A NEW METHODOLOGY FOR HUMAN MOVEMENT ANALYTICS: FROM CHEMICAL ENGINEERING PRINCIPLES TO NEW SPORTS SCIENCE

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ABSTRACT

This work deals with the development of the first theory for human movement during resistance training developed from first-principles. The theory is based on the integration of sub-models related to energy consumption, velocity-dependent force development, fatigue, and recovery of an athlete following an exercise protocol. Models based on this theory can evaluate the current condition of an athlete in a much deeper and objective manner and then use this evaluation to develop personalized training programs according to the current condition of the athlete and their specific needs. The models were validated in a small study clearly demonstrating the power of this approach. More broadly this theory can be implemented to non-athletes and even for medical applications to evaluate the condition of patients (e.g., sarcopenia, frailty, functional capacity) and also to connect and empower synergistically other available datasets, e.g., in rehabilitation.

KEYWORDS: Movement analytics, resistance training, energetics, kinematics, personalized

INTRODUCTION

In the last decade the area of Sports Science has been developing rapidly with the appearance of advanced biomechanical models [1], introduction of metabolomics and genomics [2], and has been further empowered by the introduction of numerous new techniques for measuring movement and performance in general [3]. However, in terms of analysing the current condition of athletes and then designing personalized training programs that can enhance their performance, very little progress has been achieved and mostly in the area of endurance sports [4-6]. In resistance training much less progress has been achieved and effectively methods developed over 50 years ago are still being used today to train athletes in amateur and professional sports [7,8].

In general, for resistance training the first step is to evaluate the athlete for each exercise and movement. This is typically achieved with a single metric, called the *one-repetition-max*, 1RM, which is the maximum resistance that can be moved one time. For each exercise or movement the coach then designs a training program based on the *percent 1RM*, %1RM, assuming that all athletes, independent of their condition, scale similarly with respect to the 1RM. Therefore, the training coach assigns a number of *repetitions* with a resistance corresponding to a specific %1RM. The repetitions are executed over a period of time that could be free or controlled. Very often, coaches dictate a cadence for the entire movement, e.g., 3-2-1 or three seconds for the eccentric movement, two seconds pause, and one second for the concentric portion of the movement. This sequence constitutes a single *set*. The coach assigns a number of *sets*, sometimes with varying resistance and repetitions in way to achieve a desired %1RM, also called *intensity,* and total generated work, also called *volume.* Note that, terms such as *intensity*, *volume, set, repetition*, are common in Sports Science literature and used here in italics. During preparation for an athletic event, or preseason training, the coach will vary the *volume* and *intensity* in order to gradually increase the stimulus for change and adaptation while preventing overtraining. This entire procedure is also called *periodization training* and has been at the core of resistance training for many decades [9].

There are several problems with this paradigm of resistance training. For example, it is known that athletes with identical 1RM do *not* have similar NRM, i.e., the maximum weight that can be moved N times [10]. For example, there is large difference between endurance athletes and power athletes most likely due to composition of muscle fiber type [11]. Other causes include biomechanical differences, e.g., joint mechanics, tendon attachment and degree of training. It is also notable that different metrics of *intensity* have been proposed such as time under tension, recovery between sets, suggesting different emphasis, e.g., on the eccentric portion of movement in eccentric training, or velocity training [12,13]. Indeed, the importance of velocity of motion and power have been noted and implemented in new training protocols but with unclear outcomes or advantages. Therefore, it is known that athlete's performance does not scale with a single parameter, i.e., the 1RM, and instead depends on multiple factors. Attempts to further the field have not led to much progress in this area. Also, repeated efforts to implement data-based approaches have also not yielded any progress. The key reason for the lack of progress has been that there is no fundamental theory of sports performance especially in resistance training. Indeed, the need for a "Grand Unified Theory of sports performance" was recently suggested [14].

In this work a fundamental theory for movement evaluation and resistance training is developed based on Chemical Engineering and Sports Science principles. New athlete evaluation metrics are extracted from the model and new performance metrics are generated which can be used by the coach to develop personalized training programs depending the current status of the athlete and their needs based on their role in the team.

