TITLE: Recovery and fatigue behavior of forearm muscles during a repetitive power grip gesture in racing motorcycle riders

AUTHORS: Marina M[1*].; Torrado P[1].; Bescós, R[2].

Authors Institutions:

[1] Research Group in Physical Activity and Health (GRAFiS), Institut National d'Educació Física de Catalunya (INEFC) – University of Barcelona (UB). Barcelona, Spain.

[2] Faculty of Health, University of Plymouth (Plymouth, United Kingdom)

* Corresponding Author:
Dr Michel Marina
Institut Nacional d'Educació Física de Catalunya (INEFC)
Av de l'Estadi 12-22. 08038. Barcelona, Spain
Tef: + 34 616 845 407
Fax: +34 93 426 36 17
E-mail: michel.marina.1964@gmail.com

ABSTRACT

Despite a reduction in the maximal voluntary isometric contraction (MVC_{isom}) observed systematically in intermittent fatigue protocols (IFP), decrements of the median frequency, assessed by surface electromyography EMG (sEMG), has not been consistently verified. This study aimed was to determine whether recovery periods of 60 s were too long to induce a reduction in the normalized median frequency (MF_{EMG}) in of the flexor digitorum superficialis and carpi radialis muscles. Twenty-one road racing motorcycle riders performed an IFP that simulated the posture and braking gesture and posture onabove a motorcycle. An The MVC_{isom} decrement was reduced by of 53% confirmed fatigue. Regression analysis confirmed A positive and significant a linear relationship (p <…) was found between MF_{EMG} and duration of… when 5 s contractions at 30% MVC_{isom} were interspersed by 5 s recovery in both muscles. both muscles were exercised intermittently at 30% MVC_{isom}, with pauses of 5 s between each 5 s contraction. In contrast, no relationship was found ($p > 0.133$) when 10 s contractions at 50% MVC were interspersed by 1 min recovery. when both muscles were exerted continuously during 10 s at 50% MVC, with after recovery pauses of 1 min, no relationship was observed ($p > \geq 0.133$). Analysis of variance (ANOVA) As a second approach with the same objective, comparative ANOVA analysis confirmed within the same IFP a decrement of MF_{EMG} in the when both muscles exerted intermittently at IFP at 30% MVC_{isom} including short recovery periods (5 s) with a duty cycle of 100% (5 s / 5 s = 1), whereas no differences were observed when theyin the IFP at worked at 50% MVC_{isom} and longer recovery periods., with a duty cycle of 16%. These findings show is observation stand out that recovery periods during IFP are more relevant than the intensity of MVCisom the relevance recovery durations inserted in between the working periods of intermittent fatiguing tasks. Thus, we recommend the use of short recovery periods between 5 and 10 s after submaximal muscle contractions forFor specific forearm muscle training and testing purposes in motorcycle riders we recommend using very short recovery periods of 5 to 10 s as a maximum between each submaximal effort.

Keywords: Handgrip, carpi radialis, flexor digitorum superficialis, neuromuscular fatigue, motorcycle, recovery.

Commented [RB1]: Poner p value aqui

Commented [RB2]: duration of the recovery??? Anadir palabra aqui

Commented [RB3]: MVCisom??? Revisar

Commented [RB4]: No entiendo muy bien que quiere decir esto

Commented [RB5]: No entiendo bien este valor 16%???

Commented [RB6]: Revisar si esto es correcto!

Tambien podria decirse: These findings show the relevance of the recovery period in IFP.

1. Introduction

Stimulation of intermittent muscle contractions during motorcycle competitions are currently under investigation because of their relationship with the development of clinically significant conditions especially in the hand/forearm. These conditions, characterized by pain and loss of the hand or forearm function (forearm syndrome), can lead to long periods of illness in motorcycle riders especially in those participating in endurance competitions such as 24 h races where they must brake more than 4,000 times and make 10,000 gear changes [6]. (ref). Similar pathological patterns can also happen among workers in the manufacturing industry [1].

The fact that many athletes, manual workers and musicians must endure their mechanical work The fact that many athletes, manual workers and musicians must endure their mechanical work over long periods of time, at the muscle contraction intensities that characterize each activity, explains the large number of studies focused on neurophysiological fatigue of the forearm mucles [7-11]. These muscles are involved in a great variety of repetitive grip tasks that can lead to neuromuscular fatigue and functional impairment when these tasks are sustained become chronic. Thus, it is important to obtain better knowledge and understanding of the mechanisms involved in these physiological situations to prevent forearm syndrome.

When assessing human muscle fatigue with sEMG, the power spectrum displacement towards lower frequencies has been extensively documented in continuous fatiguing protocols (CFP), in which submaximal voluntary contractions are maintained until exhaustion [9,12-16]. Intermittent fatiguing protocols (IFP) have been extensively studied as well because Intermittent contractions at different intensities are also common in the every-day life of the majority of workers and athletes [17,18], and consequently, . We investigated differences between CFP and IFP adapted to motorcycle riders and we found that IFP [19]. [9] showed a strong relationship with the level of motorcyclist forearm discomfort compared to CFP.

The relative intensity of the contraction in relation to maximal voluntary isometric contraction (MVC_{isom}) registered in a non-fatigued condition ($\%MVC_{isom}$) is a key factor that modulates muscle

Commented [RB7]: Referencias 2-5

Commented [RB8]:

fatigue. Studies looking at CFP that the the intensity of the effort, the shorter the time to task failure [14,16,22], obviously because of the lack of recovery periods. . Moreover, it has been generally observed that $\%MVC_{isom}$ and time to task failure (also called .

Moreover, it has been generally observed that $\%MVC_{isom}$ and time to task failure (also called time limit) have a significant effect on the decrement of sEMG frequency (MF_{EMG}) and increment of the sEMG amplitude (RMS_{EMG}) [14,15,23]. A reduction in MF_{EMG} was observed during CFPs at 10% MVC [24,25], 25% MVC [25-27], 30% [28], 40% [9,27,29], 60% [30], 55, 70, 80, and 90% of MVC [27]. Nevertheless, some caution is needed in regard to CFP because $\%MVC_{isom}$ should not be considered as a definitive factor explaining the absence of a reduction in MF_{EMG} during fatiguing protocols [27,30].

A second factor that is necessary to consider when measuring fatigue is the duration of the effort or exertion time. It is known that the duration of the fatiguing task at a constant relative submaximal $\%MVC_{isom}$ is negatively associated with the MVC_{isom} decrement, reaching the maximal point at time to task failure [31]. Duration of the effort induces a linear decrement of MF_{EMG} [14,27,32] that may differ slightly depending on the muscle group and type of movement [15,16,23,29]. In CFPs, $\%MVC_{isom}$ and duration of the effort are the main triggers of fatigue, with particular emphasis on the influence of longer durations with respect to MF_{EMG} decrements due to lower %MVCs [33].

A third factor must be taken into account in IFP: the duration of the recovery interspersed between muscle contractions. Controversial MF_{EMG} results have been observed when applying IFP, despite the lower MVC_{isom} recorded at the end of such fatigue protocols. For example, some authors, but not all [36,37], reported a reduction in MF_{EMG} during an IFP [34,35],. MF_{EMG} was similar to pre-fatigue values with different work–rest cycles, whatever the intensity used in the IFP, [25]. These results are consistent with the findings of Mundale [33], who also studied the factors that lengthen the endurance time of an IFP. They suggested that the duration of the recovery period could be one of the key factors explaining the disparity in MF_{EMG} results particularly among IFPs. Looking at motorcycle riders, we [38] observed no significant MF_{EMG} decrement throughout a 24-h motorcycle endurance race despite the significant decrease in MVC. Following

Commented [RB9]: Esta frase no me queda clara. Se puede eliminar???

previous studies [39-41], the gap between the end of each relay and the handgrip assessment did not go over of 4–5 min . The lack of MF_{EMG} decrement led them to conclude that this interval was too long. According to these findings, we decided to compare an intermittent (IFP) and continuous (CFP) fatigue protocol specifically adapted to motorcycle riders [19]. The lack of a reduction in MF_{EMG} in their IFP suggested that rest cycles were too long achieving basal values of MF_{EMG} between the work cycles. These findings are in agreement to another study by Krogh-Lund and Jorgensen [26] that compared two pairs of fatiguing sustained isometric contractions at 40% MVC separated by different rest intervals. They found that the sEMG frequency at the start of the second contraction did not recover to pre-fatigued values when the rest interval was less than 1 min, [26]. Other studies reached similar conclusions when they used intermittent contractions [30,42,43], suggesting that MF_{EMG} shift toward the pre-fatigue state occurs independently of the load applied (25–50%) [43].

