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DETERMINATION OF INDIVIDUAL NEUROMUSCULAR PROPERTIES AND APPLICATIONS IN SPORTS SCIENCE

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Abstract. An essential factor in modelling human movements is to find the values of the subjects' neuromuscular properties individually and in vivo. We describe a method for determining movement independent neuromuscular properties of knee extensors and elbow extensors. We show the inter- and intra-individual differences in these property values by comparing different muscles and different subject groups. Furthermore, we relate the neuromuscular properties to fibre distribution and efficiency of the muscle. We show the influence of changes in movement conditions on the movement and we give examples of applications in planning and controlling of training. We define a performance space and construct a mapping between the set of relevant properties and the performance.

1 Introduction

The essential part of most mathematical models describing human movements is Newton's fundamental equation of motion. In Physics, the forces in this equation are given as force laws, that is, the parameters in the force laws are invariant and describe properties of the object (e.g., the spring constant for springs) or conditions of the movement (e.g., the temperature or the air pressure). In many models of human movement the input quantities are not independent of the movement (e.g., torques as function of time) or they are combinations of conditions and properties (e.g., explosive force, start gradient), thus leading to a movement specific result. Furthermore, many applications of models found in literature use mean values for the persons' properties, possibly scaled to body dimensions, as input parameters for the model equations. In these cases, the results are not specific to a subject, or only to a certain extent. Therefore, obtaining individual values for the input parameters of the model equations is a crucial challenge but essential for predicting subject specific movements.

Most models of human movements describe the muscle with Hill-type contracting elements. Conditions under which it is possible to combine different muscle fibres were investigated in [7], [9]. For single muscles, muscle properties have been determined by different methods, see, e.g., [14], [6], [5]. Conditions under which it is possible to combine several muscles to model muscles have been investigated in [9], [5]. Conditions for describing the activation in such a way that the forces are still a force law have been investigated in [8]. Conditions on the structure of force laws for muscle forces are given in [7].

The paper is organized as follows: In the method section we first describe briefly the model and the kind of neuromuscular properties we want to determine. We define the performance space and the performance function. The application section is devided into 4 subsections. In subsection 1 we deal with the relation between determined property values and several other quantities such as fibre distribution, efficiency, and endurance. Subsection 2 shows the differences in properties between individuals. Subsection 3 deals with the effect of a change in conditions to the movement. Subsection 4 concentrates on the influence of property values on the movement and the consequences for the planning and controlling of individual training. The last section concludes the paper and summarizes the most important facts.

2 Method

2.1 Model equation

We use a model for the extension movement of a hinge joint (see, e.g., [5]). The extensor muscles are described by a model muscle. The force-velocity relation of this muscle is given by

$$f = \frac{c}{v + b} - a\,, \tag{1}$$

f and v denoting the force and the contraction velocity in the muscle, respectively, and a, b, c being positive constants describing the properties of the muscle [1]. Instead of the constants a, b, c one could equivalently use the parameters $f_{iso} = c/b - a$, $v_{max} = c/a - b$, and $p_{max} = ab + c - 2(abc)^{-2}$, f_{iso} describing the isometric force, v_{max} describing the maximum possible contraction velocity, and p_{max} describing the maximum possible power.

The activation process of the muscle under maximum voluntary contraction is described by a time dependent function $S(t)$

$$S(t) = 1\text{-exp}(\text{-}A(t\text{-}t_0)+ 1\text{-exp}(\text{-}A(t\text{-}t_0))). \tag{2}$$

Therefore, we get for the force f_m of the muscle $f_m = A(t).f$

Finally, the connection between the muscle force f_m and the external force F can be calculated via a geometry function $G(X)$ depending on the distance X between hip and ankle, $F = f_m .G(X)$. To formulate G individually for the knee joint anthropometric data like the radius of the knee joint, the length of upper and lower leg and the distance between the middle of patella and tuberositas tibiae are needed. Detailed instructions for the measurement of these quantities are given in [9] for the knee joint and in [2] for the elbow joint.

