A new method for quantification of muscular force and fatigue by using surface electromyographical measurements

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1 Introduction

Objective testing of individual physiological working capacity needs a quantitative measurement of muscular fatigue under real or simulated working conditions.

Another example where this measurement is needed is medical muscular training, where it is often necessary to use a well-quantified portion of the maximum voluntary force.

The goal of our research was to develop a measurement and calibration algorithm which allows that

- the muscular fatigue and the remaining muscular capacity can be quantified by using surface-electromyographical (SEMG) parameters only,
- the calculated fatigue is comparable between different individuals,
- the remaining muscular capacity is predictable at any time during strain periods
- the maximum force of a muscle can be predicted by stressing the muscle with particular forces.

To reach this aim, an equation for calculating muscular fatigue, based only on the surface electromyographical parameters “electrical activity” (EA) and “median frequency” (MF) was built.

The derivation of the determined equation is not the content of this paper. The present article only describes a small section of the proof of the equation. The calculated values were compared with well-approved values of maximum dwell time for a defined relative static force determined by *Rohmert [3], Monod & Scherrer [2] and Warlo [5]*. They were also compared to the graph of fatigue derived from results determined by *Rohmert [3]* for static strain of large trunk muscles.

A short outlook of the usability of the EMG-fatigue-equation for dynamic forces is given.

2 Basic principle

To calculate the muscular fatigue by using only the SEMG-parameters “electrical activity” and “median frequency” the following fatigue-equation was determined:

$$\mathbf{fatigue}(\mathbf{EA}, \mathbf{MF}) := \left(\frac{\mathbf{EA}}{\mathbf{EA_{zf}}} - 1\right)^{\mathbf{p1}} \left[-\left(\frac{\mathbf{MF}}{\mathbf{MF_{zf}}} - 1\right)^{\mathbf{p2}} \right] \cdot \mathbf{p3}$$

figure 1: SEMG-based equation to calculate the muscular fatigue

This equation can be used to calculate the existing fatigue at any time-point without any knowledge about the elapsed time in which a load was applied. To calculate the fatigue at an arbitrary time point the actual measured “electrical activity” and the actual measured “median frequency” are used. The parameters p1, p2 and p3 depend on the type of the muscle (ratio of fibre types), the positions of the EMG-electrodes and could be taken from a calibration algorithm that should be done before the measurements start.

For the special conditions “large trunk muscle”, “static force” and “constant electrode position” used in the following explanations, the parameters p1, p2 and p3 could be set to one. It is done, because the resulting error should be small and the equation becomes much clearer. For the explanation of the special condition “constant electrode position” see chapter “Discussion” and “EMG recordings and calculations”. The Values “EA_{zf}“ and MF_{zf} “ are explained in chapter “Calibrations / Pre-experiment measurements”.

$$\mathbf{fatigue_{simplified}}(\mathbf{EA}, \mathbf{MF}) := \left(\frac{\mathbf{EA}}{\mathbf{EA_{zf}}} - 1\right) \cdot -\left(\frac{\mathbf{MF}}{\mathbf{MF_{zf}}} - 1\right)$$

figure 2: Simplified SEMG-based equation to calculate the muscular fatigue, usable only under “special conditions”

The maximum dwell time for a static force, which causes strain in a large trunk muscle, is examined by different scientists for many subjects. Generally, the maximum dwell time increases when the necessary force to hold the applied load decreases. To compare the results from different subjects the relative force with a maximum of one (corresponding to 100%) is used. Therefore, the value of the needed force measured in Newton [N] is divided by the individual maximum voluntary force, known as “maximum voluntary contraction (MVC)”, of the muscle in consideration. In different studies, different equations were determined to calculate the maximum dwell time. Studies by *Rohmert [3], Monod & Scherrer [2] and Warlo [5]* are well known examples. These equations show large differences for the dwell time at low forces but above a force level of 40% the differences are relatively small.

In the section of the study on hand, only forces above 40% of MVC were used and the results by *Rohmert [3]* were used to prove the new EMG-fatigue-equation.

This relationship between maximum dwell time and the relative force determined by Rohmert is shown in figure 3.

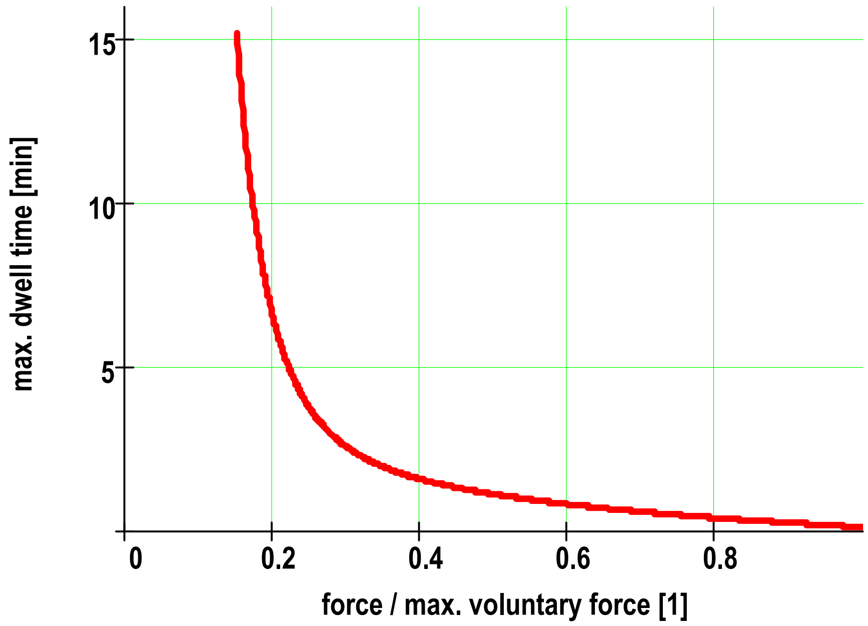

figure 3: Max. dwell time vs. relative force for static strain of trunk muscles, determined by Rohmert.