METHODOLOGY

Following an approach that is very common in Chemical Engineering, a fundamental theory of athlete evaluation and resistance training is developed that considers both the energetics and the kinematics of the system. Another common approach in Chemical Engineering and Materials Science, a multi-scale approach, can be implemented to connect with sub-models and reduce the space of parameters. Specifically, a multi-joint kinetic-chain is considered moving under an imposed resistance with a micro-mechanical model of a muscle fiber is effectively a sub-model (Figure 1).

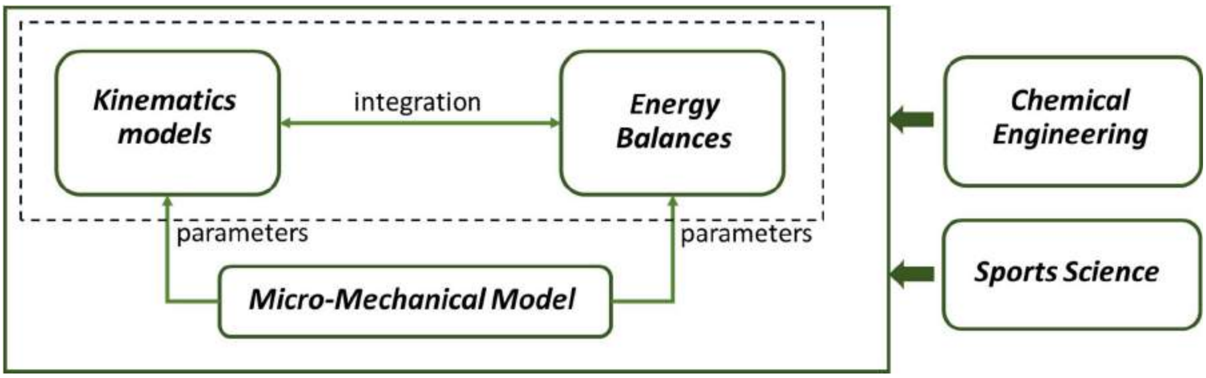

Figure 1. *Strategic approach for development of a fist-principles theory for human movement in resistance training.*

The micro-mechanical model for a single muscle fiber is typically some variation of the Hill equation [15]:

$$(F + a)(b + V) = \frac{c}{b}(b - V) \approx c \tag{1}$$

where F is the applied force on a muscle fiber and V the velocity while *a, b,* and *c* are constants. This equation can be derived by considering the velocity-dependent interaction of myosin proteins with actin elements in muscle fibers. For small to moderate values of velocity the RHS of the expression simplifies to a constant *c* which is the original Hill equation [15]. This expression is then generalized to multiple muscle fibers (which may include different fiber types) in macro-scale kinetic model.

The energy balance is a critical component of the theory. In the literature, it is known that the total energy consumed during a single repetition, E_C, is the sum of the static, E_S, and the dynamic, E_D, energy components [8]:

$$E_C = E_S + E_D \quad (2)$$

The static component reflects that energy can be consumed even if the resistance is stationary. The dynamic component is directly related to the work generated in order to move a resistance, e.g., against gravity. It is also well-known that the consumed energies depend on the resistance, or applied force, F, and/or the velocity of movement, V, so Equation 1 becomes:

$$E_C(F,V) = \dot{E}_S(F)\, t_1 + \int_0^L \frac{F(t)}{e(V)} dx \quad (3)$$

where e(V) is the velocity-dependent efficiency of work production during the repetition over a distance of L, F(t) is the instantaneous applied force, $\dot{E}_S$ is the force-dependent rate of energy consumption due to static holding, and t_1 is the duration of the repetition given by:

$$t_1 = \int_0^L \frac{1}{V(t)} dx \quad (4)$$

It should be mentioned that both an instantaneous or a discrete point of view can be implemented where quantities that vary with time, such as F(t) and V(t), are represented with their averaged values over a repetition, e.g., F and V.