To describe the movement of pushing a sliding sledge with mass m on an inclined leg press we get the following model equations [5]:

$$m \cdot \ddot{X} = -m \cdot g \cdot \sin\alpha + S(t) \cdot G(X) \cdot \left(\frac{c}{G(X) \cdot \dot{X} + b} - a \right), \tag{3}$$

$$G(X) = \frac{r \sin\beta}{l_o l_u \sin\sigma} \cdot X,$$

$$\sigma = 2\beta + \arcsin(\frac{r}{k_o} \sin\beta) + \arcsin(\frac{r}{k_u} \sin\beta),$$

$$X = \sqrt{l_o^2 + l_u^2 - 2 l_o l_u \cos\sigma}.$$

For the leg extension, σ denotes the knee angle, and β is the angle between muscle and knee. l_o is the length of the thigh, l_u the length of the shank, k_o, k_u the position of the muscle, and the r knee radius. For the arm extension the parameters are defined in an analoguous way. The anthropometric parameters can be approximately measured directly, whereas the neuromusclular parameters a, b, c, and A have to be identified. In equation (3) the mass m, the gravitational acceleration g, the inclination angle α, and the initial position and velocity are conditions of the movement, all other parameters are properties of the subject.

2.2 Parameter identification

In order to determine the model input parameters, isometric and dynamic knee and elbow extensions, respectively, are performed by pushing against a fixed or sliding sledge on an inclined leg press (Tetra Illmenau). We measure the position as well as the velocity and force of the pushed sledge. The parameters in the model equations are either conditions of the movement or properties of the subject. Conditions such as moved load and inclination of the leg press as well as some properties can be measured directly. All other parameters are estimated with the software JOP kinematics using a modified Levenberg- Marquardt algorithm. For details see [5]. Among the identified parameters are the neuromuscular properties describing the activation rate by an activation parameter S [1/s] and the parameters f_{iso} [N] (isometric force in the muscle), p_{max} [W] (maximum possible power of the muscle), and v_{max} [m/s] (maximum possible contraction velocity) of a Hill-type extensor model muscle.

2.3 Performance function

Let n be the number of parameters in the model equations, $k < n$ the number of parameters describing the movement conditions (such as the mass of pushed object, inclination of plane,…) and $m < n$ the number of the person's properties (such as activation rate, mass, muscle properties,…), $n = k + m$. Let the parameter values of conditions be arbitrary but fixed. Then for every possible set of values of properties we can define a performance z of the movement, e.g., the maximum velocity of the sledge. Therefore, we can construct a performance function f between the set D of properties and a one-dimensional performance space by

$$f : D \subset R^m \to R, \tag{4}$$

$$x \in D \mapsto z \in R,$$

where x is the state of the person, a m-tuple of relevant properties. The graph of this mapping is a surface showing the relation between the properties and the performance.

Definition: Let $E_1, \ldots E_m$ be the properties of the person.

1. E_i is called performance determining factor, if for fixed values of E_j, $j \neq i$, a change in the value of E_i changes the performance z.
2. E_i is called performance limiting factor, if any change of E_j, $j \neq i$, E_i fixed, does not influence the performance z.

3 Applications

3.1 Relation between neuromuscular properties and other quantities

The shape of Hill's force-velocity relation provides information about the endurance of the muscle. The curvature can be measured by the ratio of a/f_{iso}. Endurance athletes and beginners have more curved force-velocity relations (a/f_{iso} <0.30) than athletes in power sports (a/f_{iso} > 0.30) [15]. Another relationship with the curvature can be found in the efficiency, defined as ratio c/p_{max}. The muscle fibre distribution is related to b_n, the value of b normed to the muscle length n. [9], [13]. Larger values of b_n correlate with a higher percentage of fast twich fibres. Figure 1 shows the distribution of a/f_{iso} for male and female subjects for the knee extensor muscles (62 subjects, 29 male: 22.5 ± 2.4 yrs, 1.81 ± 0.05 m, 76.1 ± 9.6 kg, 33 female: 20.4 ± 1.9 yrs, 1.70 ± 0.07 m, 60.2 ± 7.7 kg). Figure 2 shows the relation between endurance and fibre distribution for 12 subjects (26.2 ± 5.4 yrs, 1.76 ± 0.10 m, 71.8 ± 8.5 kg) for the elbow extensors.[13], [12].

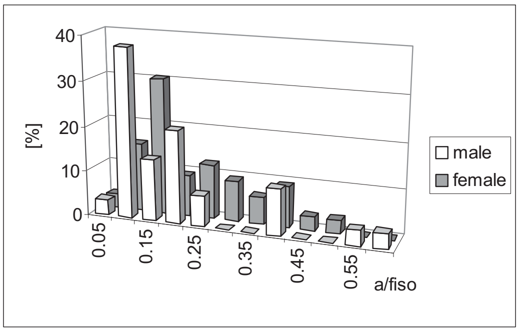

Figure 1. Distribution of the parameter a/f_{iso} for male and female subjects, showing the efficiency and endurance property of the subjects