The “theoretical muscular fatigue” – derived from Rohmerts results – depends on the height of the required relative force and the elapsed dwell time. These curves end at the maximum corresponding dwell time. The curves are valid only for static forces. The curves at 33 % and 66 % of MVC are shown exemplarily in figure 4.

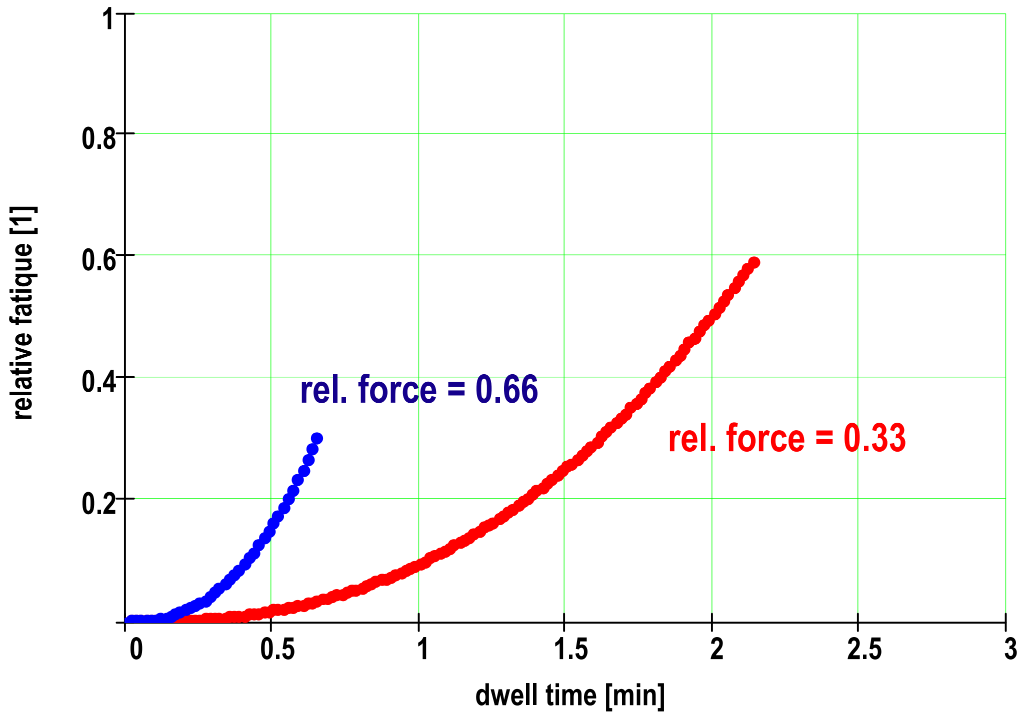

figure 4: Relative fatigue vs. dwell time for static strain of large trunk muscles, derived from Rohmert, W.

A lower and an upper limit of the "theoretical muscular fatigue" were built for a given relative force by allowing a 5 % error in force-measurement and an additional 5 % error in the resulting fatigue values. If the fatigue values calculated only from EMG-data with the new EMG-fatigue-equation are correct, then they should be within these limits at any time during the fatiguing load period.

3 Methods of the empirical verification

3.1 Subjects and technical conditions

In the present study, five subjects (2 female and 3 male) at the age between 26 and 65 years were involved. As a large trunk muscle, the "musculus biceps brachii" was used under isometric and isotonic conditions. The caput longum and the caput breve were measured separately. The position of the upper part of the body and the positions of elbow and wrist were fixed, and rotation of the forearm was prevented.
All this is shown in figure 5.

