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# Implementing a robust wrist dynamic fatigue task: repeatability and investigation of the features involved

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*Abstract*— **In this study, we implemented a protocol for the robotic assessment of the effects of forearm muscle fatigue on wrist dynamics. The potential of robotic devices lies in the possibility to control and measure a wide variety of kinematic and physiological variables, both in repeated sessions over time and during real-time assessments. The implemented fatigue task is tailored to the robotically assessed single-subject maximal force and based on a real-time evaluation of muscle activity. The protocol resulted to be repeatable across sessions evaluated on the same subject and a preliminary step toward a better understanding of which features should be monitored to design a robust and strongly controlled dynamic fatiguing task.**

## I. Introduction

Fatigue is defined as a decline in muscle performance that largely recovers after a period of rest [1]. Although in clinics the occurrence of fatigue seems to have no impact on the functional outcome of rehabilitation [2], its insurgence causes a decline in motor performance, affecting quality of life and activities of daily living. Fatigue is commonly included as a symptom of Multiple Sclerosis, Parkinson's disease, muscle dystrophies, spinal cord injuries, and stroke. Healthy subjects can experience fatigue (both central and/or peripheral) after maximal or submaximal muscle contraction. At the periphery, sustained contractions produce higher quantities of lactate, whose presence lead to extra- and intra-cellular pH changes [3]. Muscle acidosis and other cellular mechanisms are related to muscle contraction failure and the consequent decrease in performance. The number of catabolites produced by muscle fibers during activity was found to be proportional to the decrement in the mean frequency of the surface electromyographic (sEMG) signals [4]: changes in the ion concentration influence membrane excitability of muscle tissue, resulting in a reduced muscle fiber conduction velocity (MFCV) [5]. This decrease in MFCV is largely responsible for the observed spectral shift towards lower frequencies often noted in the sEMG signal during fatigue. During sustained isometric or repetitive muscle contractions, an increase in the amplitude of the sEMG can also be observed. Combining sEMG spectral and amplitude information, Luttmann et al. [6] proposed the JASA method to discriminate fatigue from other factors, such as recovery or changes in force production. However, an index of fatigue based on sEMG amplitude changes could be feasible only when the required force production is constrained and identical, a limitation not always achievable in clinical practice. Finally, fatigue can be related not only to peripheral but also central aspects that could induce a decrease in maximal voluntary activation, through inhibition of the neural drive. This work investigated the kinematic and physiological effects produced by a fatigue task, targeting wrist flexor muscles. The objective was to identify specific features that should be monitored to meet the conditions of a repeatable and strongly controlled submaximal, dynamic fatiguing task.

## II. Methods

### A. Experimental Setup

The experimental setup involved the WristBot [7], a robotic manipulandum that allows wrist movements along three degrees of freedom (DoF), namely flexion-extension (FE), radial-ulnar deviation (RUD), and pronation-supination (PS). The device is equipped with four brushless motors, controlled in order to deliver a desired torque or oppose the wrist motion. Angular displacements of each DoF are measured by high-resolution incremental encoders. An additional encoder is mounted under the robotic handle to assess the lever arm and a custom-made soft-grip sensor is wrapped on the robotic handle to measure the intensity of the grip force. Throughout the study, the sEMG signals of four wrist muscles were recorded using bipolar Ag/AgCl electrodes with a sampling rate of 2048 Hz: the flexor carpi radialis (FCR), the extensor carpi radialis (ECR), the flexor digitorum superficialis (FDS), and the extensor digitorum (ED). Additionally, a hand-held hydraulic dynamometer was used to measure maximum grip force in kg.

### B. Experimental Protocol

Nine healthy, right-handed volunteers were recruited into the experimental protocol, approved by the ethical committee of Liguria Region (n.222REG2015), under the Declaration of Helsinki and all signed an informed consent. In the initial phase of the experiment, we explained the purpose and procedure of the experimental protocol, cleaned the skin of the right forearm, and placed the bipolar electrodes in parallel with the muscle fibers over the belly of each muscle, using manual palpation. Maximum grip force ($grip_{kg}$) was collected using a hand-held hydraulic dynamometer. After this