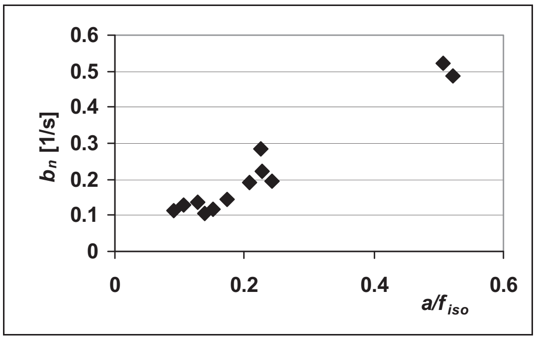

Figure 2. Relation between the parameter bn, describing the fibre distribution, and the parameter a/fiso, describing the efficiency of the muscle

3.2 Inter- and intra-individual differences in neuromuscular properties

The values of muscle properties differ substancially between subjects as can be seen in Figure 3, showing the force-velocity relation of the elbow extensors from three subjects. Comparing the neuromuscular properties of knee and elbow extensors from 8 male sports students (24.4 ± 1.6 yrs, 1.82± 0.06 m, 76.4 ± 6.8 kg) no significant correlation for f_{iso}, v_{max} and A ($r < 0.4$) could be detected. Positive correlation coud be found in the maximum possible power p_{max} ($r = 0.77$). The mean values of f_{iso}, v_{max} , p_{max} and A differed significantly ($p < 0.05$) between the two muscle groups. [12].

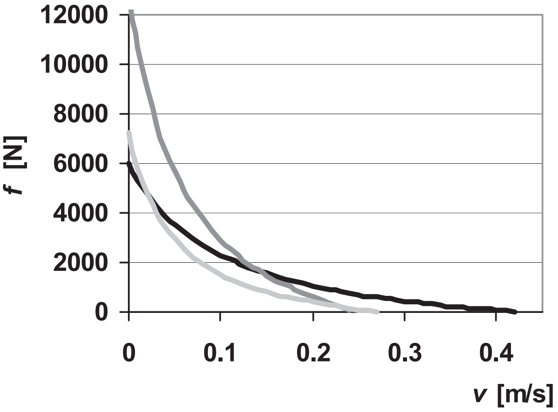

Figure 3. Force-velocity relation of the elbow extensors of three subjects.

3.3 Effect of changes in the movement conditions on the resulting movement

Altered movement conditions may change the resulting movement substantially. It may even happen that the ranking in performance of two persons changes. An example is the long jump as it was performed in the ancient Olympic games. During the jumping contest the athletes held additional weights, so-called halteres, in their hands. These weights had masses of about 1 to 4 kilograms. Simulations and measurements demonstrated that not all athletes had an advantage from the halteres.[4]. Calculations of a model jump with arm movements using individual neuromuscular parameters show that the effect of the additional masses depends on the values of all other properties. In our study the individual muscle properties were determined as described above (10 subjects, 23.3 ± 2.64 yrs, 1.71 ± 0.1 m, 68.1 ± 10.1 kg). Although for some subjects, the halteres increase the performance, for other subjects, the effect of the additional masses is negative. Figure 4 shows the simulation of the jump height of a vertical jump without and with arm movements and with additional masses.

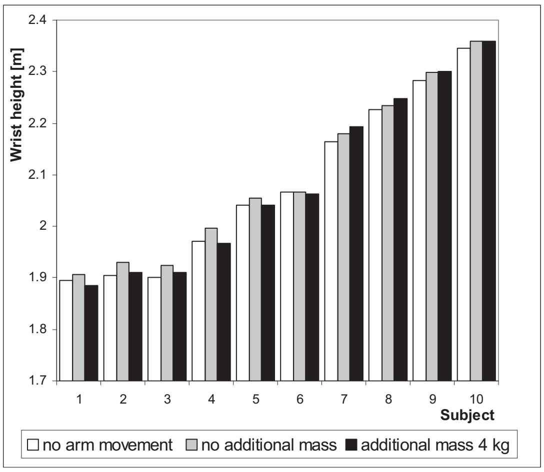

Figure 4. Simulation of the effect of an arm movement on the wrist height in a vertical jump for 10 subjects: all subjects can increase their jumping height by the use of arm movements. Additional masses of 2 kg per arm are only an advantage for some persons.

3.4 Effect of propertiy alterations on the resulting movement

The performance function shows the relation between the individual neuromuscular properties and the resulting performance for a specific movement. To visualize this function, we let all but two properties (f_{iso} and v_{max}) be arbitrary but fixed. Let the conditions of the movement also be fixed. Then for every fixed set of values we get a graph of a function between R^2 and R (see Figure 5), mapping the properties f_{iso} and v_{max} to the corresponding performance.