Commented [RB10]: Tratemos de ser consistentes con la terminologia. Usar la misma palabra en el articulo: rest o recovery La que os guste mas

Commented [RB11]: Intensity of the contraction???

Some authors [20] suggest that the validity of the spectral shift of the sEMG signal in assessment of fatigue must be taken with caution because a clear MVC decrement is sometimes weakly reflected in the sEMG signal [44], This is supported by studies that used IFP to assess muscle fatigue [36,37,45,46]. In contrast to This is supported by studies that used IFP to assess muscle fatigue [36,37,45,46]. In contrast to this, we and others believe that sEMG signal is a good approach for studying muscle fatigue in occupational field studies [47] [34,35], taking into account that Overall, the combination of different contraction–relaxation periods, intensity of muscle contractions ($\%MVC_{isom}$), muscle groups and other non-controlled or non-reported factors, are critical to understand muscle fatigue in IFPs [18,25,48].

Therefore, this study aimed to verify in road racing motorcycle riders whether the recovery period performing an IFP matching the braking movement was more relevant than the contraction intensity and effort duration in two forearm muscles (flexor digitorum superficialis and carpi radialis). We hypothesize that MF_{EMG} will not decrease during the contractions performed at 50% MVC_{isom} because they are preceded by long recovery periods. On the contrary, MF_{EMG} recorded at 30% MVC_{isom} and during shorter exertion time (5 s) may decrease due to short recovery periods (5 s).

2. Methods

2.1. Subjects

Twenty-one road racing motorcycle riders aged 29.1 ± 8.0 years (body mass: 72.1±5.5 kg; height: 176.2 ±4.9 cm) participated in this study. 48% were winners of races within the Spanish and/or World Championships and 24% were on the podium of the Championship at the end of the season over the previous 6 years. The remaining 28% of the participants participated in races at regional level with at least 5 years of racing experience. The study was approved by the Clinical Research of the Ethics Committee for Clinical Sport Research of Catalonia (Ref. number 15/2018/CEICEGC) and written consent was given by all the participants. The data were analyzed anonymously, and the clinical investigation followed the principles of the Declaration of Helsinki.

2.2. Procedures

Before the assessment, the brake lever to handgrip distance was adjusted to the participant's hand size to ensure that hand placement in relation to the brake was similar across all subjects. Afterwards, during the familiarization period the subject practiced six to ten submaximal non-stationary contractions watching the dynamometric feedback displayed on the PC screen, while the researcher provided feedback about how to interpret the auditory and visual information. A continuous linear feedback and a columnar and numerical display showed the subject the magnitude of the force he exerted against the brake lever. In addition, a different tone was provided depending on the force level. Dynamometric and sEMG signals were recorded and these signals were synchronized with an external trigger. Five minutes before the beginning of the intermittent fatigue protocol (IFP), two MVC_{isom} trials, separated by a 1-min rest, were performed to provide a baseline value of MVC_{isom}. The 1-min resting period between the two MVC_{isom}s was considered sufficient to avoid fatigue from the previous contraction [49,50]. The higher MVC_{isom} was recorded as the basal value of that day and used to calculate the submaximal efforts (50% and 30% of the maximum). During the IFP, the subject adopted the "rider position" with both hands on the handlebar.

2.3. Sequence and structure of the IFP

The intermittent protocol comprised a succession of a maximum of 25 rounds. Each round comprised two sections (Fig. 1A). Section one consisted of six 5-s voluntary contractions of 30% MVC_{isom}, with a resting period of 5 s between each contraction. Section two comprised a 3-s MVC_{isom} followed by a 1-min resting period and a 50% MVC_{isom} maintained for 10 s. During the 1-min resting period subjects were in the seated position with their hands resting on their thighs.

Intensities ranging from 10% to 40% of MVC have previously been used to carry out a continuous or intermittent fatigue protocol [18,25,51]. A sequence of 30% of MVC_{isom} was finally adopted after consulting with expert riders (exclusively winners of races at the national and world level) who agreed about the perception of applying approximately this percentage of force during very strong braking in a real situations.

Section two was designed to replicate an experimental protocol from one of our previous studies of motorcycle riders [6]. The test stopped when the subject was unable to maintain the established 50% of MVC_{isom} for 10 s, or the concurrent MVC_{isom} was 10% lower than 50% of the MVC_{isom} value. The number of rounds achieved by each subject was used as a performance measure.

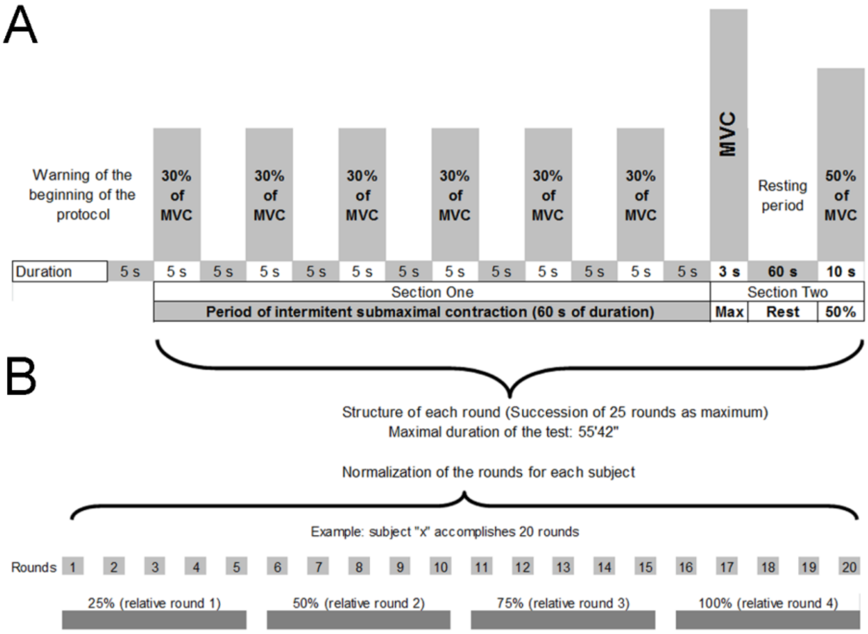

Figure 1: Description of the sequence and structure of the intermittent protocol. Auditory feedback was provided to ensure the exact duration of each contraction and resting period. Bottom section represents an illustration of a subject who performed 20 rounds, which means that each one of the four successive *relative* rounds is composed by five rounds

2.4. Dynamometric assessment

To simulate the overall position of a rider on a 600–1000-cc racing motorcycle, a static structure was built to preserve the distances between the seat, stirrups, and particularly the combined system of shanks, forks, handlebar, brake and clutch levers, and gas (Fig. 2). Like it happens in a road race motorcycle, levers tilt, distances between levers and handle gas, and distance between handle bar and seat were modified according to the ergonomic requirements of the rider (Fig. 2).

