ratings. Bosch et al. (2011) did not observe a significant difference between high and low work pace. Finally, Iridiastadi and Nussbaum (2006) demonstrated that CL and DC had a significant effect on perceived discomfort.

3.4. Quality assessment

Table 4 shows the methodological quality assessment of the included studies. The scores on the methodological quality assessment ranged from 4 to 8 (on a scale from 0 to 8). Two studies (Bosch et al., 2011 and Wells et al., 2010) met the assessment criteria in full. However, the criteria related to study design, variables, data sources/measurement as well as outcome data were fulfilled for all studies included in this review. Nine studies did not define clearly the eligibility criteria and methods of selection of participants (Horton et al., 2012, Keir et al., 2011, Raina and Dickerson, 2009, Bosch et al., 2007, Balci and Aghazadeh, 2004, Gerard et al., 2002, Christensen et al., 2000, Mathiassen and Winkel, 1996 and Sundelin, 1993). Though, all studies included reported that participants did not have history of musculoskeletal injury. Regarding the criteria defined to item bias, three studies did not refer any effort to address bias or imprecision (Raina and Dickerson, 2009, Balci and Aghazadeh, 2004 and Gerard et al., 2002) and two did not describe clearly the measures to minimize it (Bosch et al., 2007 and Christensen et al., 2000). Additionally, only six studies discussed the external validity of the results (Horton et al., 2012, Bosch et al., 2011, Keir et al., 2011, Wells et al., 2010, Raina and Dickerson, 2009 and Bosch et al., 2007).

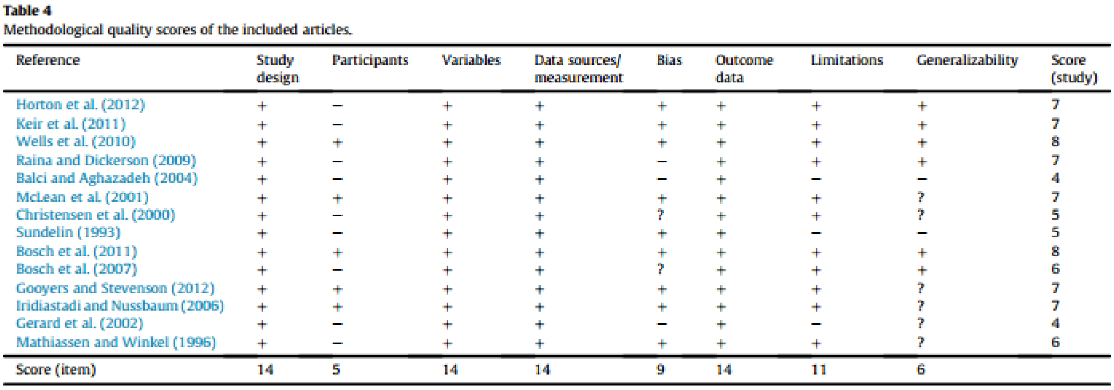

Table 4
Methodological quality scores of the included articles.

Reference	Study design	Participants	Variables	Data sources/ measurement	Bias	Outcome data	Limitations	Generalizability	Score (study)
Horton et al. (2012)	+	−	+	+	+	+	+	+	7
Keir et al. (2011)	+	−	+	+	+	+	+	+	7
Wells et al. (2010)	+	+	+	+	+	+	+	+	8
Raina and Dickerson (2009)	+	−	+	+	−	+	+	+	7
Balci and Aghazadeh (2004)	+	−	+	+	−	+	−	−	4
McLean et al. (2001)	+	+	+	+	+	+	+	?	7
Christensen et al. (2000)	+	−	+	+	?	+	+	?	5
Sundelin (1993)	+	−	+	+	+	+	−	−	5
Bosch et al. (2011)	+	+	+	+	+	+	+	+	8
Bosch et al. (2007)	+	−	+	+	?	+	+	+	6
Gooyers and Stevenson (2012)	+	+	+	+	+	+	+	?	7
Iridiastadi and Nussbaum (2006)	+	+	+	+	+	+	+	?	7
Gerard et al. (2002)	+	−	+	+	−	+	−	?	4
Mathiassen and Winkel (1996)	+	−	+	+	+	+	+	?	6
Score (item)	14	5	14	14	9	14	11	6	

The analysis of the methodological quality revealed that, in general, the included laboratory studies, investigated young small samples in contrast with field studies or studies with samples of workers. Considering that some authors found age differences in responses to fatiguing tasks (Adamo et al., 2009 and Avin and Law, 2011), these factors could limit generalization of the outcomes to older workers. Only three studies (Bosch et al., 2007, Christensen et al., 2000 and Mathiassen and Winkel, 1996) performed their evaluations in specific moments of a full workday or longer periods of work. So, other critical factor of the experimental protocol tested in the laboratory studies was the representativeness of the period of trials. Thus, the results may not be representative of fatigue experienced by workers in real-occupational settings. Only one study obtained EMG signals exclusively during a pre-defined test contraction (Bosch et al., 2007) and three studies compared EMG measures from work period and reference test contraction (Horton et al., 2012, Christensen et al., 2000 and Mathiassen and Winkel, 1996). These two methods can be applied to EMG evaluation of fatigue yet the results can be analyzed considering some constraints. Under dynamic conditions, EMG is no stationary and some confounding factors are difficult to control such as modifications in force output, muscle length, position and distance of electrodes, as well as movement velocity during the task (Farina, 2006 and Madeleine et al., 2001). EMG analysis of muscle groups with highly dynamic movements in manual tasks, such as wrist flexors and extensors, these factors are more uncontrolled and may lead to interpretation errors of the EMG signals. However, test contraction method has also disadvantages, since may not represent accurately the workload and motor unit recruitment during real work tasks.

