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# Model-based Prediction of the Individual N-Repetition Maximum with Application to Physical Rehabilitation

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Abstract: The individual adjustment of the training intensity during physical training of the lower back muscles plays a crucial role in strength rehabilitation of chronic low back pain patients. Since an one-repetition maximum test may increase injury risk and a common N-repetition maximum test with several trials is stressful for the patient and in many cases inaccurate, in this paper a model-based approach is proposed for predicting the N-repetition maximum. The individual N-repetition maximum is predicted by means of a biomechanical model together with fatigue parameters obtained from an isometric maximum voluntary muscle contraction measurement and allows for a proper adjustment of the training intensity.

Keywords: Rehabilitation engineering, Biomedical system modeling, Simulation

## 1. INTRODUCTION

Low back pain has become a huge health and socioeconomic problem in industrialized countries. The life-time prevalence of low back pain is about $60-80\%$ as pointed out in Krismer and van Tulder [2007] and McBeth and Jones [2007] where its resulting disabilities cause a large number of work days lost (in average $10-40$ days of back-related absence per year and patient) and high treatment costs Nachemson [1992], Wynne-Jones et al. [2007].

About $5-10\%$ of patients with acute non-specific low back pain eventually develop chronic low back pain. As shown in Nachemson [1992] this group accounts for $75-90\%$ of the societal costs of low back pain. Treatment targets are the reduction of pain and increasing activity level and functional ability. Different treatment principles are proposed for the reduction of chronic low back pain associated disability: strength therapy, cognitive-behavioral therapy, and multidisciplinary treatment combining several treatment modalities (Smeets et al. [2007]).

Strength therapy combines muscle strength and endurance training with aerobic training. The assumption behind strength therapy is that an increased aerobic capacity in combination with muscle reconditioning, especially of the deep lumbar extensor muscles, supports better functioning. Muscle strength training of the lower back muscles is usually supervised by physiotherapists, where the patients are invited to perform the strength training on a specific training device with a certain training intensity (Smeets et al. [2006]) and range of motion (ROM).

Training intensity of muscle strengthening is usually quantified as a portion of the 1-Repetition Maximum (1-RM) or by the N-Repetition Maximum (N-RM), where $N$ denotes a number. The N-Repetition Maximum is the weight on a training device an individual can lift exactly for $N$ repetitions. Performing an 1-RM is a highly specialized skill, requires proper warming up and is associated with a high risk of muscoskeletal injury. A more save but very time-consuming procedure is determining the N-RM. Starting with an initial - usually low - weight the weight is increased step by step until the weight can be lifted exactly for the desired number of repetitions. A proper recovery time is required before increasing weight and starting the next trial. Effects of fatigue following multiple trials may reduce the accuracy for determining an equivalent repetition maximum.

In Smeets et al. [2006] the training intensity for chronic low back pain patients is proposed to be approximately 70% of the 1-RM which approximately allows for $15-18$ repetitions.

## 2. PROBLEM FORMULATION

For treatment of chronic low back pain the proper adjustment of the individual training intensity plays a crucial role. Due to the increased injury risk a 1-RM test is not acceptable for chronic low back pain patients. Repeated trials for determining the N-RM are stressful, inaccurate and time-consuming.

In contrast to statistical approaches (see for example Willardson and Bressel [2004] or Mayhew et al. [1992]) the intention of this paper is to develop a model-based method for predicting the $N-$repetition maximum from an isometric maximum voluntary contraction (MVC) measurement of the lower extensor muscles. With specialized devices (Total Trunk, Technogym - as shown in figure 1) an isometric MVC measurement in a neutral position of the lower spine can be obtained more safely compared to an 1-RM test.

Figure 1. Device for measurement of the isometric contraction force of the lower back extensors (Total Trunk, Technogym).