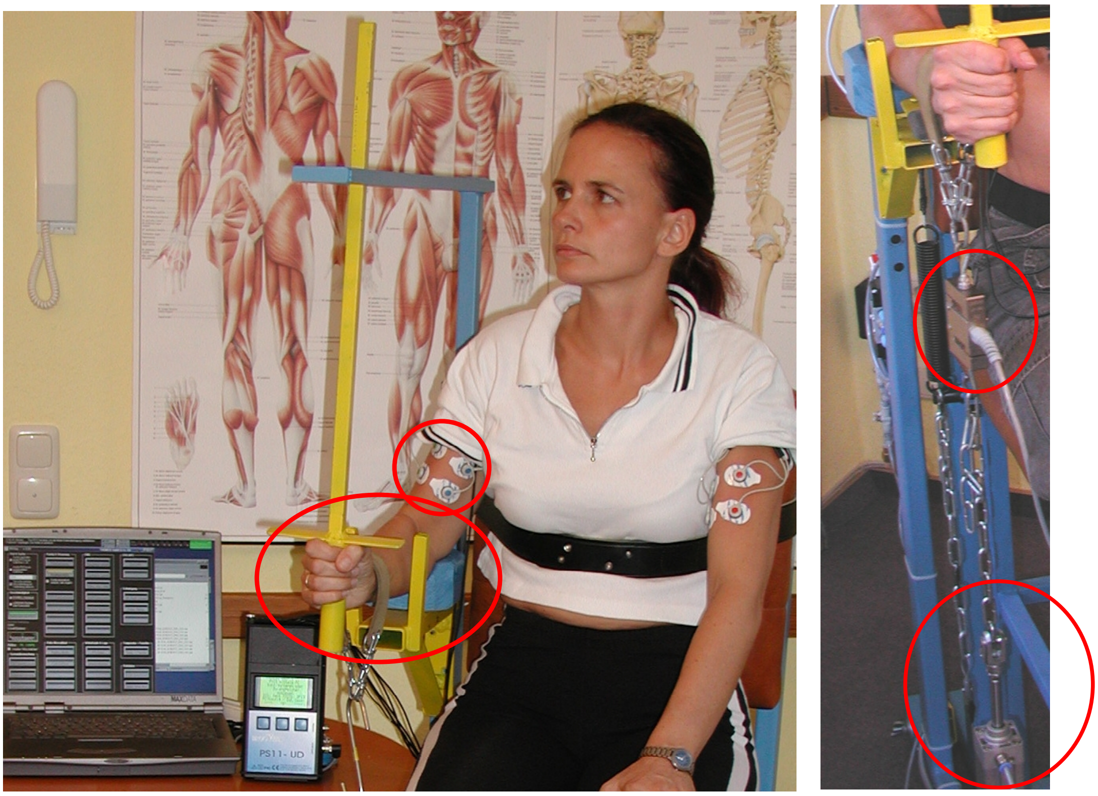

figure 5: Test setup, fixation, force generation and measurement.

The load was applied at the wrist. The desired force was generated by a computer controlled pneumatic cylinder, measured by a sensor and recorded synchronously with the EMG-data (figure 5). Thought was given also to the force generated by the weight of the forearm and the technical support tools like the force sensor and the chain.

A one-week break was given to each subject after each test. The subjects were advised to avoid muscular training in that period.

3.2 EMG recordings and calculations

The surface EMG was sampled with 4096 Hz after filtering with an 11th-Order anti-aliasing-filter. The chosen EMG-bandwidth was 16 Hz to 1250 Hz (-3 dB). Possible errors caused by parasitic frequencies at 50 Hz and multiples of 50 Hz were prevented. The electrical activity EA (RMS) was calculated as root mean square. The median frequency was taken from the power spectrum, calculated with FFT after triangle-windowing with 50 % overlap. The resolution of the median frequency was 1 Hz. Since the measured EMG-values are affected by the electrode position, the position of each electrode for each subject was saved. A stencil for both arms of each subject was made which includes the electrode positions. By using this stencil, the EMG-electrodes could be placed exactly at the same position over the entire test series.

3.3 Calibrations / Pre-experiment measurements

As a first step the maximum voluntary force of the right and the left arm (biceps) of each subject was measured. This measurement was done four times with a two-minute break in between. As described by *Ulmer and Winter* [4] these kinds of measurement should determine 95% of the subject's real maximum force (the given high motivation of the subjects should also be considered). The maximum-force-measurements were done again at the end of the test series. The variation of the maximum voluntary force was below 7% for all subjects.

As shown in chapter “basic principle” the equation to calculate the muscular fatigue from the EMG measurements includes the values “EA_{zf}“ and MF_{zf} “. These values are the electrical activity and the median frequency from a non-fatigued muscular state as a function of the relative force. These two necessary curves were taken from each subject at the beginning and at the end of the test series.
Figure 6 and figure 7 show two examples. The “*MF* vs. *force“ and* “*EA vs. force“ curves* are different for each subject and are largely influenced by the positioning of the electrodes.

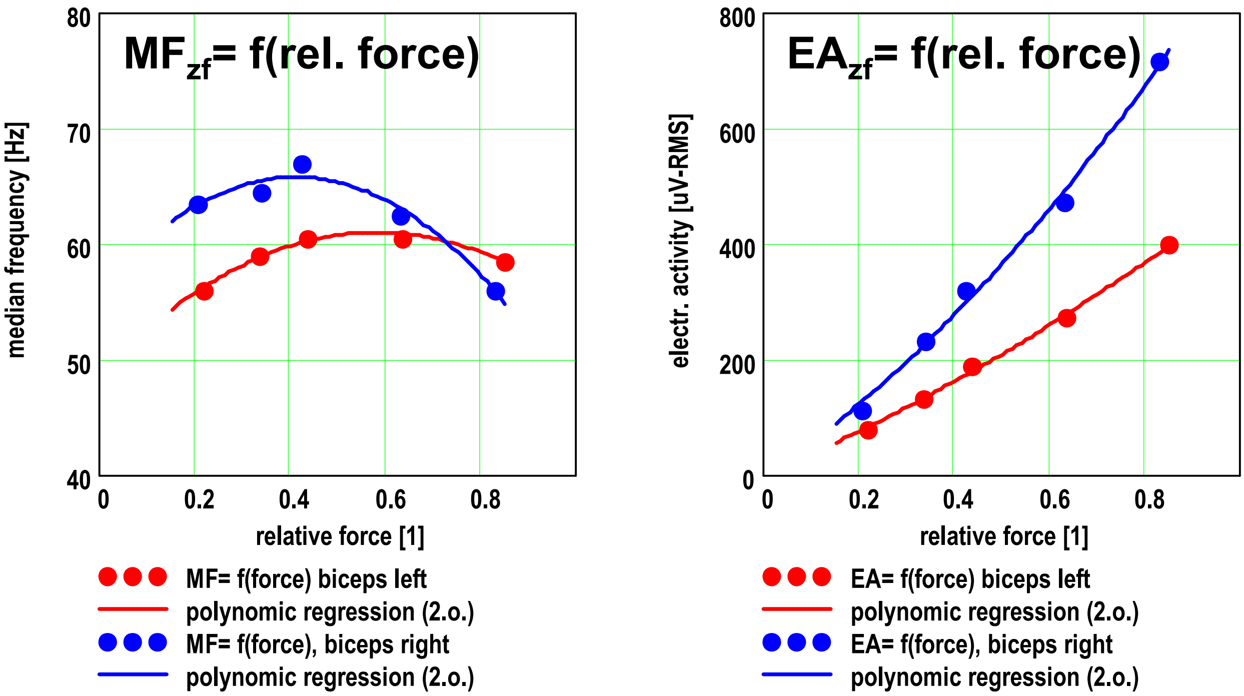

figure 6: “MF vs. force” and the “EA vs. force” curves from the muscle with zero fatigue (P05002)