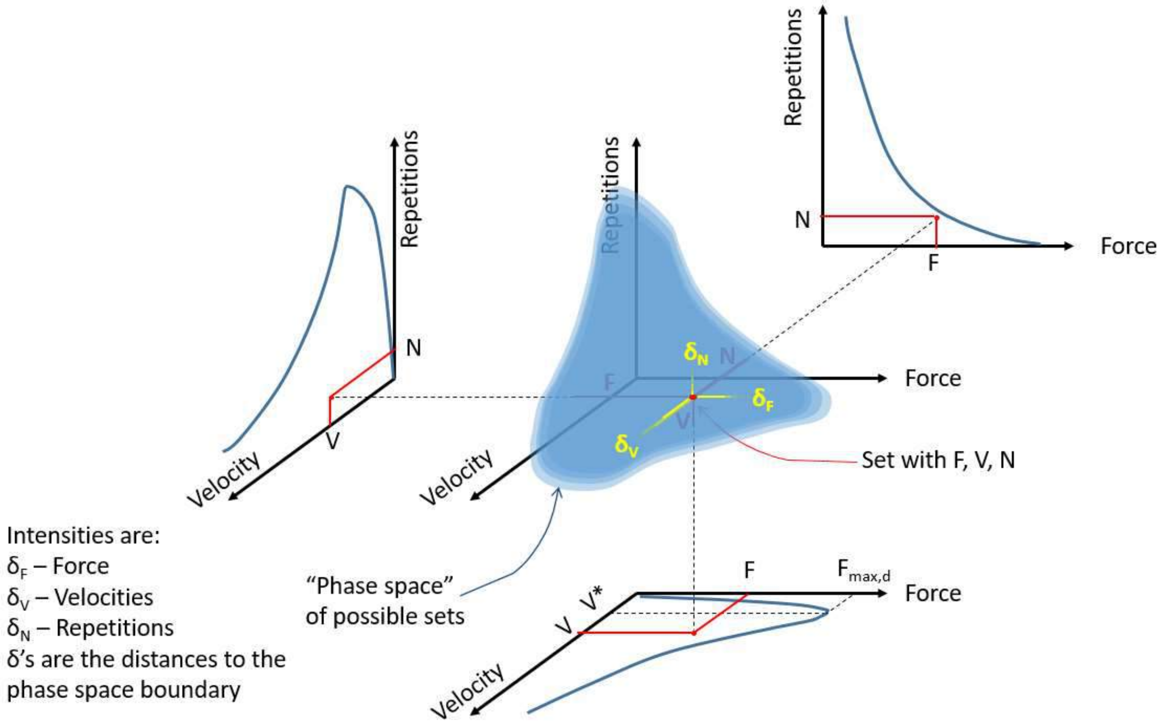

Figure 2. *Phase space of possible sets in terms of repetitions, N, force, F, and velocity, V.*

In Equation 3 the unknown functions are $\dot{E}_S(F)$ and e(V). A key additional equation of the model provides the maximum number of repetitions, $N_{max}(F,V)$, for a given resistance, F, and a given velocity of movement, V. No exact expression exists in the literature as the problem of muscle fatigue is highly complex. However, approximate expressions can be developed to connect with the above equations.

The overall model reveals a highly complex behavior during execution of a series of repetitions, of a movement against resistance. In Figure 2 the shaded area indicates the region of feasible movements for a *repetition* beginning the *set* for different values of F, V, and *number of repetitions*, N. This is effectively a phase space of possible sets for a specific subject, at their current condition, and for a specific degree of fatigue. The 2D sections passing through the selected point within the phase space are also shown. One should note that the V-N and the F-V curves are different than those commonly presented in the Sports Science literature as they include the entire curve and not just the easily accessible portion of the curve. The distance of the selected set point to the bounding surface of the phase space can be related to the difficulty of movement. The ratio of the distance to the boundary over the total range can be considered a dimensionless measure of the difficulty of execution, or *intensity*. It is also interesting to note that several of the *intensities* derived in this work are extracted directly from the theory and have a clear physically relevance to movement and performance. In contrast the very few metrics of *intensity* used in Sports Science are proposed with little theoretical justification.