The subjects were asked to exert a force against the brake lever (always right hand) using the the second and third finger to hold the lever half way, and the thumb and other fingers grasping the handgrip at the same time, which is the most common way of braking of road racing motorcycle riders

(Fig. 2). Both arms had a slight elbow flexion (angle 150–160º), forearms half-pronated, wrist
(Fig. 2). Both arms had a slight elbow flexion (angle 150–160º), forearms half-
pronated, wrist in neutral abduction/adduction position and alienated with respect to the forearm, dorsal flexion of the wrist no bigger than 10º, and legs flexed with feet above the footrests; in short, the typical overall position of a rider piloting a motorcycle in a straight line. Special attention was given for controlling the handgrip position, and the wrist, elbow and trunk angles to avoid any modification of the initial overall body position during the test. One experimenter supervised the recording of force and sEMG signal, and another continuously checked the maintenance of body position. It has been reported that variation of body posture [52] and wrist angles [53] alter the behaviour of the forearm muscles during handgrip force generation.

To measure the force exerted against the brake lever we used a unidirectional gauge connected to the MuscleLab™ system 4000e (Ergotest Innovation AS, Norway). The frequency of measurement was 400 Hz and the loading range was from 0 to 4000 N. The gauge (Ergotest Innovation AS, Norway), with a linearity and hysteresis of 0.2%, and 0.1 N sensibility, was attached to the free end of the brake lever in such a way that the brake lever system and the gauge system laid over the same plane and formed a 90º angle approximately when the subject was exerting force. The MVC at the end of the IFP was compared to the MVC in the pre-fatigued state. The 30% and 50% MVC contractions were used for sEMG analysis.

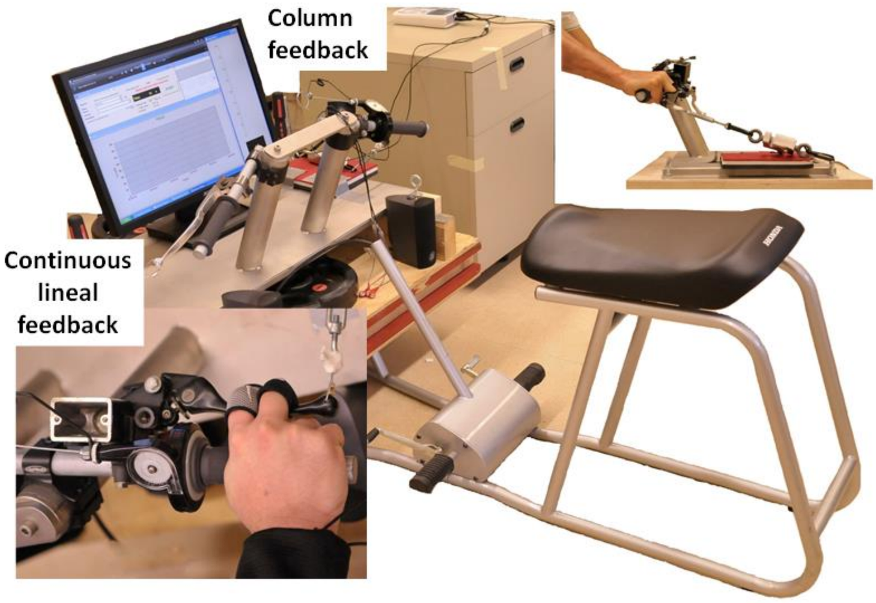

Figure 2: Simulation of the overall position of a rider above a motorcycle race from 600 cc to 1000 cc, a static structure was built to preserve the distances between seat, stirrups, and particularly the combined system of shanks, forks, handlebar, brake and clutch levers, and gas.

2.5. Electromyography

A ME6000 electromyography system (Mega Electronics, Kuopio, Finland) was used to register flexor digitorum superficialis (FS) and carpi radialis (CR) EMG signals. Adhesive surface electrodes (Ambu Blue Sensor, M-00-S, Denmark) were placed 2 cm apart (from center to center) according to anatomical recommendations of the SENIAM Project [54,55]. The raw signal was recorded at a sampling frequency of 1000 Hz. Data were amplified with a gain of 1000 using an analog differential amplifier and a common mode rejection ratio of 110 dB. The input impedance was 10 GΩ. A Butterworth band pass filter of 8– 500 Hz (–3 dB points) was used. To compute the median frequency (MF_{EMG}, Hz), Fast Fourier Transform was used with a frame width at 1024, a shift method of 30% of the frame width, and the "flat-topped" windowing function. The power spectrum densities were computed and averaged afterwards to obtain one mean or median for each submaximal contraction of 30% MVC_{isom} (5 s duration) and 50% MVC_{isom} (10 s duration). Afterwards, the median frequency (MF_{EMG}) was normalized with respect to the basal condition during the MVC_{isom}.

In order to obtain the same number of MF_{EMG} values from the IFP of each individual, and for each round and MVC intensity, the six 30% MVCs of the first section (Fig. 1A) were averaged to obtain one MF_{EMG} (MF_{EMG30}). Each MF_{EMG30} was paired with the only MF_{EMG} of the second section (Fig. 1A) obtained from the 50% MVC (MF_{EMG50}).

2.6. Statistics

Parametric statistics were used after confirming the normal distribution of the normalized parameters used in this study (MVC_{isom}, MF_{EMG30}, and MF_{EMG50}) with the Shapiro-Wilk test. Descriptive results were reported as mean and standard deviation. A paired sample t-test was used to compare the MVC_{isom} in the pre-fatigued state and at the end of the IFP. Two methodological approaches were used to verify the study's hypothesis. First, we used regression analysis for each individual, to study the strength of the relation and detect possible trends between the number of rounds accomplished (independent variable) and the MF_{EMG30} (dependent variable). Second, we used a 2 (time points: T_1 and T_2) x 2 (muscles: FS and CR) x 2 (%MVC_{isom}: 30 and 50) ANOVA of repeated measures to compare all MF_{EMG} values at the beginning and the end of the IFP, and to study potential interactions with the two muscle groups analyzed (CR and FS) and the two intensities that were preceded by distinct recovery periods (5 s for 30% MVC_{isom} and 1 min for 50% MVC_{isom}). When necessary, the Greenhouse-Geisser's correction was used if the sphericity test to study matrix proportionality of the dependent variable was significant ($p < 0.05$). Then, when a significant effect was found, a post-hoc analysis was carried out conducting multiple comparisons between the normalized rounds with Sidak's adjustment. Partial Eta squared ($\eta^2 p$) was used to report effect sizes (0.01 ≈ small, 0.06 ≈ medium, >0.14 ≈ large). Statistical analysis was performed using PASW Statistics for Windows, Version 18.0 (SPSS, Inc, Chicago, IL, USA). The level of significance was set at 0.05.

3. Results

At baseline conditions, MVC_{isom} (276 ± 46.6) was 53% lower) than the MVC_{isom} at the end of the IFP (147 ± 46.3; $p < 0.001$).

Individual regression analysis (Table 1, Fig. 3) was conducted to verify possible trends between the NMF of the CR and FS and the number of rounds accomplished by the motorcycle riders during an intermittent fatigue protocol (IFP) at two different intensities (30% and 50% of MVC_{isom}). The overall individual regression analysis showed a significant linear relationship

($p \leq 0.005$) between the MF_{EMG} and the number of rounds accomplished by both muscles when they were exercised at 30% MVC_{isom} (CR_{30} and FS_{30}), with pauses of 5 s between each contraction. In contrast, when both muscles were exerted at 50% MVC_{isom} (CR_{50} and FS_{50}), after 1 min of recovery, no significant relationship was observed ($p \geq 0.133$). The higher correlation observed in CR_{30} and FS_{30} ($r \geq -0.71$) in comparison to CR_{50} and FS_{50} ($r \leq 0.59$) supports the hypothesis of a weaker relationship between the MF_{EMG30} and the number of rounds when both muscles have the opportunity to recover for longer (1 min for CR_{50} and FS_{50}). Similarly, the overall individual regression analysis showed that the fraction of MF_{EMG} variance, explained by the number of rounds attained during the intermittent protocol, was bigger with CR_{30} and FS_{30} ($r^2 \geq 0.50$) in comparison to CR_{50} and FS_{50} ($r^2 \leq 0.40$) (Table 1).