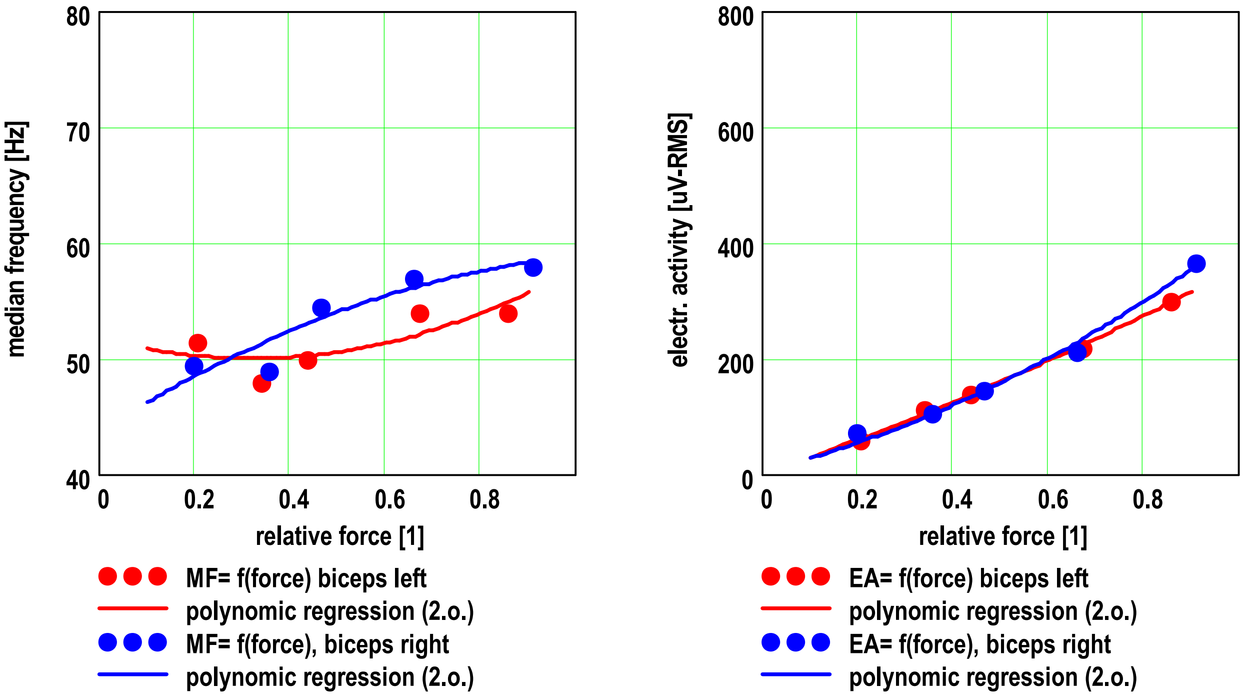

figure 7: "MF vs. force" and the "EA vs. force" curves from the muscle with zero fatigue (P05004)

As can be seen, the MF_{zf} - and the EA_{zf} - values depend on the necessary relative force of the muscle. In real world measurements, where the relative force is probably unknown, additional calibration procedures and special pre-load-tests are necessary to make the fatigue-calculation independent from the applied load. However, this task is not the topic of the present article and, first of all, the necessary relative force has to be known for the measurements made to prove the calculated fatigue at static strain! Otherwise, the comparison to Rohmert's results would be impossible!

To extract the force-depending MF_{zf} - and EA_{zf} - curves the subjects' muscles were stressed with different relative loads for a short time. The time of the load period depends on the height of the load and varied from 16 to 8 seconds (the lower the load, the longer the time). The partial forces selected for these tests were about 20 %, 33 %, 50 %, 66 % and 85 % of the subjects' MVC. These measurements were done three times. Large breaks – one to three minutes – were given between the load periods and the repetitions to avoid muscular fatigue. The applied, effective force was measured simultaneously to the EMG-recordings. Linear equations and different polynomials were tested for the approximation of the values. Best results were reached with a polynomial of 2nd degree, which was used accordingly.

3.4 Static strain tasks

To fatigue the muscle with a defined static strain, the applied force generated by the pneumatic cylinder was controlled. If a subject moves its forearm up or down – although the subjects were advised to hold the desired position exactly – the applied force was nearly constant. There were two causes for the measured variation of the force: The mechanical friction inside the pneumatic cylinder and the force generated by the mass inertia of the forearm, the load sensor and other parts. The accelerating force is mainly generated by the observed tremor of the stressed muscle. The slightly varying effective force (black line in figure 8) was considered in the calculation of the theoretical fatigue, which depends on the relative force and grows with the time the load was applied.

The static force was applied until the subject was unable to continue. The subjects were highly motivated. Each subject was stressed with static loads, which require 70 %, 45 %, 20 % and 10 % of its MVC. (To allow a complete recovery from muscular fatigue the break between these tasks lasted one weak.)

Only the results from 70 % and 45 % of MVC were used to compare it with Rohmert's results! The other values will be used for further determination of muscular fatigue at lower static forces.

The ten fatigue-curves recorded, result from the five subjects and the two static forces. Figure 8 shows an example (P05002 / T2): The load applied was calculated to require 70 % of the subject's MVC. The course of the black curve in figure 8 illustrates the effective relative force. The red line in the next chart shows the measured electrical activity and the blue line below shows the median frequency.