## 3. BIOMECHANICAL MODEL

As depicted in figure 2 the biomechanical model of muscle strengthening of the lumbar extensor muscles consists of two parts, a *mechanical model* which represents the training device itself and the mechanics of the muscoskeletal system, and a *physiological model* which describes the generation of extensor muscle force and the associated muscle fatigue.

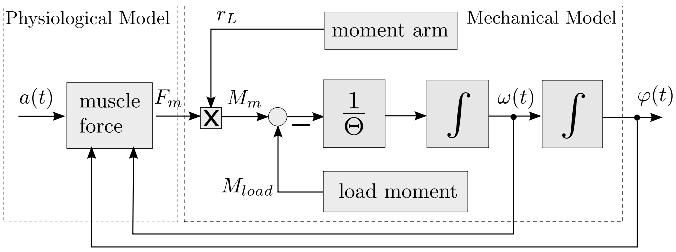


Figure 2. Biomechanical model of the lumbar extensor muscles and the training device.

### 3.1 Mechanical Model

The motion of the trunk, which for simplicity is assumed as stiff body, can be modeled by

$$\Theta \frac{d^2\varphi(t)}{dt^2} = M_m(t, \varphi(t), \dot{\varphi}(t)) - M_{load}(\varphi(t)), \tag{1}$$

where $\varphi(t)$ is the extension angle, $\Theta$ summarizes the inertia of the trunk and the training device, $M_m$ the moment generated by the lower lumbar extensor muscles and $M_{load}$ the loading moment of the training device.

The resulting muscle moment is

$$M_m(t, \varphi(t), \dot{\varphi}(t)) = r_L F_m(t, \varphi(t), \dot{\varphi}(t)) \tag{2}$$

with the moment arm $r_L$ and the muscle force $F_m$ of the lumbar extensor muscles. The loading moment depends on the weight $m$ selected for training as

$$M_{load} = r_{load} m g, \tag{3}$$

where $r_{load}$ is the effective moment arm of the load acting on the joint and $g$ the gravity constant.

The muscle force $F_m$ generated by the lumbar extensors is modeled by

$$F_m(t, \varphi(t), \dot{\varphi}(t)) = F_{max} f_{fat}(t) f_{fl}(\varphi(t)) f_{fv}(\dot{\varphi}(t)) \tag{4}$$

where $F_{max}$ denotes the maximum voluntary isometric muscle force, $f_{fat}(t)$ the influence of muscle fatigue, $f_{fl}$ the force-length relation and $f_{fv}$ the force-velocity relation of the lower back extensor which both depends on the extension angle $\varphi$. Hereby $f_{fat}$, $f_{fl}$ , and $f_{fv}$ are within the range of $[0, 1]$.

### 3.2 Muscle Modeling

*Muscle Fatigue:* Modeling muscle fatigue plays a central role for predicting the N-RM. We propose to model the effect of muscle fatigue

$$f_{fat}(t) = a(t) fit(t) \tag{5}$$

by a fitness function $fit(t)$ as proposed by Riener et al. [1996]:

$$\frac{d fit(t)}{dt} = \frac{(fit_{min} - fit(t))\, a(t)}{T_{fat}} + \frac{(1 - fit(t))\,(1 - a(t))}{T_{rec}}, \tag{6}$$

together with the muscle activation $a(t)$ with $0 \leq a \leq 1$. This first-order relation describes muscle fatigue (first term) as well as recovery (second term). If the muscle is activated by 100% ($a(t) = 1$) then the fitness function decreases and no recovery is possible. On the other hand if there is no muscle activation ($a(t) = 0$) recovery of muscle fitness takes place. The corresponding time constants are $T_{fat}$ and $T_{rec}$ respectively. The minimum fitness is given by $fit_{min}$.

