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Original paper

# Validity analysis of the Biodex System 3 dynamometer under static and isokinetic conditions

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Isokinetic dynamometers are frequently used as training devices. They are also regularly employed to measure the characteristics of skeletal muscles under dynamic conditions. The combination of published data of such measurements and the authors' own experience led to the present investigation of the validity of measurements performed using the Biodex System 3 dynamometer. Two individual dynamometers of the same type were used. A calibration technique was used to test the validity of measured torque and the angular coordinate of the position of the lever arm of the dynamometer under static conditions. The results of measurements performed under dynamic (isokinetic) conditions were verified by comparing numerical values of tests provided in the Biodex report and raw data collected directly from the measuring computer of the same isokinetic machine. The shapes of experimentally determined characteristics of torque $M_{\max}(\omega)$ and power $P(\omega)$ were also analysed, taking into consideration their conformity with the laws of thermodynamics and known properties of skeletal muscles. The static tests showed that the indications of the Biodex System 3 dynamometer lay within the error range specified by the manufacturer. Therefore, the results of static measurements can be considered accurate. According to the isokinetic tests, the values of angular velocity were also accurate. However, indications of torque and power were much less accurate, justifying the uncertainty over whether they can be considered true results of measurement.

*Key words*: *Hill-type curve, muscle torque, power, velocity*

## 1. Introduction

Skeletal muscles produce forces necessary to initiate and sustain human body movements. During contraction, muscles perform work whose value depends on muscular force $F_m$ and displacement $\Delta l$ considered as a change of length of a muscle. Power $P_m$ developed by a muscle is the derivative of work with respect to time, and can therefore be expressed as the product of muscular force $F_m$ and muscle shortening velocity $v_m = \Delta l/\Delta t$ as follows:

$$P_m = F_m \cdot v_m.$$

As follows from the principles of thermodynamics, the maximum mechanical power produced by any energy converter, and hence also skeletal muscles, is limited, therefore:

$$P_m = F_m \cdot v_m \le P_{\max}.$$

This inequality defines an area – limited from above by the hyperbola of maximum power – which contains the curve of the force–velocity characteristics of a muscle. It follows from these simple considerations that the maximum value of force produced by a skeletal muscle must depend on its shortening velocity and that this dependence, at least at high values of velocity, has a character of inverse proportionality. This was first experimentally confirmed by A. V. Hill, whose name is now used to denote hyperbolic force–velocity characteristics, which are typical of skeletal muscles. Hill's equation describes the interdepend-

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ence of three quantities: muscular force $F_m$, muscle shortening velocity $v_m$, and muscular power $P_m$, and is thus an example of a convenient synthetic characteristic of a muscle under dynamic conditions.

During the last quarter of the 20th century, attempts were made to design a dynamometer which could be used to measure the force–velocity characteristics of the main muscle groups of the human musculoskeletal system under in vivo conditions. Several dynamometer designs were created (Lido, Cybex, Ariel, etc.). They were equipped with a controlled brake which allowed the velocity of movement in a joint to be parametrically set. The system designed by Biodex is an example of such a device which is used nowadays. According to the information provided in the marketing materials, the Biodex dynamometer can be used for exercise and to test and rehabilitate patients. In addition, it is often used in scientific research to perform measurements [1]–[4], and sometimes the results of such measurements help to draw far-reaching conclusions [5]. However, measuring error analysis was not performed in these studies, which can be partially explained by an insufficient information on metrological properties of the dynamometer. The manufacturer provides only limited information on the measuring error: velocity (±1 deg/s), angle (±1 deg), and torque (±1%), and no additional information is given on whether the errors relating to angle or torque values refer to static or dynamic conditions. Most of the studies where a dynamometer was considered as a measuring device were focused on analysing the repeatability or reliability of the results of tests carried out on humans (in such cases, only the diagnosability of isokinetic tests could be examined, not the validity of measurements) [6]–[8]. Another approach was to analyse the influence of inertia of the movable parts of the dynamometer on the torque and power values obtained [9], [10], or to check the validity of gravity correction procedures in isokinetic dynamometry [11], [12]. Although each of these approaches refers indirectly to the validity of indications of the isokinetic machine, they do not allow the more general question of whether Biodex is a valid measuring device to be answered.