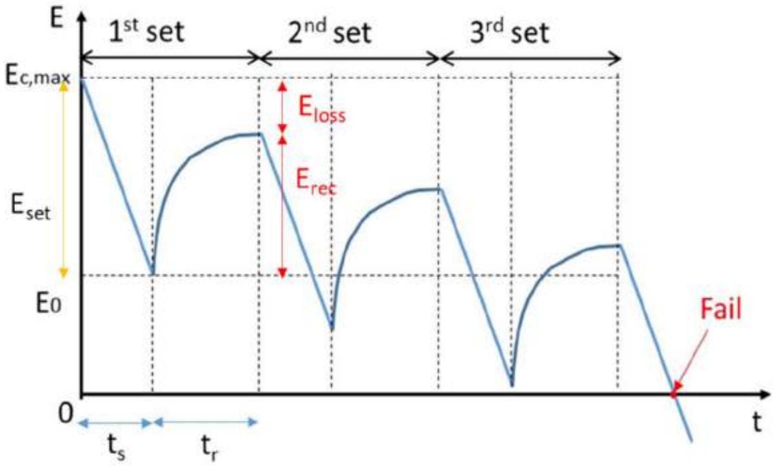

Figure 3. *Phase space of possible sets in terms of repetitions, N, force, F, and velocity, V.*

In Figure 3 the energy consumption across multiple *sets* is shown assuming a linear consumption rate and a first order recovery process. $E_{c,max}$ is the maximum available energy for a fully rested individual. E_{set} is the amount of energy consumed during the execution of the *set* over a time of t_s, E_{rec} is the total amount of energy recovered during a rest period of t_r in between sets and E_{loss} is the amount of energy expended during the set that is not recovered during intra set rest. Clearly E_{loss} accumulates over multiple sets until the individual is no longer capable of executing the set. Several work or *volume* based, as well as fatigue based metrics, can be defined in this view. For example,

$$I = \frac{E_C(F)}{E_{c,max}(F)} \tag{5}$$

where E_C is the amount of energy consumed over a single or multiple repetitions. The consumed energy, the proximity to failure, the repetition under uncomplete recovery conditions, as well as the total work generated, are all significant to the coach and they should be monitored during the course of a training program. For example, overtraining and incomplete recovery of an athlete can not only inhibit progress but also increase the risk of injury during training.

RESULTS AND DISCUSSION

Consequently the general procedure for implementation of this approach is shown in Figure 4.

The general approach for athletes consists of two parts. The first is movement evaluation which is achieved by a series of tests emphasizing different aspects of the movement. This analysis provides insights into how an individual performs a movement by determination of physically meaningful model parameters. Typically between 8 and 10 well designed test movements are necessary for this evaluation. Compared to standard practice of measuring a single parameter, the 1RM, this is a much more involved procedure as it determines 8 parameters of the model but can still be accomplished in less than 30 minutes with minimal supervision.

The second part of the model utilizes the determined individual parameters of movement extracted from the first model to optimize a series of dimensionless metrics of performance. Thus, instead of using a single metric of movement, e.g., 1RM, to outline a training program with two parameters, e.g., %1RM or *intensity* and *volume*, one can now utilize many more metrics of movement to prescribe multiple parameters of training. Some of the additional metrics of difficulty that are utilized to design a training program are: strength intensity, %1RM or F/F_{max}, velocity intensity or $V/V_{max}(F)$, local force intensity of $F/F_{max}(V)$, rep intensity $N(F/V)/N_{max}(F)$, local rep intensity $N(F,V)/N_{max}(F,V)$, power intensity $P(F)/P_{max}(F)$, work related intensity metrics, e.g., Equation 5, and many more (not all independent).

The second model not only determines a set of intensities describing how challenging the exercise is for the specific subject in different ways but it also predicts if the exercise is possible or dangerous for the athlete.