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evaluation, subjects sat next to the WristBot, with their right forearm strapped to the robot via Velcro bands and blindfolded to reduce their cognitive load for the whole duration of the experiment. While grasping grip sensing robotic handle, subjects were asked: 1) to exert their maximum grip force (*grip$_V$*) and 2) to perform their *maximum voluntary isometric wrist contraction* along with the flexion ($MVIC_f$) and extension ($MVIC_e$) directions. After that, the fatigue task began (Figure 1, see section C for more details). Following the fatigue task, subjects performed the same maximal contractions, including: $MVIC_f$, $MVIC_e$, and maximum grip force on both the robot handle and the hand-held hydraulic dynamometer. Lastly, we asked subjects to rate their perceived level of fatigue on a scale from 0 (“no fatigue”) to 10 (“severe fatigue”). The whole experiment was repeated in two sessions (*test* and *retest*) separated by at least 6 hours.

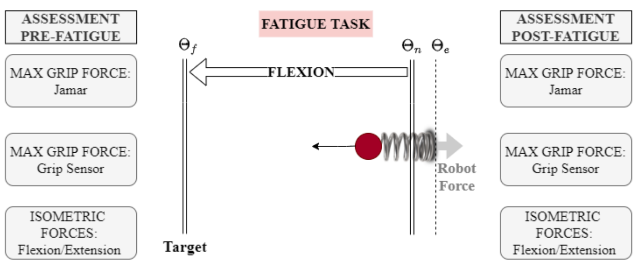


*Figure 1: Experimental protocol schematic representation. In the fatigue task, vertical lines identify the haptic walls perceived by subjects.*

## C. Fatigue Task

The fatigue task consisted of a sequence of continuous reaching movements along the FE DoF, while the other DoFs were blocked. These movements were performed in a visco-elastic force-field emulated by the robotic device. Specifically, starting from the neutral wrist position, subjects were asked to perform flexion movements to reach targets at a distance of $\theta_f = 45°$. Since subjects were blindfolded, targets were perceived as haptic walls (Figure 1): the instruction was to reach the endpoint as fast as possible. The visco-elastic force was implemented as a virtual spring, with equilibrium angle at $\theta_e = 15°$. This force-field opposed flexion and facilitated extension movements to the neutral posture, $\theta_n = 0°$. The formula of the virtual spring was:

$$F = -k(\theta - \theta_e) - b\dot{\theta} \qquad (1)$$

$k$ and $b$ are the stiffness and viscous coefficients of the force-field, respectively. In particular, the $k$ value was chosen to tailor the force on the target $\theta_f$ to be 60% of each subject $MVIC_f$, while the $b$ was equal for all subjects (5 Ns/rad). A real-time algorithm was implemented to detect when the FCR mean power frequency of two consecutive movements fell below 50% of the maximum mean frequency reached during the fatigue task. Trigger signals sent from the robot to the sEMG base unit synchronized sEMG signals and kinematic data, to associate each muscle activation with the corresponding movement. Each time an entire flexion movement was performed, the related sEMG signal of FCR was band-pass filtered (10-350 Hz) with a second-order Savitzky-Golay filter and the corresponding mean frequency computed. When the desired threshold (below 50%) was reached, a trigger signal was sent to the robot and the protocol terminated automatically.

During the execution of the task, subjects were encouraged verbally to keep moving as fast as possible until the algorithm detected the required drop of FCR mean frequency. Therefore, the number of repeated flexion movements ($N$) changed across subjects and, to compare subjects, the time series was normalized [0, 100%], independent of $N$.

## D. Post-processing and data Analysis

Kinematic data from the robotic device were processed with a sixth-order Savitzky-Golay low-pass filter, while raw sEMG data of all muscles were band-pass filtered (10-350 Hz) with a second-order Savitzky-Golay filter. sEMG data were segmented according to the trigger signal to focus the analysis on the concentric phase of the flexion movements ($N$). For each obtained segmentation, a single value of mean frequency ($F_{mean}$) was derived and thus, for each subject and each muscle, we obtained $N$ values of $F_{mean}$. An illustrative example of $F_{mean}$ changes during the task is reported in Figure 2.