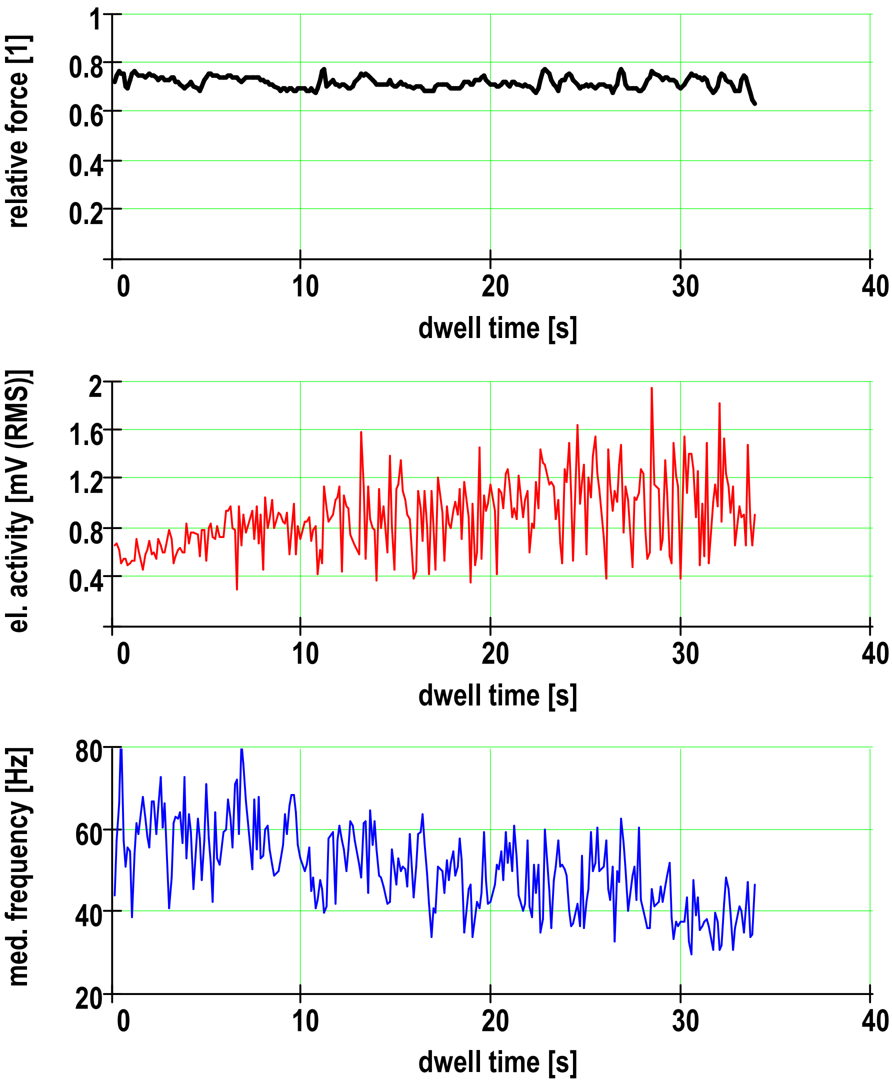

figure 8: Recorded relative force, electrical activity (EA_{RMS}) and median frequency (MF)

Once again, the black line in figure 9 shows the effective relative force. The red lines illustrate the curves of the theoretical fatigue, which were used to prove the new EMG-fatigue-equation. As described above, a maximum error of 5 % for the force-measurement and an additional 5 % - error for the resulting fatigue was allowed. These errors cause a lower and an upper limit (l.l./u.l.) of the theoretical fatigue, which lead to the two curves.