*Force-Length Relation:* Due to the microscopic structure of the actin and myosin filament interaction during isometric muscle contraction, each muscle has an optimal length $l_{opt}$ at which the highest force can be produced. In case where the muscle is shorter or even longer less force can be produced, where this relationship is modeled by the following force-length relationship,

$$f_{fl}(\varphi(t)) = \exp\left[-\left(\frac{(l_0 + r_L\varphi(t))/l_{opt} - 1}{\varepsilon}\right)^2\right] \tag{7}$$

where $l_0$ denotes the initial muscle length and $\varepsilon$ a muscle-dependent shape factor (see Happee [1994]).

*Force-Velocity Relation:* As a consequence of several effects, but mainly due to an inefficient coupling of the cross bridges between actin and myosin filaments the force of muscle contraction decreases if the filaments slide quickly past each other. This reduction of muscle force is known as the force-velocity relation which originates from Hill's experiment. A parametric model of the force-velocity relation is proposed by Happee [1994] as

$$f_{fv}(\dot{\varphi}(t)) = a_0 + a_1 \arctan\left(a_2 \frac{r_L\dot{\varphi}(t)}{v_m} + a_3\right), \tag{8}$$

where $a_0$, $a_1$, $a_2$, and $a_3$ are parameters to be estimated, and $v_m$ denotes the maximum contraction velocity of the muscle.

### 3.3 Model Equations

With $\dot{\varphi}(t) := \omega(t)$ the biomechanical model equations can be summarized as follows

$$\frac{d\varphi(t)}{dt} = \omega(t) \tag{9}$$

$$\frac{d\omega(t)}{dt} = \frac{1}{\Theta}\left[M_m(a(t)fit(t), \varphi(t), \omega(t)) - M_{load}\right] \tag{10}$$

$$\frac{df_{fit}(t)}{dt} = \frac{(fit_{min} - fit(t))\,a(t)}{T_{fat}} + \frac{(1-fit(t))\,(1-a(t))}{T_{rec}}. \tag{11}$$

which describe the behavior of the muscoskeletal system during strength training of the lumbar extensors. Hereby the muscle activation $a(t)$ is considered as model input and the extension angle $\varphi(t)$ as model output. The initial conditions are $\varphi(0) = \varphi_0$, $\omega(0) = 0$, $a(0) = a_0$, and $fit(0) = 1$ respectively.

## 4. PREDICTING THE N-RM

In order to predict the $N$-RM, the patient has first to undertake an isometric MVC experiment where the maximum voluntary contraction force and its related moment is measured. Several unknown model parameters corresponding to muscle fatigue can be estimated from the measurement data. The parametric structure of the mathematical model for parameter estimation can be obtained from the biomechnical model (9)-(11) when considering isometric conditions.

Once these parameters are estimated the required muscle activation $a(t)$ can be obtained by simulating the inverse model of (9)-(11) with respect to a given reference of $\varphi(t)$. The $N$-RM is that load $m$ which allows for exactly $N$ repetitions until $a(t)$ hits 100%. Hence the determination of the $N$-RM requires an iterative procedure where using the inverse model the load $m$ is increased stepwise until exactly $N$ repetitions are achieved.

In order to overcome the drawback of an iterative procedure a direct prediction of the load corresponding to the $N$-RM can be obtained by an approximation of the solution obtained from model inversion. With this approximate prediction the $N$-RM can be directly predicted from the results of the isometric MVC experiment.

### 4.1 Isometric Contraction Measurement

In case of an isometric MVC measurement the load moment $M_{load}(t)$ is exactly the moment which is produced by the person (see figure 1). This load moment can be measured by a moment measurement system with dynamics

$$\frac{dM_{meas}(t)}{dt} = \frac{1}{T_s}\left(M_{load}(t) - M_{meas}(t)\right) \tag{12}$$

where $T_s$ is the time constant of the measurement system. Furthermore no movement is possible and hence $\dot{\omega} = \omega = 0$. In case of the maximal voluntary contraction the muscle activation is constant at 100% i.e. $a(t) = 1$ so that the model equations (9) - (11) simplify to