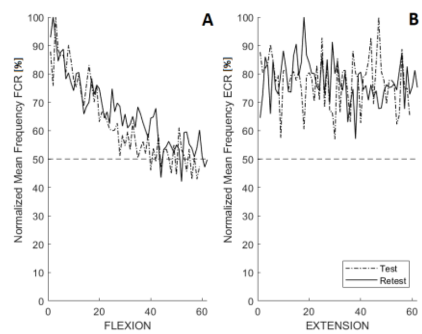


*Figure 2: Example of $F_{mean}$ percentage values for FCR, during flexion (Panel A) and for ECR, during extension (Panel B) in each trial of the fatigue task, in both test and retest sessions (Subject 1). $F_{mean}$ of each muscle was normalized by its maximum.*

The focus of this work was to assess which variables might be involved in the fatigue process. Therefore, we selected crucial measures and studied their changes before, during, and after the fatigue task: 1) the *maximum grip force* exerted on both the sensorized handle (*grip$_V$*) and the hand-held dynamometer (*grip$_{kg}$*); 2) the $MVIC_f$ and $MVIC_e$ in Newton, calculated as the ratio of the current delivered by the robotic control unit and the corresponding lever arm of the robotic handle; 3) the *maximal voluntary excitation* (*MVE*), i.e. the maximal sEMG amplitude in µV. In the concentric phase of the flexion movements during the fatigue task, we focused on the *mean velocity* ($v_{mean}$), the *time to velocity peak ratio (TPR)*, i.e., the ratio of time to peak velocity to the total duration of the movement [8], the amplitude (*root mean square: RMS)* and the spectral ($F_{mean}$) analysis of all muscles. Additionally, we computed a *muscle co-contraction index* (*CCI*) [9] of the lowest and highest normalized EMG for each agonist-antagonist muscle pair (FCR-ECR, FDS-ED for flexion movements). For each subject, these variables were calculated as the mean value in three different intervals of the duration of the fatigue task, i.e., at 0-25% (*I*), 25-75% (*II*) and 75-100% (*III*) of the entire duration of the task.

## E. Statistical Analysis

Given the small sample size, we chose non-parametric tests for the analysis. A Wilcoxon signed-rank test was used for the comparison of *test* vs *retest* outcome measures and for the evaluation of the same metrics pre- and post- fatigue task. Additionally, we analyzed changes related to the measures assessed during the fatigue task. A Friedmann Repeated Measures were used to assess the presence of difference among the values of each variable computed in the three task intervals (*I*, *II* and *III*). In case of significant differences ($p < 0.05$), pairwise Bonferroni-corrected Durbin tests were performed. The presence of any relation between dynamic changes among different variables were assessed by running a Spearman correlation ($r$). In particular, the dynamic changes for each variable were calculated as the ratio of the value in the final interval (*III*) to the value in the first interval (*I*). A correlation was considered excellent if $|r| > 0.60$. Jamovi Statistical Data Analysis tool (JSDA, version 1.6.23) was used to conduct statistical analysis.

# III. Results

## A. Repeatability

Test repeatability was assessed by means of Wilcoxon signed-rank tests on the same metrics assessed in the first session (*test* session) with those in the second one (*retest* session), both pre and post the fatigue task. $MVIC_f$, $MVIC_e$ and $grip_{kg}$ did not present significant differences between *test* and *retest*, both pre ($MVIC_f$ W = 33.0 p = 0.25; $MVIC_e$ W = 39.0 p = 0.06; $grip_{kg}$ W = 25.0 p = 0.36) and post ($MVIC_f$ W = 30.0 p = 0.43; $MVIC_e$ W = 32.0 p = 0.30; $grip_{kg}$ W = 18.5 p = 1.00) the fatigue task. Differently, $grip_V$ differed significantly between *test* and *retest* session only in the post-fatigue assessment (pre: W = 11.0 p = 0.20, post: W = 4.0 p = 0.03), that presented stronger forces exerted in the *retest* session. *MVE* did not show presence of significant difference between test and retest sessions.