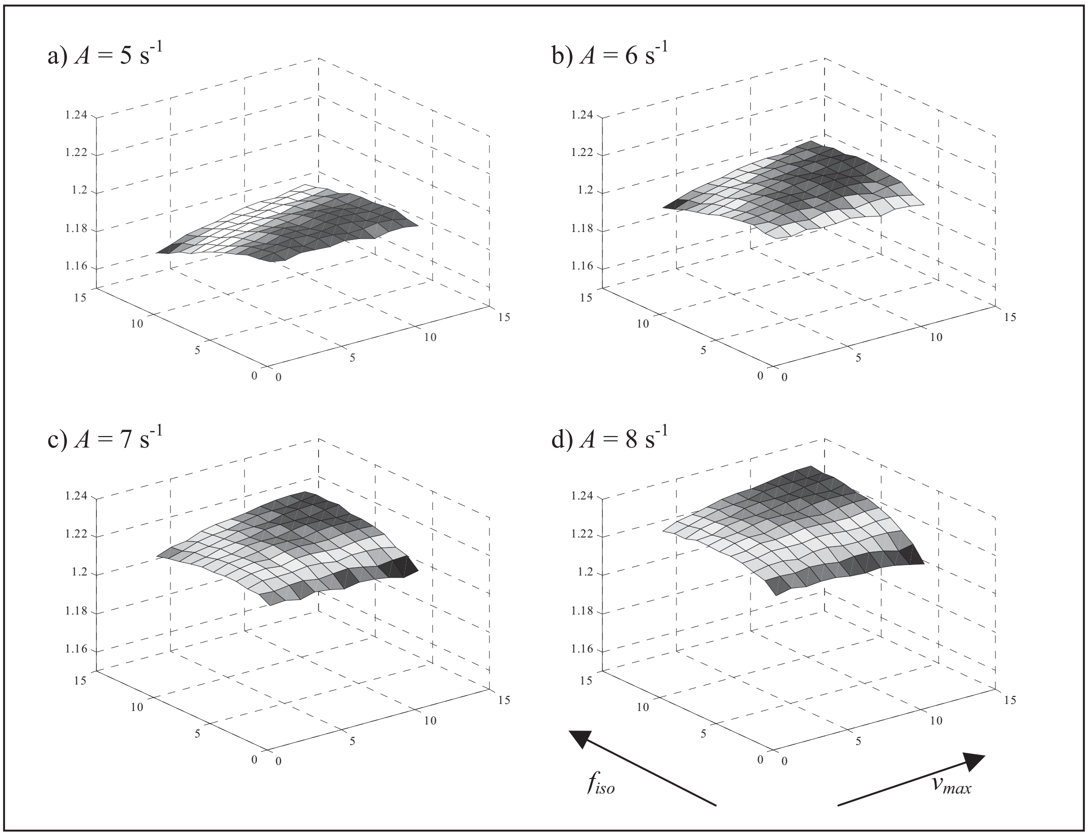

Figure 5. Performance function. The graphs a) - d) show a mapping between the two muscular properties f_{iso} and v_{max} and the corresponding performance. The values of f_{iso} (to the left) and v_{max} (to the right) are plotted on the horizontal axes, the performance is plotted on the vertical axis. From a) to d) the activation parameter A increases. All other properties are kept constant.

Depending on the initial values of the properties, i.e., the state of the person, the maximum performance can be achieved by different changes in the property values. The state of the person and the corresponding performance can be seen as a point on the surface of the performance function. The highest increase of performance can be achieved by following the direction of the gradient of the surface. [3] and [10] investigated the change in muscle properties applying several training programs.

Using the performance function, the performance determining and performance limiting factors can be calculated. In Figure 5 graph d) shows that for low f_{iso} the maximum possible contraction velocity v_{max} cannot be a performance determining factor. A change in v_{max} does not (or not much) change the performance. Low f_{iso} is a performance limiting factor: any change in the value of v_{max} does not increase the performance.

4 Conclusions

Individual measurements confirm that the variation in neuromuscular properties between different subjects is substancial. In order to get reliable results from subject specific simulations, the individual determination of these properties is of great importance. Modelling a specific movement the performance function provides information about which property change would lead to the largest increase in performance. Therefore, simulations with subject specific neuromuscular properties is a promising method for the planning and controlling of training.

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