$$\frac{d\varphi(t)}{dt} = 0$$

$$0 = \frac{1}{\Theta}\left[r_L F_{max} fit(t) f_{fl}(\varphi(t)) - M_{load}\right]$$

$$\frac{dfit(t)}{dt} = \frac{(fit_{min} - fit(t))}{T_{fat}},$$

which can be solved for $\varphi$, $fit$ and $M_{load}$. With the isometric measurement system the sitting position can be adjusted so that the maximum muscle force can be generated in initial position $f_{fl}(\varphi_0) = 1$. Together with (12) and the fact that $T_s \ll T_{fat}$ it follows that the measurable muscle moment $M_{m,meas}$ can be represented by

$$M_{m,meas}(t) = M_{max}\left(1 - \exp\left(-\frac{t}{T_s}\right)\right) \times \left[fit_{min} + (1 - fit_{min})\exp\left(-\frac{t}{T_{fat}}\right)\right], \tag{13}$$

where the maximum moment of the lumbar extensor muscles is denoted by $M_{max} = r_L F_{max}$. The unknown parameters in (13) represented by the parameter vector

$$\theta = \left(M_{max}, T_s, fit_{min}, T_{fat}\right)^T$$

are estimated from measurement data $M_{meas}(t)$ (see figure 3) by solving the nonlinear least squares problem

$$\hat{\theta} = \arg\min_{\theta}\left(\|M_{m,meas}(\theta, t) - M_{meas}(t)\|_2^2\right). \tag{14}$$

Since (14) represents a non-linear, non-convex optimization problem, an iterative Levenberg-Marquardt algorithm is used for parameter estimation.

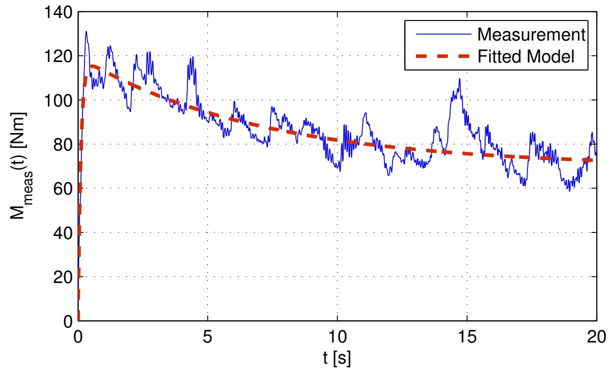


Figure 3. Isometric MVC: measurement data and estimated model.

For the isometric MVC measurement depicted in figure (3) the following parameters

$$M_{max} = 119.82\,Nm$$
$$T_s = 0.11\,s$$
$$fit_{min} = 0.58$$
$$T_{fat} = 6.99\,s$$

are obtained. Based on the isometric MVC measurement the muscle activation can now be obtained by inversion of the proposed biomechanical model.

### 4.2 Model Inversion

Once the main parameters are obtained from the isometric MVC measurements the next step is to compute the required

$f_{fat}(t) = a(t)fit(t)$ for a given reference movement $\varphi(t) = \varphi_{ref}(t)$. Using goniometer measurement data it can be shown that during correct exercise the movement of the trunk and therefore the extension angle $\varphi(t)$ can be represented by a sinusoidal function with frequency $\Omega$, Offset $A_0$ and amplitude $A_1$

$$\varphi_{ref}(t) = A_0 + A_1 \sin(\Omega t). \tag{15}$$

Inserting $\varphi_{ref}(t)$ together with its first- and second order derivatives $\dot{\varphi}_{ref}(t)$, $\dot{\omega}_{ref}(t)$ into (10) and (9) and solving for $f_{fat}(t)$ it follows

$$f_{fat}^{ref}(t) = \frac{\Theta\dot{\omega}_{ref}(t) + r_{load}mg}{M_{max}f_{fl}(\varphi_{ref}(t))f_{fv}(\omega_{ref}(t))}. \tag{16}$$