Commented [RB12]: Esto quizas tenga que ir en la discussion

Table 1: Regression analysis of normalized median frequency (MF_{EMG}, dependent variable), against the number of rounds (independent variable) accomplished by each rider (n = 21). Muscles analyzed are the carpi radialis (CR) and flexor digitorum superficialis (FS) at 30% and 50% of MVC.

n = 21		*r*	r^2	Error of estimate	*F*	*p*
CR_{30}	Mean	-0.756	0.580	0.026	54.163	0.005
	sd	± 0.176	± 0.266	± 0.012	± 57.827	± 0.009
	CI sup	0.758	0.583	0.027	54.954	0.006
	CI inf	0.753	0.576	0.026	53.372	0.005
CR_{50}	Mean	0.594	0.397	0.045	28.046	0.133
	sd	± 0.284	± 0.302	± 0.019	± 43.913	± 0.295
	CI sup	0.598	0.401	0.045	28.647	0.137
	CI inf	0.590	0.393	0.045	27.445	0.129
FS_{30}	Mean	-0.711	0.504	0.022	27.659	0.005
	sd	± 0.152	± 0.214	± 0.008	± 23.267	± 0.007
	CI sup	0.713	0.507	0.022	27.977	0.005
	CI inf	0.709	0.501	0.002	27.341	0.004
FS_{50}	Mean	-0.542	0.338	0.033	20.524	0.158
	sd	± 0.283	± 0.290	± 0.016	± 31.906	± 0.288
	CI sup	0.546	0.342	0.033	20.960	0.161
	CI inf	0.539	0.334	0.033	20.087	0.154

Pearson coefficient correlation (*r*), R squared (r^2), error of the estimate, F-statistics (*F*), level of significance (*p*), degree of freedom (df: 1, 10-23). The minor number of accomplished rounds was 10. Five riders succeeded to perform the all 25 rounds of the intermittent protocol.

Table 2: Frequency table. Number of motorcycle riders who match the condition reported in the individual linear regression analysis. Normalized median frequency (MF_{EMG}) was the variable taken for analysis against the number of rounds accomplished during the intermittent fatigue protocol.

n = 21	*r*			*p*		
	> 0.70	0.40-0.69	< 0.39	≤ 0.001	0.001 - 0.05	ns
CR_{30}	13	8	0	14	7	0
CR_{50}	10	7	4	10	7	4
FS_{30}	13	8	0	12	9	0
FS_{50}	7	7	7	9	5	7

In addition to the regression analysis performed for each individual, Table 2 shows the number… reveals how more riders satisfied the better levels of statistical condition in CR_{30} and FS_{30} in comparison to CR_{50} and FS_{50}. ~~That is, whereas t~~The higher correlation values ($r > 0.70$) and higher levels of significance ($p \leq 0.001$) were associated with higher frequency values in

Commented [RB13]: No entiendo esta frase. Pondria lo que pone en la tabla

Number of motorcycle riders who match the condition reported in the individual linear regression analysis.

CR_{30} and FS_{30}, and lower correlation values ($r < 0.39$) and lower levels of significance ($p \geq 0.05$) were associated with the higher number of riders in CR_{50} and FS_{50}.

Figure 4 is an example of the regression analysis carried out in one subject showing higher MF_{EMG} values for the CR in comparison to the FS. Moreover, at 50% MVC, the MF_{EMG} of the CR never dropped below the MF_{EMG} level established during the basal assessment (Figure 4B), which is consistent with the comparative results (Table 3).

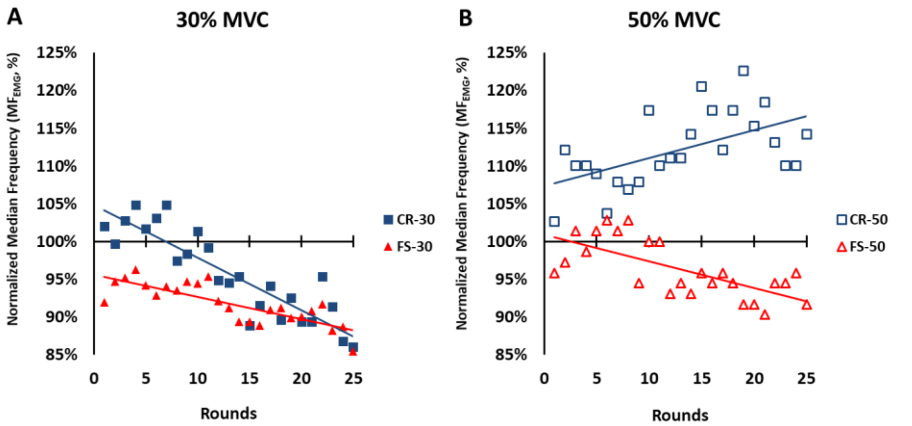

Figure 3: Example of a comparative regression analysis of an individual. Regression of the carpi radialis (CR) and flexor superficialis digitorum (FS) at the two intensities (30% and 50% of MVC) used in the intermittent protocol.

The second methodological approach was used to determine whether less intense and shorter muscle contractions (30% MVC_{isom} instead of 50%; 5 s instead of 10 s) could induce bigger MF_{EMG} decrements in the CR and FS, The second objective was to determine whether the two muscles (CR and FS) had a similar The second objective was to determine whether the two muscles (CR and FS) had a similar MF_{EMG} decrement due to fatigue. Thus, we compared two times of measurement (T_1 and T_2), two muscles (CR and FS) and two contraction intensities (30% and 50% of MVC_{isom}) (Table 3).

A significant three-way interaction was found ($p < 0.001$) with a large effect size ($\eta^2 p = 0.5$) (Table 3). Paired comparisons found lower values for the FS than the CR at both times and both intensities. Moreover, we observed a higher MF_{EMG} in the CR muscle at 30% MVC_{isom} (CR_{30}) than at 50% MVC_{isom} (CR_{50}) at the beginning of the fatiguing task, but the opposite response was observed at the end. Finally, regarding the carpi radialis (CR), while MF_{EMG} was lower at the end than at the beginning of the IFP at the 30% MVC_{isom} (CR_{30}), the opposite was observed at the 50% MVC_{isom} exertion (CR_{50}) (Table 3).

Table 3: 2 (Time) x 2 (Muscles) x 2 (% MVC_{isom}) ANOVA of repeated measures between the beginning (T_1) and the end (T_2) of the intermittent fatiguing protocol (IFP). The parameter of analysis is the normalized median frequency (MF_{EMG}) of the Carpi Radialis (CR) and Flexor Digitorum Superficialis (FS).

Effect	*F*	*df*	*p*	η^2p	Paired comparisons	*p*
T x In x M	20.04	1, 20	$\leq$ 0.001	0.50	T_1 & T_2: $FS_{30} < CR_{30}$; $FS_{50} < CR_{50}$	$\leq$ 0.001
					T_1: $CR_{30} > CR_{50}$; T_2: $CR_{30} < CR_{50}$	$\leq$ 0.002
					CR_{30}: $T_1 > T_2$; CR_{50}: $T_1 < T_2$	$\leq$ 0.001
T x In	33.60	1, 20	$\leq$ 0.001	0.63	In_{30}: $T_1 > T_2$	$\leq$ 0.001
					In_{50}: $T_1 < T_2$	$\leq$ 0.024
T x M	0.74	1, 20	ns	0.04		
In x M	3.02	1, 20	ns	0.13		
T	1.43	1, 20	ns	0.07		
In	28.58	1, 20	$\leq$ 0.001	0.59		
M	42.43	1, 20	$\leq$ 0.001	0.68		

Time (T), Intensity (In) of 30% MVC_{isom} (In_{30}) and 50% MVC_{isom} (In_{50}), Muscle (M)

In addition, a significant two-way interaction was found between the time and MVC_{isom} intensity (time per intensity) with a large effect size (η^2p = 0.63), but not for the other interactions (time per muscle, and intensity per muscle) with a small and medium effect size respectively (Table 3). The MF_{EMG} was higher at the beginning than at the end of the IFP when both muscles were exerted at 30% MVC_{isom}, ~~whereas~~ but no significant differences were observed when they were exerted at 50% MVC_{isom}. Finally, we observed a significant main effect for intensity and muscle factor (Table 3).