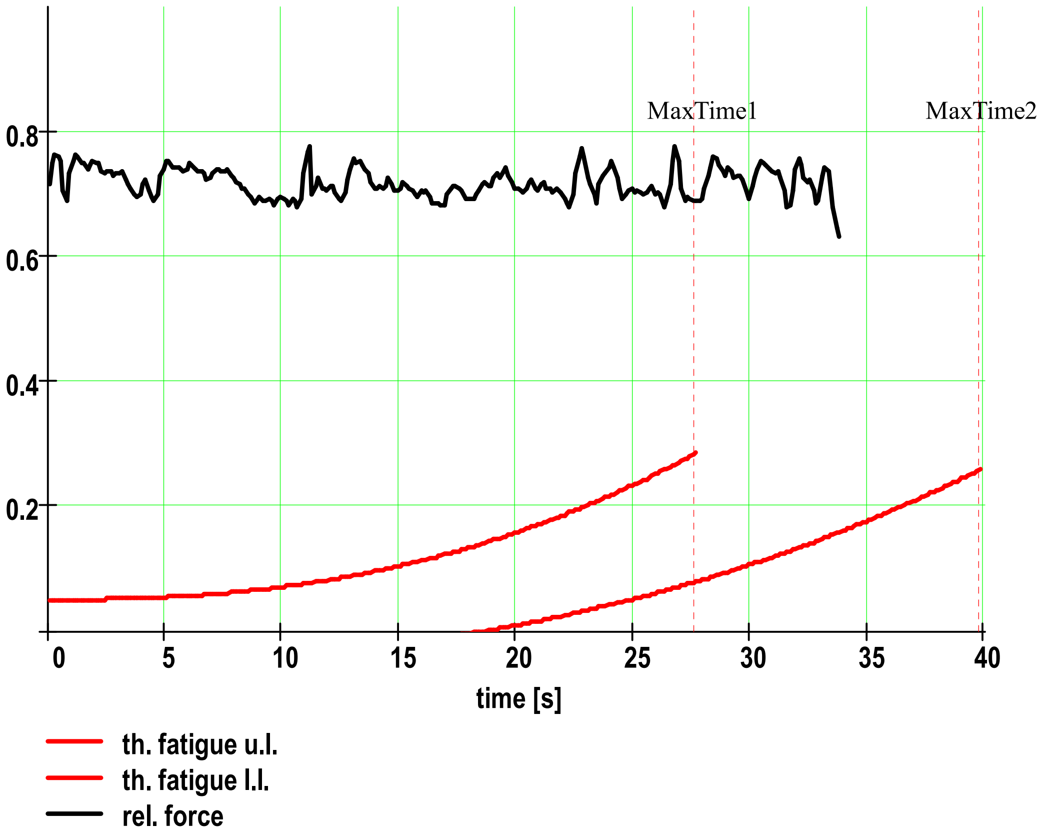

figure 9: *Recorded relative force and upper and lower limit (u.l./l.l.) of the theoretical fatigue, derived from Rohmerts results*

4 Results of the empirical verification

The thick blue line in figure 10 indicates the fatigue, calculated using the new EMG-fatigue-equation. As can easily be seen, the blue line is completely within the error-limits of the theoretical fatigue.

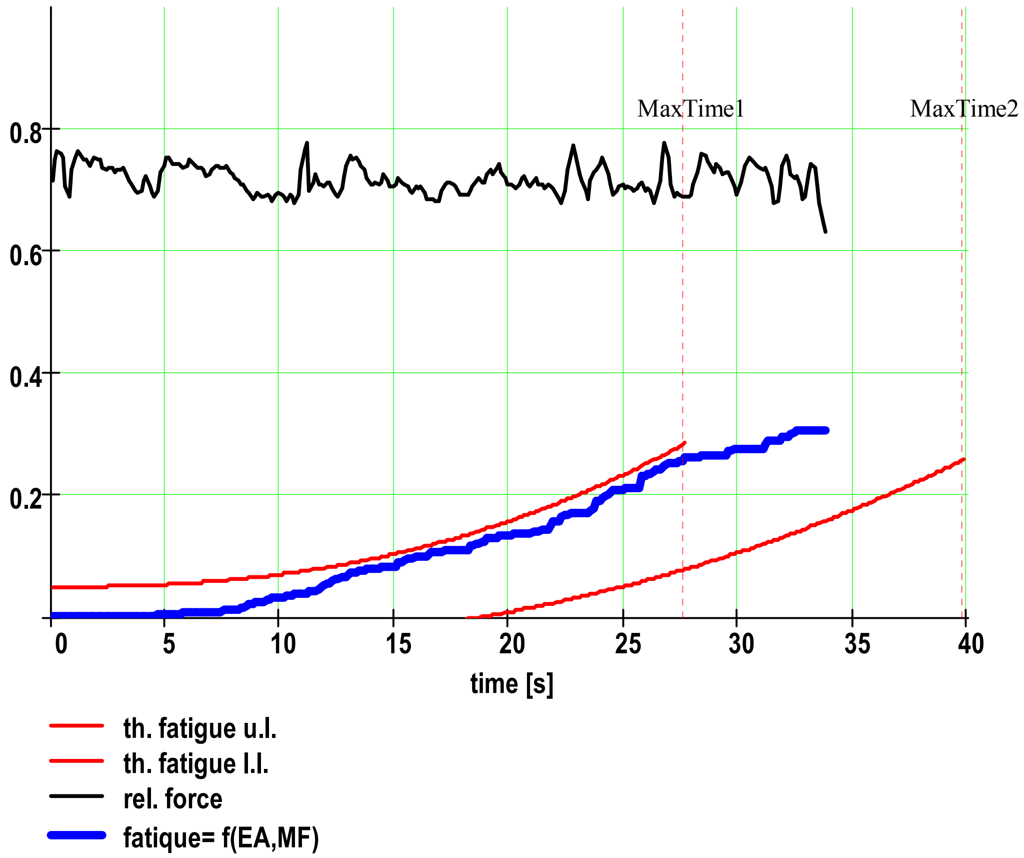

figure 10: EMG-based calculated fatigue (blue) is completely within the allowed error limits

90 % of the EMG-calculated muscular fatigue curves of the study in hand were completely within the allowed error-limits. The only curve that exceeds the allowed region was caused by a temporarily loosen contact between the EMG-electrodes and the subjects skin.

Although the five subjects and the ten tests are not enough to evaluate it statistically, the new EMG-based equation for the calculation of muscular fatigue seems to be correct since the allowed errors are small. It should be considered that the “theoretical fatigue” which is used here to prove the EMG-fatigue-calculation was derived from a study with hundreds of tests.

Please remember that the new equation did not use the elapsed dwell time! That means, even if you start your EMG-recordings at an arbitrary time point during the load period, the muscular fatigue calculated from the EMG-data is reliable!

In addition, the measured maximum dwell time was within the predicted limits in 100% of the tests (“MaxTime1” and “MaxTime2” in figures 9 and 10). These time limits were built from the maximum dwell time, determined by Rohmert, in consideration of the above-described errors in the force and fatigue-measurements.

5 Discussion

As mentioned above the small test series are not enough for a statistical evaluation. Therefore, further tests at large trunk muscles were done but have not been analysed yet. Additional tests are in progress.

The EMG-based fatigue-calculation seems to be independent from the individual: Although the measured absolute values of EA (RMS) and MF, and also the variation of this values, are largely different between the involved subjects, the EMG-based fatigue-calculation delivers correct results under all circumstances.

For different loads, the slope of the EMG-calculated fatigue-curves is different, too, and delivers a correct relation to the time- and load-dependent muscular fatigue. For static forces, this different slope should allow to predict the further fatigue and the maximum dwell time by measuring the EMG-data for a while and extrapolating the curve.