Once $f_{fat}^{ref}(t)$ is computed the resulting fitness function $fit(t)$ can be obtained by solving the differential equation

$$\frac{dfit(t)}{dt} = \frac{(fit_{min} - fit(t))\frac{f_{fat}^{ref}(t)}{fit(t)}}{T_{fat}} + \frac{(1-fit(t))\left(1-\frac{f_{fat}^{ref}(t)}{fit(t)}\right)}{T_{rec}}, \tag{17}$$

which results from inserting (5) into (6) together with $f_{fat}^{ref}(t)$. Since for (17) a closed solution is not achievable, it is proposed to solve (17) with a numerical integration algorithm. The solution of (17) is denoted by $fit_{ref}(t)$ from which the desired muscle activation can be obtained by

$$a(t) = \frac{f_{fat}^{ref}(t)}{fit_{ref}(t)}. \tag{18}$$

Figure 4 shows the simulation results for the same person of which the isometric MVC measurement is depicted in figure 3. With increasing time the fitness function $fit(t)$ decreases and hence the muscle activation $a(t)$, required for moving the training device as represented by $f_{fat}(t)$, increases. Notice that 10 repetition are possible until the muscle activation reaches 100%. Hence the load $m$ used for simulation represents the person's individual 10-RM.

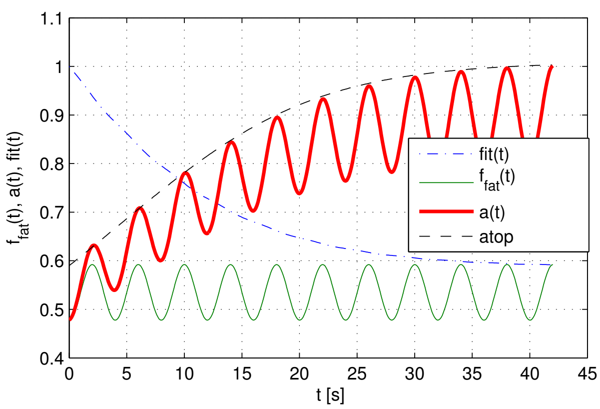


Figure 4. Simulation of the muscle activation corresponding to the same person with measurements depicted in figure 3 for a sinusoidal reference angle.

### 4.3 Approximate Prediction of the N-RM

By inverting the biomechanical model it is possible to compute the required muscle activation $a(t)$ for a given reference movement $\varphi_{ref}(t)$ and a given load $m$. Up to now determining the N-RM requires an iterative process, where the load $m$ has to be increased until the muscle activation computed from model inversion (18) allows for $N$ repetitions until it hits 100% or $a(t) = 1$.

To be able to compute directly the load $m$ which allows for exactly $N$ repetitions, some sensible approximations are required. According to the fact, that the recovery time is much longer than fatigue time $T_{rec} \gg T_{fat}$ (see for example Riener et al. [1996]), the second term in (17) can be neglected. So the much simpler differential equation

$$\frac{dfit(t)}{dt} = \frac{(\tilde{fit}_{min} - fit(t))\frac{f_{fat}^{ref}(t)}{fit(t)}}{T_{fat}} \tag{19}$$

is obtained which approximates (17). Hereby $\tilde{fit}_{min}$ denotes the corrected minimal fitness such that the stationary solution of (6) agrees with that of (19). Observing figure 4 the top envelope of the muscle activation determines the time, where $a(t)$ crosses 100%. Since the $\varphi_{ref}$ and its velocity during training are in a small range compared to the physiological range of the extensor muscles the influence of the force-length and force-velocity relation is approximated by constant values $\bar{f}_{fl}$ and $\bar{f}_{fv}$ respectively. In order to compute now the top envelope of $a(t)$, denoted by $a_{top}(t)$, we observe that $f_{fat}^{ref}(t)$ can be divided into a constant and periodic part

$$f_{fat}^{ref}(t) = \lambda + \eta \sin(\Omega t)$$

with

$$\eta := -\frac{\Theta A_1 \Omega^2}{M_{max}\bar{f}_{fl}\bar{f}_{fv}}, \; \lambda := \frac{r_{load}mg}{M_{max}\bar{f}_{fl}\bar{f}_{fv}}.$$