4. Discussion

~~Accepting the definition of f~~ The MVC_{isom} decrement observed in our IFP confirmed the occurrence of muscle fatigue as this physiological phenomenon ~~atigue~~ is commonly defined as the "loss of the maximal force-generating capacity" [20,21], ~~the MVC_{isom} decrement observed in our IFP confirmed the occurrence of fatigue~~. ~~Having confirmed fatigue f~~From ~~a~~the functional and neurophysiological point of view, and according to the literature, the MF_{EMG} decrement of

Commented [RB14]: Puedes usar IFP???

Commented [RB15]: Creo que mas arriba solo se utiliza la forma abreviada (CR). Repasaria the sEMG power spectrum is related, among other factors, to: 1) a reduction in the conduction velocity of the active fibers [24,41] ; 2) impairment of the excitation–contraction coupling [28] related to metabolic changes that occur during fatigue [59]; 3) the recruitment of new units [60], related to metabolic changes that occur during fatigue [59]; 3) the recruitment of new units [60], based on the knowledge that subjects with a high relative number of fast twitch fibers may have higher sEMG frequency values [61], and that during fatigue, they show a greater shift towards lower MF_{EMG} compared to subjects with a low relative number of fast twitch fibers [62]; 4) structural damage to muscle cells when muscle soreness is reported by the subjects [18]; 5) other reactions taking place beyond the muscle cell membrane [63], based on observations that short resting periods between each muscle activation are sufficient to maintain the neuromuscular excitability at normal levels during IFP.

It must be highlighted that this study did not intend to explain the changes in MF_{EMG} induced by fatigue from a physiological persepective, , we were focus on the relationship between the MF_{EMG} and the two factors controlled in our IFP: the load intensity and the work–rest cycle.

High variability of MF_{EMG} values at low loads has been attributed to the influence of the number of recruited muscle fibers and the synchronism and firing rate [64]. According to this, it could be more difficult to find a significant pattern at 30% MVC_{isom} rather than 50% MVC_{isom}, but we found that the MF_{EMG} of the CR and FS decreased more consistently throughout the IFP when the muscles were exerted at 30% MVC_{isom} in comparison to 50% MVC_{isom}. The regression analysis of each individual revealed systematically stronger correlations, coefficients of determination and statistical significance with CR_{30} and FS_{30} in comparison with CR_{50} and FS_{50}. Moreover, particiapants reported a stronger relationship between the number of rounds accomplished and the MF_{EMG} at 30% MVC_{isom}, rather than 50% MVC_{isom}, in both muscles that were assessed. In agreement to this, we found a higher and more significant MF_{EMG} decrement when the participants performed the IFP at 30% MVC_{isom}, which it may suggest different neuromuscular fatigue patterns between the CR_{50} and FS_{50} during the IFP [19]. If force intensity would be the only one factor explaining these differences, it would be difficult to argue that the time to exhaustion of any

fatigue protocol would be longer when muscles work at higher intensities, when other studies, as expected, proved the opposite [25,28,65]. Moreover, when studying the magnitude of fatigue in two different IFPs at two different intensities (25 and 50% MVC), Seghers and Spaepen [48] observed very similar relative MF_{EMG} decrements in the two muscles analyzed (IFP at 25% MVC_{isom}: 29%, and 30%; IFP at 50% MVC_{isom}: 29%, and 28%), when sustaining an isometric contraction at 75% of prefatigued MVC_{isom} at the end of both protocols [48]. On the other hand, whereas the same authors observed a significant negative slope of the MF_{EMG} during the IFP at 25% MVC_{isom}, during the IFP at 50% MVC_{isom} the slope did not differ significantly from zero. It is possible that the differences in MF_{EMG} changes during the two IFPs could be more related to differences in their work–rest cycles (10+10 s in 25% MVC_{isom} and 5+15 s in 50% MVC_{isom}) than in the contraction intensity . In rock climbers, the significant reduction in the MF_{EMG} observed during an intense IFP (80% MVC_{isom}) [66], with a work–rest cycle of 5 + 5 s (same cycle as in our IFP for the 30% MVC_{isom}), indicates that the majority of the frequency components of the MF_{EMG} are unaffected by tension [42]. Thus, we believe that the key point for understanding the different MF_{EMG} patterns during our IFP must be the resting period before the two intensities. Only 5 s of recovery were interspersed between braking muscle contractions of the forearm at 30% MVC_{isom} compared to the 60 s (1 minute) at 50% MVC_{isom}. This clearly indicates that MF_{EMG} can be explained to a greater extent when the riders have a very short recovery time despite a smaller contraction intensity (30% MVC_{isom} instead of 50% MVC_{isom}) and a shorter contraction time (5 s for 30% MVC_{isom} instead of 10 s for 50% MVC_{isom}). Similar results were reported by Nagata et al. [30],. Nevertheless, it is important to highlight that these authors used a continuous
Nagata et al. [30],. Nevertheless, it is important to highlight that these authors used a continuous
Nagata et al. [30],. Nevertheless, it is important to highlight that these authors used a continuous
Nagata et al. [30],. Nevertheless, it is important to highlight that these authors used a continuous
Nagata et al. [30],. Nevertheless, it is important to highlight that these authors used a continuous
Nagata et al. [30], . Nevertheless, it is important to highlight that these authors used a continuous fatigue protocol . Nevertheless, it is important to highlight that these authors used a continuous fatigue protocol in which the force was maintained at an intensity of 60% MVC_{isom} until exhaustion, which substantially differs to the IFP in our study.

Commented [RB16]: Esta frase es bastante complicada. Propongo:

In agreement with these findings and in contrast to previous studies using CFP, force intensity cannot be the main factor to explain these differences being the recovery period a key factor to consider as well...

Before undertaking this study, it was not evident that 1 min of recovery before the 50% MVC_{isom} could be long enough to allow a systematic recovery of the MF_{EMG} towards baseline levels (pre-fatigued) . The MF_{EMG} recovery curve towards pre-fatigued values can be characterized by an exponential function [67-69], as well as a logarithmic course characterized by large inter-individual variations [67,70]. Therefore, a large proportion of the MF_{EMG} spectrum recovery corresponds to the first 1 min of the exponential recovery curve [24,26,49,50,67-71]. However, depending on the fatigue protocol, this does not mean full restoration comparable to pre-fatigued or basal MF_{EMG} values. Following the completion of ten cycles of work/rest (10 s/10 s) at MVC_{isom}, Mills [68] observed that the mean power frequency of a compound muscle action potential evoked by supramaximal nerve stimulation required 3 min to recover 50% of its initial values. Three to six minutes, depending on age, are sometimes necessary to recover the prefatigued MF_{EMG} values of the abductor digiti-minimi muscle after a MVC_{isom} exertion maintained until 50% MVC_{isom} [72]. Other studies [57,70,73] have confirmed that the majority of the MF_{EMG} spectrum is reestablished after 1 and 3 min of recovery, but full recovery it may take until the fifth minute [26,70]. Interestingly, Krogh-Lund and Jorgensen [26] observed that the restoration of MF_{EMG} paralleled that of conduction velocity for the last 4 min of recovery. Regarding the first part of the exponential recovery curve, 35 s were sufficient to allow restoration of 50% of the decline in MF_{EMG} during the previous fatigue protocol [67], but a longer interval (1.4 min) was required to reach 50% of pre-fatigued values for the biceps brachii [74]. Faster MF_{EMG} recovery (up to 85% of the pre-fatigued state during the first minute) was found by Krogh-Lund in the brachioradialis and biceps brachii muscles .