If the absolute value of the applied load is known but the subjects maximal voluntary contraction (max. force) is unknown, the EMG-based fatigue-calculation could be used to find out the MVC: Each force applied generate an fatigue-curve whose shape only depends on the height of the applied load in relation to the subject's MVC of the stressed muscle. Therefore, the relation between the applied load and the MVC could be extracted from the recorded fatigue-curve. If the height of the applied load is known, then the MVC of the stressed muscle can be derived. The results are more reliable if two known, different loads are used to stress the muscle. However, at the present stage of the investigation it is necessary to start both load periods with a non-fatigued muscle.

An experiment besides the test series indicates that the stability of the electrodes' position is very important. Movements of the electrodes' by millimetres could be enough to destroy the results completely, above all, if the electrodes' are positioned near by motor endplates. It can be shown, that the EMG-based fatigue-measurements are not reliable if electrodes with a small active area are used and the skin over the considered muscle is moved as it is expected from non-isometric contractions. Further tests with EMG-electrodes of different size (different active area) are planned to investigate if this problem is solvable.

The results shown above are proven for large trunk muscles only. It should be considered that the measured EMG-data from other muscle-types differ largely. The subjects' "musculi abductor digiti minimi" were also included in the studies. As described by *Luttmann et al. [1]* the median frequency changes much more and the electrical activity varies less in that muscle which belongs to the muscles with a larger portion of type-I-fibres. The measured data have not been completely analysed yet but a first view raises the hope that the EMG-based fatigue-calculation works for this muscle-types as well. For acceptable errors, the parameters p1 to p3 (figure 1) have to be considered in this case.

The results need to be confirmed using more subjects and different muscles in the next tests.

6 Conclusions

As shown in the introduction the determination of muscular fatigue and maximum voluntary force is necessary for an objective testing of the individual physiological working capacity and for medical muscular training. But under real circumstances there are usually no static conditions as in the described test setup. This leads to the next necessary steps, which have to be done. These real conditions were simplified as “steps in force” and, as a special case, as “dynamic forces” or “intermittent static forces”.

“Steps in force” were simulated by an enhancement of the described test setup. At the end of the static strain task, when the subjects were unable to continue, the applied load was reduced immediately. The lower force was also applied until the subjects were not able to continue. Figure 11 shows an example of this test cycle (P05002/T2). The calculated fatigue is shown in blue. Although the equation can be used to determine the fatigue of the muscle, the correctness of the results cannot be proved at the moment, because there are no standard results to compare with. Therefore, other ways of evaluation have to be used but would be outside the scope of this paper.

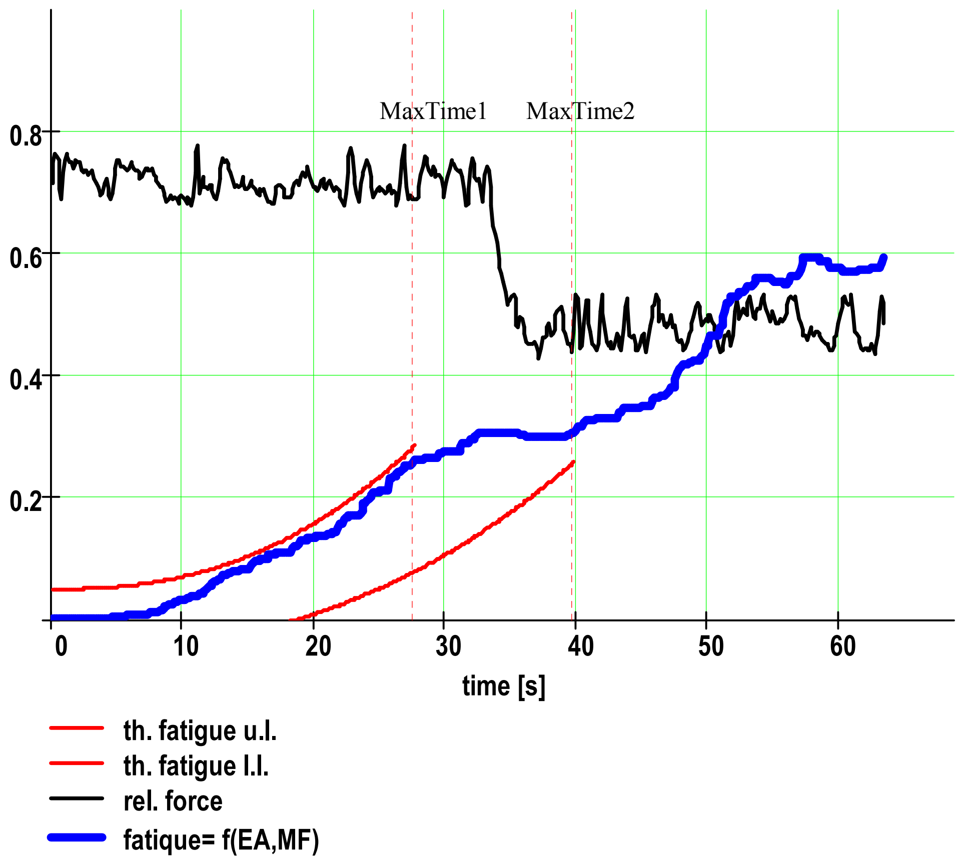

figure 11: calculated fatigue in case of the test setup “step in force“

In another test setup, the intermittent static forces were analysed. Every subject was stressed by a dynamic load with a load-relation of 50 percent, this means, the load- and pause-times were equal. The determined equation for calculating the muscular fatigue can also be used in this case. A close look at the results is shown in figure 12.