As a consequence the solution of (19) can be represented by a constant and periodic part. Since $|\eta| \ll \lambda$ the mean value of the fitness function is determined by the constant part of $f_{fat}^{ref}(t)$ given by $\lambda$. With this assumptions (19) can be solved in closed form and we obtain the mean value of the fitness function

$$\bar{fit}^{ref}(t) = K \exp\left[-\lambda\frac{t}{\tau} - W\left(K\frac{\exp\left[-\lambda\frac{t}{\tau}\right]}{\tilde{fit}_{min}}\right)\right] + \tilde{fit}_{min}.$$

Hereby the following abbreviations are used

$$K := (1-\tilde{fit}_{min})\exp\left[\frac{1}{\tilde{fit}_{min}} - 1\right],$$

$$\tau := T_{fat}\tilde{fit}_{min},$$

where $W(\cdot)$ denotes the *Lambert-W function*. Together with (18) the top envelope $a_{top}(t)$ of the muscle activation is given by

$$a_{top}(t) = \frac{\lambda + |\eta|}{\bar{fit}^{ref}(t)}. \tag{20}$$

For a given number $N$ of repetitions and a given frequency $\Omega$ of training the time $t_m$ which allows for exactly $N$ repetitions is

$$t_m = \frac{N2\pi}{\Omega}.$$

Exactly at time $t_m$ the top envelope of the muscle activation should hit 100% . Inserting $a_{top} = 1$ into (20) the $N-$repetition maximum can be obtained by solving for the unknown load $m$:

$$\tilde{m} = \frac{M_{max}\bar{f}_{fl}\bar{f}_{fv}}{r_{load}g} \left\{ \frac{\tau}{T_{fat}+t_m} f_W + (\tilde{fit}_{min} - |\eta|) \right\} \quad (21)$$

with

$$f_W := W \left( \frac{T_{fat}+t_m}{\tau} K \exp\left[ -(\tilde{fit}_{min} - |\eta|)\frac{t_m}{\tau} \right] \right).$$

For the isometric MVC measurement shown in figure 3 the approximate top envelope of muscle activation $a_{top}(t)$ is depicted in figure 4. For this measurement the approximate $10-$repetition maximum ($N = 10$) can be determined from (21) to $\tilde{m} = 38.7\,kg$, where the value obtained from iterative simulation is $m_{sim} = 39.5\,kg$ and from experimental determination we obtained $m = 40\,kg$.

## 5. RESULTS

In order to verify the applicability of the proposed method an isometric MVC measurement and the determination of the $10-$repetition maximum was performed with 9 healthy persons. Table 1 summarizes the results from the isometric MVC

| # | $M_{max}$ [Nm] | $T_{fat}$ [s] | $fit_{min}$ [-] | $\tilde{m}$ [kg] | $m_{sim}$ [kg] | $m$ [kg] |
|---|---|---|---|---|---|---|
| 1 | 126.87 | 5.77 | 0.37 | 28.5 | 30.0 | 20.0 |
| 2 | 119.82 | 6.99 | 0.58 | 38.7 | 39.5 | 40.0 |
| 3 | 96.46 | 37.40 | 0.05 | 30.4 | 31.0 | 27.5 |
| 4 | 138.81 | 3.12 | 0.70 | 55.6 | 56.5 | 47.5 |
| 5 | 153.51 | 28.54 | 0.05 | 37.9 | 39.0 | 60.0 |
| 6 | 58.56 | 1.80 | 0.65 | 22.8 | 23.2 | 12.5 |
| 7 | 96.84 | 2.39 | 0.38 | 20.6 | 21.5 | 20.0 |
| 8 | 42.69 | 13.95 | 0.44 | 12.5 | 13.0 | 12.5 |
| 9 | 285.06 | 1.77 | 0.38 | 57.9 | 59.2 | 45.0 |

Table 1. Main parameters from isometric MVC measurements, predicted 10-RM, simulated 10-RM and the experimental determined 10-RM.

measurement, the iterative simulation, the approximate prediction of the 10-RM and the experimental determination of the 10-RM.