4. Conclusions and future research

In general, the articles analyzed in this systematic review demonstrated that the influence of task design on muscle fatigue and performance are not completely understood. The studies reviewed did not demonstrate a significant effect of job rotation on perceived discomfort and objective EMG indicators of fatigue. In these studies the duration of trials and number of participants appears to be the factors which have the most influence on the results. However, Srinivasan and Mathiassen (2012) proposed an alternative intervention to job rotation, based on variation in postures, movements and muscle activity during the performance of tasks – motor variability – on muscle fatigue.

Regarding the studies which analyzed the temporal aspects of work on muscle fatigue, it was found that the introduction of breaks had a positive effect on subjective feelings in the office work studies. However, no clear relationship was found between perceived discomfort and objective measurements of fatigue. Overall, an increase of work pace resulted in higher manifestation of muscle fatigue in the EMG signal (higher amplitude and lower frequency). In these studies the demographic characteristics, in particular, age and experience in the tasks may have influenced the results.

Therefore, future studies should extent the period of experiments to be more representative of fatigue in real work conditions. In addition, it is crucial to study the effects of temporal aspects of work and rotation schemes in specific populations such as older workers. Recognizing the limitations of surface EMG to detect fatigue at low-load work, future research should be focused on the improvement of instrumentation for data collection and analysis in occupational settings. These advances will allow detect the causes of muscle fatigue and prevent its development in the workplaces.

Some limitations were present in this review that should be noted. This review only included research published in English peer-reviewed journals, not including potential relevant studies in other languages. Additionally, the electronic search was limited to three databases.

Appendix A.

Search strategy used in Pubmed

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*Muscle fatigue[Title/Abstract] AND forearm muscles[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

*Muscle fatigue[Title/Abstract] AND workload[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

*Muscle fatigue[Title/Abstract] AND work-related musculoskeletal disorders[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

*Muscle fatigue[Title/Abstract] AND repetitive movements[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

*Muscle fatigue[Title/Abstract] AND repetitive work[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

*Muscle fatigue[Title/Abstract] AND assembly work[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

*Muscle fatigue[Title/Abstract] AND low-force work[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

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*Muscle fatigue[Title/Abstract] AND low-load work[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

*Muscle fatigue[Title/Abstract] AND work cycle time[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

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*Muscle fatigue[Title/Abstract] AND work rest pattern[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

*Muscle fatigue[Title/Abstract] AND rest breaks[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

*Muscle fatigue[Title/Abstract] AND work duration[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

*Muscle fatigue[Title/Abstract] AND work pace[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

*Muscle fatigue[Title/Abstract] AND job rotation[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

*Muscle fatigue[Title/Abstract] AND task design[Title/Abstract] AND (Journal Article[ptyp] AND English[lang]).

Search strategy used in Scopus

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Search strategy used in Web of Science

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*(TS=(muscle fatigue AND forearm muscles) NOT TS = patients NOT TS = sports) AND Idioma: (English).

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*(TS=(muscle fatigue AND assembly work) NOT TS = patients NOT TS = sports) AND Idioma: (English).

Appendix B. Operationalization of the methodological quality assessment

Criteria

Study design

1. Positive if the duration and schedule of measurements were clearly described;
2. Positive if the tasks tested were clearly defined.

Participants

3. Positive if eligibility criteria and methods of selection of participants were clearly described.

Variables

4. Positive if the exposure to temporal aspects or task rotation schemes tested were clearly described (*independent variables*);
5. Positive if the variables to assess fatigue were clearly defined (*dependent variables*);
6. Positive if the method of variables analysis was clearly described.

Data sources/measurements

7. Positive if the methods of assessment were clearly described.

Bias

8. Positive if any efforts to address potential sources of bias were described, in particular:

a.

Adequate data collection and processing of fatigue measures (namely, for quantitative measures of fatigue) and;

b.

Control confounders introduce by participants during trials (e.g. give visual feedback, verbal encouragement, training).

Descriptive data

9.

Positive if at least 2 of the following 3 elements were reported:

a.

Age (mean (SD) or range);

b.

Gender (number, percentage or both);

c.

Anthropometric measures (stature, weight or BMI).

Outcome data

10.

Positive if the measures over time were clearly described.

Limitations

11.

Positive if the limitations related to experimental protocol or participants were clearly describe.

Generalizability

12.

Positive if the external validity of results were discuss.

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