Nevertheless, the standard error of the measurement (about 60 s) reported by Elfving et al. [75], which was much larger than the average recovery, reflects the large between-subject variability of the MF_{EMG} parameter when studying the recovery phase. The inconclusive results reported in the literature combined with the accepted large variability that characterizes this type of analysis, support the idea that different combinations of IFP (contraction intensities and durations of contraction and relaxation) to assess muscle fatigue can provide different results [48]. Thus, it is difficult to compare sEMG data from different studies it is even more complicated when the protocol involves voluntary exercise [20]. The fact that the physiological mechanisms causing muscle fatigue are specific to the task which is performed [76], it should encourage future studies

Commented [RB17]: Esto no se entiende bien

No se si quieres decir algo asi:

MF emg went alongside the conduction velocity for the last 4 min of recvovery

Commented [RB18]: Quizas utilizaria las mismas unidades siempre: segundos en lugar de minutos.

looking at road racing motorcycle riders to focuson the specific conditions of the forearm muscles in order to understand better pathologies such as exercise-induced compartment syndrome. .

Commented [RB19]: No se si queda bien esto aqui???

The main limitations of this study were that effort duration, contraction intensity and recovery
The main limitations of this study were that effort duration, contraction intensity and recovery
The main limitations of this study were that effort duration, contraction intensity and recovery

5. Conclusions

This study reproduced, in the most accurate way and in laboratory conditions,the braking action of in road racing motorcycle riders to investigate different work–rest cycles during an IFP .

Results showed that short recovery periods between 5 and 10 s after submaximal muscle contractions are more effective to induce muscle fatigue than IFP at higher intensity and with longer recovery periods., and a duration of much less than 1 min for the resting time (no more than 30 s according to the results of previous studies [24,26,49,50,67-69,71]. Furthermore, to apply intensities above 50% MVC$_{isom}$ may not be useful for road racing motorcycle riders since they suggested that only around 30% MVC$_{isom}$ is required to break in real conditions when they have to slow down at high speed (more than 270 km/h) to connect a straight line with a slow curve [19]. Muscle contraction times longer than 10 sec are not useful either to match road racing requirements so protocols involving this type of contractions are not recommended for these individuals.

Commented [RB20]: Revisar si esto esta bien

Commented [RB21]: Esta fras no esta clara

Finally, accelerations with the right hand promote hand dorsal flexion and the assessment of both movements (braking and acceleration) has not been combined in a single IFP. This must be taken into account in future studies to match real conditions of road motorcycle racing in laboratory settings. This knowledge is needed to enhance our understanding of the most appropriate stimulus (muscle contraction intensities and recovery periods) to be applied within the training programes of road racing motorcycle riders in order to mimic racing conditions and to reduce the risk of muscle pathologies such as the compartment syndrome of forearms.

Acknowledgment

This work was supported by the Spanish Ministry of Economy and the European Funds for Regional Development under Grant [DEP2015-70701-P (MINECO/FEDER)], the Institut National d'Educació Física de Catalunya (INEFC) – University of Barcelona (UB), and the Research Group in Physical Activity and Health (GRAFiS, Generalitat de Catalunya 2014SGR/1629). We are grateful to MONLAU Competició and Dani Ribalta Pro-School.

REFERENCES

1. Silverstein, B.A.; Fine, L.J.; Armstrong, T.J. Occupational factors and carpal tunnel syndrome. *Am J Ind Med* **1987**, *11*, 343-358.
2. Goubier, J.N.; Saillant, G. Chronic compartment syndrome of the forearm in competitive motor cyclists: a report of two cases. *Br J Sports Med* **2003**, *37*, 452-453; discussion 453-454.
3. Barrera-Ochoa, S.; Haddad, S.; Correa-Vazquez, E.; Font Segura, J.; Gil, E.; Lluch, A.; Soldado, F.; Mir-Bullo, X. Surgical Decompression of Exertional Compartment Syndrome of the Forearm in Professional Motorcycling Racers: Comparative Long-term Results of Wide-Open Versus Mini-Open Fasciotomy. *Clin J Sport Med* **2016**, *26*, 108-114, doi:10.1097/JSM.0000000000000216.
4. Gondolini, G.; Schiavi, P.; Pogliacomi, F.; Ceccarelli, F.; Antonetti, T.; Zasa, M. Long-Term Outcome of Mini-Open Surgical Decompression for Chronic Exertional Compartment Syndrome of the Forearm in Professional Motorcycling Riders. *Clinical Journal of Sport Medicine* **2019**, *29*, 476-481, doi:10.1097/JSM.0000000000000539.
5. Brown, J.S.; Wheeler, P.C.; Boyd, K.T.; Barnes, M.R.; Allen, M.J. Chronic exertional compartment syndrome of the forearm: a case series of 12 patients treated with fasciotomy. *The Journal of hand surgery, European volume* **2011**, *36*, 413-419, doi:10.1177/1753193410397900.
6. Marina, M.; Porta, J.; Vallejo, L.; Angulo, R. Monitoring hand flexor fatigue in a 24-h motorcycle endurance race. *J Electromyogr Kinesiol* **2011**, *21*, 255-261, doi:10.1016/j.jelekin.2010.11.008.
7. Bystrom, S.; Sjogaard, G. Potassium homeostasis during and following exhaustive submaximal static handgrip contractions. *Acta Physiol Scand* **1991**, *142*, 59-66, doi:10.1111/j.1748-1716.1991.tb09128.x.
8. Torrado, P.; Cabib, C.; Morales, M.; Valls-Sole, J.; Marina, M. Neuromuscular Fatigue after Submaximal Intermittent Contractions in Motorcycle Riders. *Int J Sports Med* **2015**, *36*, 922-928, doi:10.1055/s-0035-1549959.
9. Marina, M.; Torrado, P.; Busquets, A.; Ríos, J.G.; Angulo-Barroso, R. Comparison of an intermittent and continuous forearm muscles fatigue protocol with motorcycle riders and control group. *Journal of Electromyography and Kinesiology* **2013**, *23*, 84-93, doi:10.1016/j.jelekin.2012.08.008.