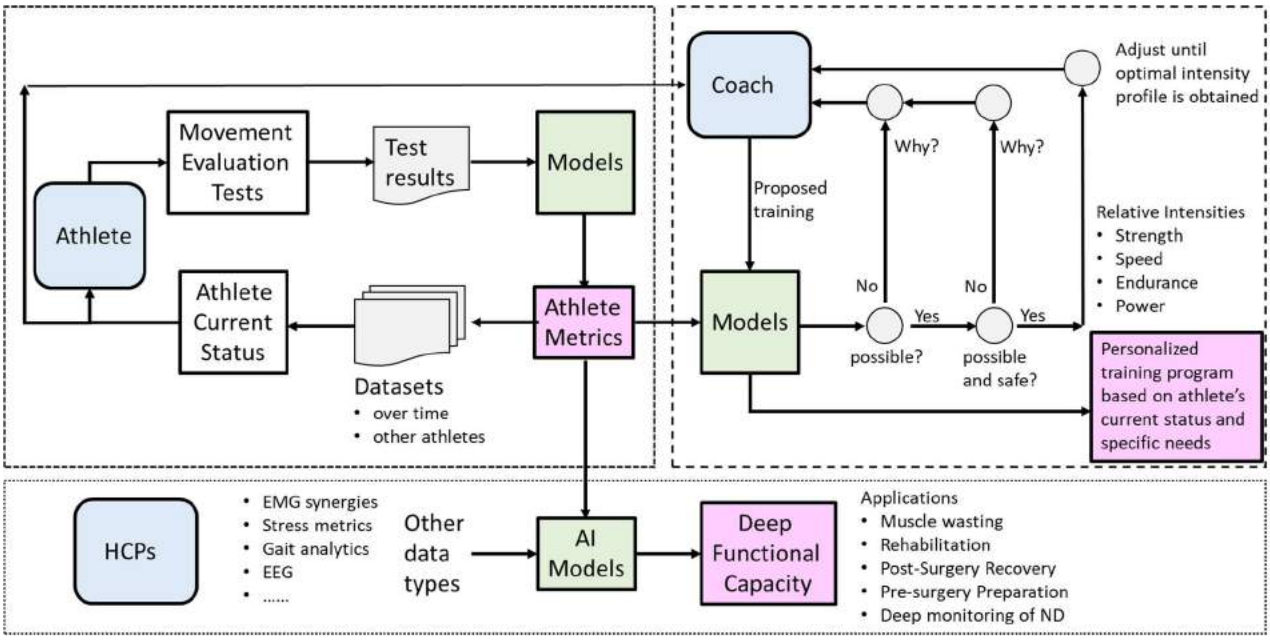

Figure 4. *Strategic approach for development of a first-principles theory for human movement in resistance training.*

This new approach for resistance training and athlete movement evaluation is the first that provides both a deep evaluation of movement and also a truly personalized resistance training depending on the current condition of the athlete but also optimized towards the desired training improvements. The models were validated in a study of students at the Democritus Univ. Thrace over a period of 4 weeks unilateral training with a leg extension machine resulting in +26% more improvement in the optimally trained group [16].

The potential of these developments are obvious in the field of Sports but extend well beyond to other areas where a deeper assessment of human movement and functional capacity is needed. These areas include rehabilitation, monitoring of movement during active living, monitoring of sarcopenia, progression of neurodegenerative disorders, and more [17-20]. In Figure 4 the combination of the human movement evaluation metrics with other data (e.g., muscle synergies or EMG data, EEG, stress, pulse rate and PRV, breath rate, etc.) using AI-based tools is indicated. The goal from the HCP perspective is to ascertain the movement and functional capacity of subjects, e.g., frail pre-operative patients, elderly, post-operative or surgical conditions, during recovery and rehabilitation.

Human movement is the central aspect of functional capacity which also involves neuromuscular, musculoskeletal, muscle quality, and CNS aspects, the tools described in this paper can prove to have a disruptive impact in this area.

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