## B. Pre- and Post- Fatigue Assessment

Then, we moved to the analysis of the same outcomes, focusing on pre- vs post-fatigue comparisons. For this purpose, we chose to restrict the analysis to the first session performed by each subject (*test* session). Results of Wilcoxon signed-rank test did not reveal a significant decrease in the maximal force produced during the isometric task both in flexion ($MVIC_f$ W = 28.0 p = 0.57) and in extension ($MVIC_e$ W = 21.0 p = 0.91). Interestingly, the assessments of grip force revealed a significantly reduced grip force after the fatigue task, when assessed by both the dynamometer ($grip_{kg}$ W = 44.0 p = 0.01) and the custom-made grip sensor ($grip_V$ W = 5.0 p = 0.04). The median decrease of grip force among subjects was 9.3% on the dynamometer and 18.9% on the embedded sensor. *MVE* did not show the presence of a significant difference between pre- and post-assessment. Additionally, the average rate of perceived level of fatigue was 8.3, with a minimum and maximum value of 6 and 10, respectively.

## C. Assessment during Fatigue Task

Next, we moved to the analysis of the dynamic changes of outcomes assessed in the concentric phase of flexion movements during the fatigue task. We focused only on *test* session data. Results of Friedmann Repeated Measures for the kinematics data revealed no significant differences in the mean velocity and time to velocity peak ratio among the three task intervals ($v_{mean}$: $\chi^2 = 5.2$ p = 0.07; *TPR*: $\chi^2 = 2.2$ p = 0.33). Differently, the assessments of grip force revealed a significant increase in grip force from the first to the last phase of the fatigue task ($grip_V$ $\chi^2 = 6.2$ p = 0.04; *I-III*: p = 0.04). On the other hand, considering sEMG outcomes, the Friedmann Repeated Measures test did not reveal significant differences across the fatigue task only for $F_{mean\text{-}ECR}$ ($\chi^2 = 1.6$ p = 0.46) and $RMS_{ECR}$ ($\chi^2 = 1.6$ p = 0.46), while all the other measures changed significantly during the fatigue task. In particular, the mean frequency of FCR, FDS and ED decreased during the fatigue task: $F_{mean\text{-}FCR}$ ($\chi^2 = 16$ p < 0.001; *I-II*: p<0.001, *II-III*: p<0.001, *I-III*: p<0.001), $F_{mean\text{-}FDS}$ ($\chi^2 = 18$ p < 0.001; *I-II*: p<0.001, *II-III*: p<0.001, *I-III*: p<0.001), $F_{mean\text{-}ED}$ ($\chi^2 = 7.8$ p = 0.02; *I-III*: p=0.01). Root mean square of FCR, FDS and ED increased during the fatigue task: $RMS_{FCR}$ ($\chi^2 = 16$ p < 0.001; *I-II*: p<0.001, *II-III*: p<0.001, *I-III*: p<0.001), $RMS_{FDS}$ ($\chi^2 = 18$ p < 0.001; *I-II*: p<0.001, *II-III*: p<0.001, *I-III*: p<0.001), $RMS_{ED}$ ($\chi^2 = 11$ p = 0.004; *I-III*: p<0.001) and the co-contraction indexes increased from the first to the last phase of the fatigue task: $CCI_{FCR,ECR}$ ($\chi^2 = 6.9$ p < 0.03; *I-III*: p=0.02), $CCI_{FDS,ED}$ ($\chi^2 = 9.6$ p = 0.01; *I-III*: p=0.02). Finally, the Spearman correlation test revealed a significant (p<0.05) and excellent correlation between $CCI_{FCR,ECR}$ - $F_{mean\text{-}FCR}$ ($r$ = -0.8); $CCI_{FDS,ED}$ - $F_{mean\text{-}FDS}$ ($r$ = -0.76); $v_{mean}$ - $grip_V$ ($r$ = 0.93). The average duration of the fatigue task was 85 s, with a minimum and maximum value of 45 s and 165 s, respectively.

# IV. Discussion

The purpose of this work was twofold: 1) to assess changes in a set of physiological and kinematics variables that might have a role in the occurrence of fatigue 2) to evaluate the repeatability of a custom-designed robotic fatigue protocol by testing it on the same subjects in 2 repeated sessions (*test* and *retest*). To meet both objectives, we designed a dynamic fatiguing task, consisting of a sequence of continuous reaching movements, during which subjects had to overcome a virtual spring opposing their flexion movements. The novelty of this work was the constrain of producing resistive torques tailored to each subject's maximal voluntary isometric wrist force, repeated identically among trials to reach targets in flexions. Additionally, we chose to avoid a subjective/voluntary evaluation of fatigue as a criterion to determine the end of the fatigue task. For this purpose, we implemented a real-time algorithm that terminated the fatigue task autonomously, given the mean frequency of sEMG activity from flexor carpi radialis.