10. Dousset, E.; Jammes, Y. Reliability of burst superimposed technique to assess central activation failure during fatiguing contraction. *Journal of Electromyography and Kinesiology* **2003**, *13*, 103-111, doi:10.1016/S1050-6411(02)00064-0.
11. Liu, J.Z.; Shan, Z.Y.; Zhang, L.D.; Sahgal, V.; Brown, R.W.; Yue, G.H. Human brain activation during sustained and intermittent submaximal fatigue muscle contractions: an FMRI study. *J Neurophysiol* **2003**, *90*, 300-312, doi:10.1152/jn.00821.2002.
12. De Luca, C.J. Myoelectrical manifestations of localized muscular fatigue in humans. *Crc Critical Reviews in Biomedical Engineering* **1984**, *11*, 251-279.
13. Merletti, R.; LoConte, L.R. Surface EMG signal processing during isometric contractions. *Journal of Electromyography and Kinesiology* **1997**, *7*, 241-250, doi:10.1016/s1050-6411(97)00010-2.
14. Mamaghani, N.K.; Shimomura, Y.; Iwanaga, K.; Katsuura, T. Mechanomyogram and electromyogram responses of upper limb during sustained isometric fatigue with varying shoulder and elbow postures. *J Physiol Anthropol Appl Human Sci* **2002**, *21*, 29-43, doi:10.2114/jpa.21.29.
15. Fuglevand, A.J.; Zackowski, K.M.; Huey, K.A.; Enoka, R.M. Impairment of neuromuscular propagation during human fatiguing contractions at submaximal forces. *J Physiol* **1993**, *460*, 549-572.
16. Gamet, D.; Maton, B. The fatigability of two agonistic muscles in human isometric voluntary submaximal contraction: an EMG study - I. Assessment of muscular fatigue by means of surface EMG. *Eur J Appl Physiol Occup Physiol* **1989**, *58*, 361-368, doi:10.1007/BF00643510.
17. Mathiassen, S.E.; Winkel, J. Quantifying variation in physical load using exposure-vs-time data. *Ergonomics* **1991**, *34*, 1455-1468.
18. Bystrom, S.E.; Mathiassen, S.E.; Fransson-Hall, C. Physiological effects of micropauses in isometric handgrip exercise. *Eur J Appl Physiol Occup Physiol* **1991**, *63*, 405-411, doi:10.1007/bf00868070
19. Marina, M.; Torrado, P.; Busquets, A.; Rios, J.G.; Angulo-Barroso, R. Comparison of an intermittent and continuous forearm muscles fatigue protocol with motorcycle riders and control group. *J Electromyogr Kinesiol* **2013**, *23*, 84-93, doi:10.1016/j.jelekin.2012.08.008.
20. Vollestad, N.K. Measurement of human muscle fatigue. *J Neurosci Methods* **1997**, *74*, 219-227.
21. Bigland-Ritchie, B.; Cafarelli, E.; Vollestad, N.K. Fatigue of submaximal static contractions. *Acta Physiol Scand Suppl* **1986**, *556*, 137-148.
22. Hunter, S.K. Sex differences in human fatigability: Mechanisms and insight to physiological responses. *Acta Physiol (Oxf)* **2014**, *210*, 768-789, doi:10.1111/apha.12234.
23. Hunter, S.K.; Enoka, R.M. Changes in muscle activation can prolong the endurance time of a submaximal isometric contraction in humans. *J Appl Physiol (1985)* **2003**, *94*, 108-118, doi:10.1152/japplphysiol.00635.2002.
24. Krogh-Lund, C. Myo-electric fatigue and force failure from submaximal static elbow flexion sustained to exhaustion. *Eur J Appl Physiol Occup Physiol* **1993**, *67*, 389-401.
25. Bystrom, S.E.; Kilbom, A. Physiological response in the forearm during and after isometric intermittent handgrip. *Eur J Appl Physiol Occup Physiol* **1990**, *60*, 457-466, doi:10.1007/bf00705037
26. Krogh-Lund, C.; Jorgensen, K. Changes in conduction velocity, median frequency, and root mean square-amplitude of the electromyogram during 25% maximal voluntary contraction of the triceps brachii muscle, to limit of endurance. *Eur J Appl Physiol Occup Physiol* **1991**, *63*, 60-69, doi:10.1007/bf00760803.

27. Petrofsky, J.S.; Lind, A.R. Frequency analysis of the surface electromyogram during sustained isometric contractions. *Eur J Appl Physiol Occup Physiol* **1980**, *43*, 173-182.

28. Krogh-Lund, C.; Jorgensen, K. Myo-electric fatigue manifestations revisited: power spectrum, conduction velocity, and amplitude of human elbow flexor muscles during isolated and repetitive endurance contractions at 30% maximal voluntary contraction. *Eur J Appl Physiol Occup Physiol* **1993**, *66*, 161-173.

29. Krogh-Lund, C. Myo-electric fatigue and force failure from submaximal static elbow flexion sustained to exhaustion. / Fatigue myoelectrique et manque de force de la flexion statique sousmaximale du coude maintenue jusqu ' a epuisement. *European Journal of Applied Physiology & Occupational Physiology* **1993**, *67*, 389-401.

30. Nagata, S.; Arsenault, A.B.; Gagnon, D.; Smyth, G.; Mathieu, P.A. EMG Power spectrum as a measure of muscular fatigue at different levels of contraction. *Med Biol Eng Comput* **1990**, *28*, 374-378, doi:10.1007/bf02446157.

31. Ratkevicius, A.; Skurvydas, A.; Povilonis, E.; Quistorff, B.; Lexell, J. Effects of contraction duration on low-frequency fatigue in voluntary and electrically induced exercise of quadriceps muscle in humans. *Eur J Appl Physiol Occup Physiol* **1998**, *77*, 462-468, doi:10.1007/s004210050361.

32. Krogh-Lund, C.; Jorgensen, K. Myo-electric fatigue manifestations revisited: power spectrum, conduction velocity, and amplitude of human elbow flexor muscles during isolated and repetitive endurance contractions at 30 percent maximal voluntary contraction. *European Journal of Applied Physiology & Occupational Physiology* **1993**, *66*, 161-173.

33. Mundale, M.O. The relationship of intermittent isometric exercise to fatigue of hand grip. *Arch Phys Med Rehabil* **1970**, *51*, 532-539.

34. Lee, C.; Katsuura, T.; Harada, H.; Kikuchi, Y. Localized muscular load to different work patterns and heat loads during handgrip. *Ann Physiol Anthropol* **1994**, *13*, 253-262, doi:10.2114/ahs1983.13.253

35. Quaine, F.; Vigouroux, L.; Martin, L. Finger flexors fatigue in trained rock climbers and untrained sedentary subjects. *Int J Sports Med* **2003**, *24*, 424-427, doi:10.1055/s-2003-41174

36. Eksioglu, M. Optimal work-rest cycles for an isometric intermittent gripping task as a function of force, posture and grip span. *Ergonomics* **2006**, *49*, 180-201, doi:10.1080/00140130500465527

37. Clancy, E.A.; Bertolina, M.V.; Merletti, R.; Farina, D. Time- and frequency-domain monitoring of the myoelectric signal during a long-duration, cyclic, force-varying, fatiguing hand-grip task. *J Electromyogr Kinesiol* **2008**, *18*, 789-797.

38. Marina, M.; Porta, J.; Vallejo, L.; Angulo, R. Monitoring hand flexor fatigue in a 24-h motorcycle endurance race. *Journal of Electromyography and Kinesiology* **2011**, *21*, 255-261, doi:10.1016/j.jelekin.2010.11.008.

39. De Luca, C.J. The use of surface electromyography in Biomechanics. *J Appl Biomech* **1997**, *13*, 135-163.

40. Merletti, R.; Sabbahi, M.A.; De Luca, C.J. Median frequency of the myoelectric signal. Effects of muscle ischemia and cooling. *Eur J Appl Physiol Occup Physiol* **1984**, *52*, 258-265.

41. Stulen, F.B.; DeLuca, C.J. Frequency parameters of the myoelectric signal as a measure of muscle conduction velocity. *IEEE Trans Biomed Eng* **1981**, *28*, 515-523.

42. Petrofsky, J.S.; Lind, A.R. Frequency analysis of the surface electromyogram during sustained isometric contractions. *Eur J Appl Physiol Occup Physiol* **1980**, *43*, 173-182.