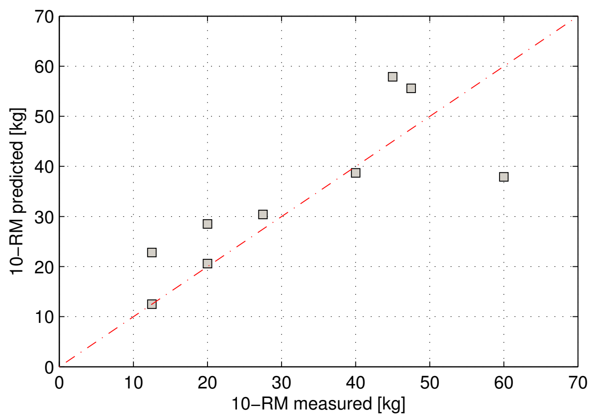


Figure 5. Comparison between measured and predicted 10-RM (correlation coefficient $r = 0.80$).

For simulation and prediction the used parameters are summarized by table 2. Hereby $h_S$ denotes the person's shoulder height

| $\bar{f}_{fl}$ [−] | $\bar{f}_{fv}$ [−] | $r_{load}$ [m] | $T_{rec}$ [s] | $\Theta$ [$kgm^2$] | $r_L$ [m] | $A_1$ [rad] | $\Omega$ [1/s] |
|---|---|---|---|---|---|---|---|
| 1.0 | 0.9 | $0.22h_S$ | $10T_{fat}$ | $0.26m_P h_S^2$ | 0.065 | $20\frac{\pi}{180}$ | $\frac{\pi}{2}$ |

Table 2. Parameter values used for simulation.

measured in sitting position from sitting support to shoulder and $m_P$ is the mass of the person.

Figure 5 shows the predicted 10-RM from the isometric MVC measurements compared to the experimental determined 10-RM for different persons. The corresponding data can be taken from table 1. In contrast to the cases where there is a good agreement between predicted and experimental 10-RMs (correlation coeff. $r = 0.8$) some outliers (especially for person #5) can be observed.

Observing the parameter values from the isometric MVC measurement for person #5 it can be seen that $fit_{min} = 0.05$. In that case the nonlinear optimization algorithm reached the lower bound of the corresponding parameter. In order to avoid parameters which lack a physiological interpretation constraints on the parameters are imposed. Removing that constraints negative values for the minimal fitness are obtained which is not feasible. By inspecting the shape of the corresponding isometric MVC force there seems to be a linear decrease of the moment rather than an exponential one. In that cases the model for fitness function does not agree with the measurement data (6) which results in a very high time constant $T_{fat}$ compared to others.

Further a slight over-prediction of the N-RM can be observed which is mainly due to a systematic error of the procedure which determines experimentally the N-RM. This testing procedure is iteratively, where with an initial load the person is encouraged to lift a weight slowly and within a predefined range of motion. The initial load is chosen such that the number of possible repetition is expected to be larger than $N$. If so, the load is increased and after an adequate recovery time the person has to repeat the exercise until a stop criterion is met. This stop criterion is observed by a skilled staff where it is checked whether the predefined range of motion can be reached and the exercise can be performed smoothly. If these conditions are not fulfilled the exercise is stopped. This procedure is repeated until exactly $N$ repetitions are obtained. In order to avoid injuries the aim was to conservatively check the stop criterion. Even though a recovery time of 5 minutes was kept effects of fatigue following multiple trials reduce the accuracy of this iterative testing procedure and leads to a slight over-prediction.