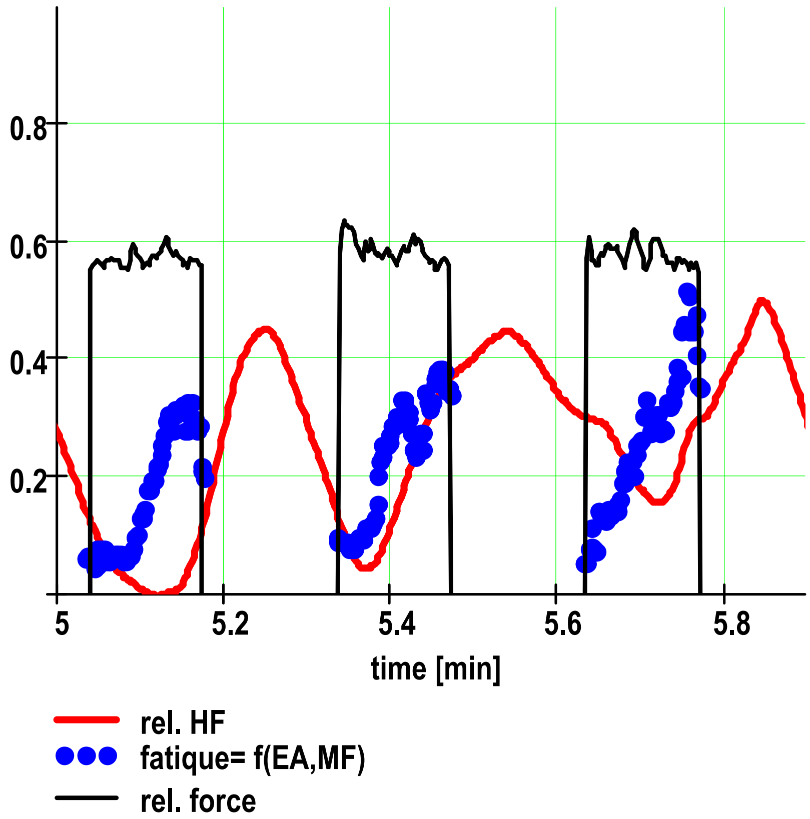

figure 12: calculated fatigue in case of the test setup “dynamic force“ in detail

As there are no approved standard results, the heart frequency (heart rate), was used for comparison. The shown value is the heart rate in relation to the heart rate at the beginning of the test and is called the “relative heart frequency (rel. HF)”. This can be seen in the chart above. The heart rate is an accepted measure for the whole body strain if large muscles are stressed.

Figure 13 shows a complete examination. The red dots represent the maximum heart frequency and the blue dots show the maximum muscular fatigue, reached in each load cycle. The close relation between heart rate and fatigue can be interpreted as a hint for the correctness of the calculated fatigue.

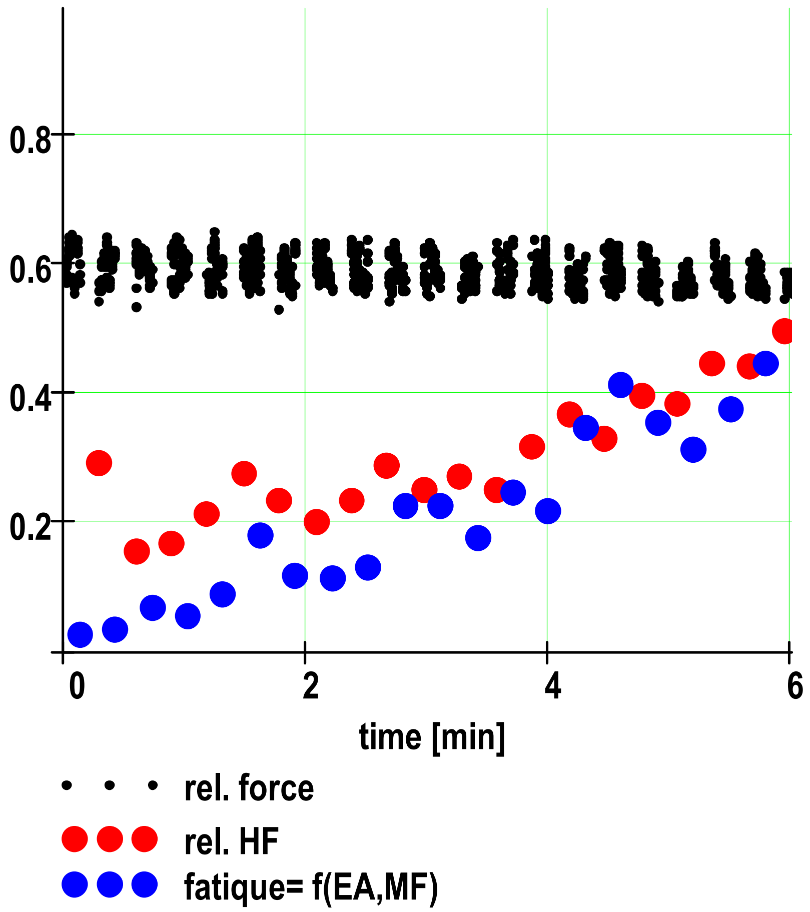

figure 13: max. fatigue and max. rel. heart rate, reached in each load cycle, in case of the test setup "dynamic force"

Nevertheless, it is necessary to find a standardised way to prove the calculated fatigue values in both cases described. This has to be the task for the next steps of investigation. However, the available data promises a successful proof.

Once the new method is fully evaluated for different muscles and also dynamic stress situations it can be used to

- test individual muscular capacity,
- analyse individual strain under real working conditions,
- design working conditions and organize sequences of working tasks under physiological aspects,
- control hardness and duration of medical muscular training by using individual constitution values.

7 Literature

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