43. Oliveira, A.S.; Goncalves, M. Neuromuscular recovery of the biceps brachii muscle after resistance exercise. *Res Sports Med* **2008**, *16*, 244-256, doi:10.1080/15438620802310800.
44. Mathiassen, S.E. The influence of exercise/rest schedule on the physiological and psychophysical response to isometric shoulder-neck exercise. *Eur J Appl Physiol Occup Physiol* **1993**, *67*, 528-539.
45. Christensen, H.; Fuglsang-Frederiksen, A. Quantitative surface EMG during sustained and intermittent submaximal contractions. *Electroencephalogr Clin Neurophysiol* **1988**, *70*, 239-247.
46. Hagg, G.M.; Milerad, E. Forearm extensor and flexor muscle exertion during simulated gripping work -- an electromyographic study. *Clin Biomech (Bristol, Avon)* **1997**, *12*, 39-43.
47. Luttmann, A.; Matthias, J.; Laurig, W. Electromyographical indication of muscular fatigue in occupational field studies. *International Journal of Industrial Ergonomics* **2000**, *25*, 645–660, doi:10.1016/S0169-8141(99)00053-0.
48. Seghers, J.; Spaepen, A. Muscle fatigue of the elbow flexor muscles during two intermittent exercise protocols with equal mean muscle loading. *Clin Biomech (Bristol, Avon)* **2004**, *19*, 24-30, doi:10.1016/j.clinbiomech.2003.08.003.
49. Kleine, B.U.; Schumann, N.P.; Stegeman, D.F.; Scholle, H.C. Surface EMG mapping of the human trapezius muscle: the topography of monopolar and bipolar surface EMG amplitude and spectrum parameters at varied forces and in fatigue. *Clin Neurophysiol* **2000**, *111*, 686-693.
50. Kamimura, T.; Ikuta, Y. Evaluation of grip strength with a sustained maximal isometric contraction for 6 and 10 seconds. *J Rehabil Med* **2001**, *33*, 225-229.
51. Green, J.G.; Stannard, S.R. Active recovery strategies and handgrip performance in trained vs. untrained climbers. *J Strength Cond Res* **2010**, *24*, 494-501, doi:10.1519/JSC.0b013e3181c06af3.
52. Keir, P.J.; Mogk, J.P. The development and validation of equations to predict grip force in the workplace: contributions of muscle activity and posture. *Ergonomics* **2005**, *48*, 1243-1259, doi:10.1080/00140130500277591.
53. Duque, J.; Masset, D.; Malchaire, J. Evaluation of handgrip force from EMG measurements. *Appl Ergon* **1995**, *26*, 61-66, doi:10.1016/0003-6870(94)00003-h
54. Hermens, H.J.; Freriks, B.; Disselhorst-Klug, C.; Rau, G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol* **2000**, *10*, 361-374, doi:10.1016/s1050-6411(00)00027-4
55. Hermens, H.J.; Freriks, B.; Merletti, R.; Stegeman, D.; Blok, J.; Rau, G.; Disselhorst-Klug, C.; Hägg, G. *SENIAM projecte: European Recommendations for Surface electroMyoGraphy*; Roessingh Research and Development: Enschede, Netherlands, 1999.
56. Enoka, R.M.; Stuart, D.G. Neurobiology of muscle fatigue. *J Appl Physiol* **1992**, *72*, 1631-1648.
57. Petrofsky, J.S. Quantification through the surface EMG of muscle fatigue and recovery during successive isometric contractions. *Aviat Space Environ Med* **1981**, *52*, 545-550.
58. Bigland-Ritchie, B.; Donovan, E.F.; Roussos, C.S. Conduction velocity and EMG power spectrum changes in fatigue of sustained maximal efforts. *Journal Of Applied Physiology: Respiratory, Environmental And Exercise Physiology* **1981**, *51*, 1300-1305, doi:10.1152/jappl.1981.51.5.1300
59. Allen, D.G.; Lamb, G.D.; Westerblad, H. Skeletal muscle fatigue: cellular mechanisms. *Physiol Rev* **2008**, *88*, 287-332, doi:10.1152/physrev.00015.2007

60. Solomonow, M.; Baten, C.; Smit, J.; Baratta, R.; Hermens, H.; D'Ambrosia, R.; Shoji, H. Electromyogram power spectra frequencies associated with motor unit recruitment strategies. *J Appl Physiol* **1990**, *68*, 1177-1185, doi:10.1152/jappl.1990.68.3.1177
61. Moritani, T.; Gaffney, F.; Carmichael, T.; Hargis, J. Interrelationships among muscle fiber types, electromyogram, and blood pressure during fatiguing isometric contraction. In *Biomechanics IX-A*, Winter, D.A., Norman, R., Well, R., Hayes, K., Patla, A., Eds.; Human Kinetics: Champaign, Illinois, 1985; Volume 5A, pp. 287-292.
62. Komi, P.V.; Tesch, P. EMG frequency spectrum, muscle structure, and fatigue during dynamic contractions in man. *Eur J Appl Physiol Occup Physiol* **1979**, *42*, 41-50.
63. Klass, M.; Guissard, N.; Duchateau, J. Limiting mechanisms of force production after repetitive dynamic contractions in human triceps surae. *J Appl Physiol* **2004**, *96*, 1516-1521; discussion, doi:10.1152/japplphysiol.01049.2003.
64. Peixoto, L.R.; da Rocha, A.F.; de Carvalho, J.L.; Goncalves, C.A. Electromyographic evaluation of muscle recovery after isometric fatigue. *Conf Proc IEEE Eng Med Biol Soc* **2010**, *2010*, 4922-4925, doi:10.1109/IEMBS.2010.5627256.
65. West, W.; Hicks, A.; Clements, L.; Dowling, J. The relationship between voluntary electromyogram, endurance time and intensity of effort in isometric handgrip exercise. *Eur J Appl Physiol Occup Physiol* **1995**, *71*, 301-305.
66. Vigouroux, L.; Quaine, F. Fingertip force and electromyography of finger flexor muscles during a prolonged intermittent exercise in elite climbers and sedentary individuals. *J Sports Sci* **2006**, *24*, 181-186, doi:10.1080/02640410500127785.
67. Elfving, B.; Liljequist, D.; Dedering, A.; Nemeth, G. Recovery of electromyograph median frequency after lumbar muscle fatigue analysed using an exponential time dependence model. *Eur J Appl Physiol* **2002**, *88*, 85-93, doi:10.1007/s00421-002-0685-2.
68. Mills, K.R. Power spectral analysis of electromyogram and compound muscle action potential during muscle fatigue and recovery. *Journal of Physiology* **1982**, *Vol. 326*, 401-409.
69. Kroon, G.W.; Naeije, M.; Hansson, T.L. Electromyographic power-spectrum changes during repeated fatiguing contractions of the human masseter muscle. *Arch Oral Biol* **1986**, *31*, 603-608.
70. Kuorinka, I. Restitution of EMG spectrum after muscular fatigue. *Eur J Appl Physiol Occup Physiol* **1988**, *57*, 311-315, doi:10.1007/bf00635989
71. Broman, H.; Bilotto, G.; De Luca, C.J. Myoelectric signal conduction velocity and spectral parameters: influence of force and time. *J Appl Physiol* **1985**, *58*, 1428-1437, doi:10.1152/jappl.1985.58.5.1428
72. Hara, Y.; Findley, T.W.; Sugimoto, A.; Hanayama, K. Muscle fiber conduction velocity (MFCV) after fatigue in elderly subjects. *Electromyogr Clin Neurophysiol* **1998**, *38*, 427-435.
73. Kadefors, R.; Kaiser, E.; Petersén, I. Dynamic spectrum analysis of myo-potentials and with special reference to muscle fatigue. *Electromyography* **1968**, *8*, 39-74.
74. Van der Hoeven, J.H.; Van Weerden, T.W.; Zwarts, M.J. Long-lasting supernormal conduction velocity after sustained maximal isometric contraction in human muscle. *Muscle and Nerve* **1993**, *16*, 312-320, doi:10.1002/mus.880160312
75. Elfving, B.; Liljequist, D.; Dedering, A.; Németh, G. Recovery of electromyograph median frequency after lumbar muscle fatigue analysed using an exponential time dependence model. *Eur J Appl Physiol* **2002**, *88*, 85-93, doi:10.1007/s00421-002-0685-2.
76. Enoka, R.M.; Duchateau, J. Muscle fatigue: what, why and how it influences muscle function. *J Physiol* **2008**, *586*, 11-23, doi:10.1113/jphysiol.2007.139477.