Of course the fitness function (6) represents a simple model of muscle fatigue. As pointed out in Chaffin et al. [2006] different factors influence muscle fatigue which are according to impaired muscle activation as well as metabolic factors. Muscle fatigue depends on the intensity and type of exercise. Since in this paper the main fatigue parameters are estimated from the measurement of the isometric MVC experiment, it turned out to be very important that the isometric measurement is supervised by professionals and should repeated several times in order to compute the averaged force-time curve. Especially with the isometric MVC experiment central factors of impaired muscle activation play an important role. Different ambition of test persons may occur and an enhancement of muscle performance in a competitive context influences the obtained results.

In Mayhew et al. [1992] different models for predicting the 1-RM from a N-RM test were evaluated and cross-validated with

435 persons. Therein the basic model structure for load $m$ (N-

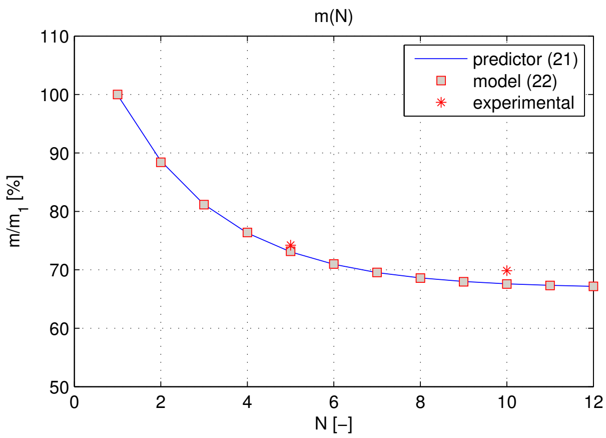


Figure 6. Relation between load $m$ and the number of possible repetitions $N$ for person #2 by using (21) and (22) respectively compared to experimental determination of the $N$-RM

RM) as a function of the 1-RM load $m_1$ and the number of repetitions is

$$\frac{m(N)}{m_1} = b_0 + b_1 \exp\left[-b_2 N\right]. \tag{22}$$

Figure 6 shows the relation between the number $N$ of possible repetitions and the associated load $m$ obtained from the prediction (21), the model (22) and the experimental determination for person #2. Observing figure 6 it can be seen that the depicted relation between load $m$ and repetition number $N$ agrees perfectly with (22). Taking the data from the prediction (21) together with the parameters of the isometric MVC measurement of person #2 (see table 1) the unknown parameters can be obtained by solving a non-linear least squares problem. Together with (22) the person's #2 individual relation is then given by

$$\frac{m(N)}{m_1}[\%] = 66.8 + 50.2 \exp\left[-0.42 \cdot N\right].$$

Observing figure 6 we can conclude that about 67% of the 1-RM would allow for more than 12 repetitions which basically agrees with Mayhew et al. [1992], where about 70% of the 1-RM allowed for about 14 to 15 repetitions for a bench press. In our case we limited $N$ since 12 repetitions took about 45 sec. while the duration with the isometric measurement was 20 sec. For prediction of N-RM with higher $N$ we propose to increase the duration of the isometric MVC measurement.

## 6. CONCLUSIONS

With the proposed biomechanical model a novel method is available which allows to predict the individual $N$-RM only from an isometric maximum voluntary contraction (MVC) measurement. The proposed predictor allows to calculate the person's individual relation between the $N$-RM and the number of repetitions $N$ which provides a valuable basis for physical rehabilitation of low back pain patients. The obtained results show a good agreement with experimental data as well as with literature. The model-based approach relies on simple yet efficient models and on suitable approximations which allow to predict directly the $N$-RM from isometric MVC measurement data. Future work will concern two main topics, the development of improved muscle fatigue models and a comprehensive validation of the proposed predictor respectively.

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