The repeatability of the experimental protocol was evaluated by comparing the outcomes assessed in the *test* and *retest* sessions. Indeed, all the selected parameters did not differ significantly except for the grip force exerted on the embedded grip sensor. This result represents evidence that the chosen parameters were completely temporally controlled and therefore potentially highly reliable. Indeed, throughout the experimental protocol, subjects sat on a chair, with their right forearm strapped to the robotic device, with a good chance to control with high accuracy both their posture between pre- and post-fatigue task and the time elapsed after fatigue. Our results confirmed that the use of a robotic device could increase protocol repeatability, through both the improved accuracy of measurements and timings [7]. This point is considered crucial in clinics, for both repeated assessment on single subjects and long-lasting rehabilitative treatments.

Further analysis was conducted on the outcomes assessed in the *test* session, focusing on pre- and post-fatigue comparisons and their dynamic changes during the fatigue task. Considerably, we detected an absence of significant declines in maximal isometric force produced in both flexion and extension. This could be due to the nature of the fatigue task itself, indeed the proposed fatigue task was a dynamic, repetitive wrist flexion tasks while maximal forces were assessed pre-post using isometric tasks [10]. In addition, future work could consider a larger than 50% decline in mean frequency as the cut-off for termination of the protocol, and/or monitor more muscles in real time. However, grip force significantly decreased immediately after the fatigue task, when assessed by both the dynamometer and the custom-made soft-grip sensor. Interestingly, subjects' grip force exerted on the custom-made grip sensor increased significantly during the fatigue task. This suggests that subjects tried to compensate for the fatigue by increasing their grasp; this could also explain the maximum grip force drop in the post-fatigue assessment mentioned above. Then, no significant differences for kinematic data (mean velocity and time to velocity peak) were assessed during the concentric phase of flexion movements, meaning that subjects did not change their motor strategy to reach targets in flexion as the task proceeded. Velocity is considered a kinematic indicator of fatigue [11] and we found mean velocity to present a decreasing tendency across trials, that significantly negatively correlated with the increased grasping on the sensorized handle. The exerted grip is a variable whose value is not controlled during the fatigue task, thus probably leading to different strategies across repeated sessions. Its variability was confirmed by the difference between the grip assessed with the custom-made sensor in the test and retest sessions, only in the post fatigue assessment. For this reason, a future perspective of this work could be to implement feedback to control grip changes during the task and avoid fatigue on non-target muscles.

Moreover, as shown in the JASA method [6], fatigue can be identified when conditions of decreased spectral components and increased amplitude of the sEMG signals are met. In this work, we detected fatigue in the target muscle (FCR): both spectral components ($F_{mean}$) and amplitude (*RMS*) of muscle activity changed during the fatigue task with a significant decrease in the former and a significant increase in the latter. The same occurred for the other flexor muscle (FDS) and one of the extensor muscles (ED). Interestingly, while ED and FDS are muscles involved in the action of grasping the handle, FCR antagonist (ECR) was not affected by fatigue, thus meeting a crucial constrain of the proposed protocol, aimed at fatiguing selectively wrist flexors. Additionally, as the fatigue task progressed, a rise in both co-contraction indices (CCI) was observed. Notably, although ECR did not show fatigue, the CCI of the FCR-ECR pair was highly negatively correlated with the spectral components of the FCR, thus presenting an increased co-contraction as the task proceeded.

Finally, at the end of the task, we asked subjects to rate their perceived level of fatigue. Although all subjects reached the same level of mean frequency decrease in FCR, fatigue perception differed deeply among subjects. This may be due to a discrepancy between target-muscle fatigue and the general perceived fatigue, thus including other non-target muscles and the cognitive load involved.

For future experimental conditions, we need to consider a warm-up procedure performed with the robot before data collection, which might involve a defined series of submaximal contractions. Nevertheless, this fatigue task laid the foundation for a better understanding of the variables involved during a fatiguing task, to control and avoid unexpected effects in practical applications. Some future steps might be to combine this fatigue task with other already tested experimental protocols [12]–[14], to investigate how sensorimotor or mechanical components change after a fatiguing task.

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