For this reason, we decided to analyse the results of measurements acquired from an isokinetic dynamometer from the point of view of their credibility, inner consistency and compatibility with the knowledge on the properties of skeletal muscles. Due to the reasons of a technical nature, we did not attempt to determine the metrological parameters of the dynamometer. Our objective was merely – by using the most simple, available to every user, means – to try to answer the question whether the Biodex System 3 can be used as a measuring instrument, or should it only be considered as a training device equipped with some control functions.

## 2. Methods

Two different methods were used to test the Biodex System 3 dynamometer under both static and dynamic conditions. Under static conditions, a standard procedure commonly used to gauge measuring instruments was followed, which consisted of comparing the indications of the device with the known values of the measured quantity.

A constant torque of known value was applied to the lever of the dynamometer kept in a horizontal position. The torque was produced by weights hung on the lever and its value is given by the equation

$$M_w = Q \cdot r,$$

where:

$M_w$ – the value of the torque,

$Q$ – the value of the weight hung on the lever,

$r$ – the lever arm of force $Q$, measured as the distance between its point of application and the rotation axis of the lever.

The influence of the angular position of the lever on static indications of the dynamometer was tested by measuring the torque produced by the weight $Q$ attached to the lever at the distance $r$ from the axis of rotation. This torque depends on the orientation of the measuring lever with respect to gravitational force and is given by:

$$M = Q \cdot r \cdot \cos\alpha = M_Q \cdot \cos\alpha,$$

where $\alpha$ is the angle between the measuring lever and the horizontal.

Simultaneously, the accuracy of the measurement of the angular coordinate of the position of the lever was indirectly verified in this test.

Under isokinetic conditions, the results of the tests cited in the Biodex report displayed on screen were compared with those obtained directly from "individual data points" logged to a file as described in the Biodex System 3 Advantage System Operations Manual on page 18. These "individual data points" will be referred to as "raw data" throughout the text. They were subjected to detailed analysis, paying particular attention to the influence of transient states taking place almost at the beginning and the end of the movement phase characterised by stabilised velocity (the isokinetic phase). In this part of the testing procedure, the results of tests performed on two Biodex dynamometers were used to eliminate the possibility of the device being faulty. The measurements were carried out for the following muscle groups: flexors and extensors of the knee joint and abductors of the arm. The manufacturer's operating instructions were followed. In total, 14 subjects participated in the tests. This study was approved by the Ethics Committee of the University College of Physiotherapy in Wrocław, Poland, and all participating subjects signed the informed consent form.

# 3. Results and discussion

The results of the static tests are displayed in figures 1 and 2. Figure 1 presents a comparison of the indications of the dynamometer with the values of the gauging torque applied. The relative value of the difference between the indications of the dynamometer and the torque applied was calculated according to the formula:

$$\delta = (M_B/M_w - 1)\cdot 100\%.$$

This value was less than 0.4% in the range tested, which was in conformity with the measuring error declared by the manufacturer (±1%). In the second part of the static tests, the influence of the angular position of the lever arm on the torque indicated by the dynamometer was analysed. The measuring lever was loaded with the weight $Q$ attached to it and produced a torque dependent on its angle $\alpha$ with respect to the horizontal, according to the formula

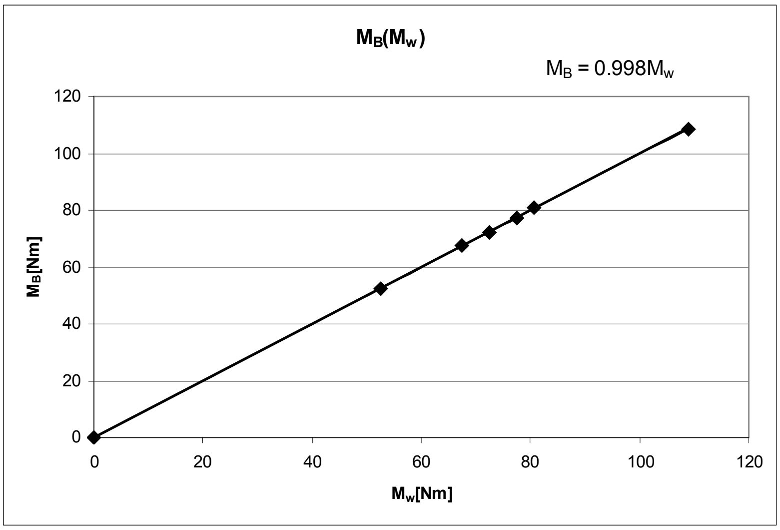



Fig. 1. Comparison of the indications of the dynamometer $M_B$ (♦) with the torque applied $M_w$ (solid line)

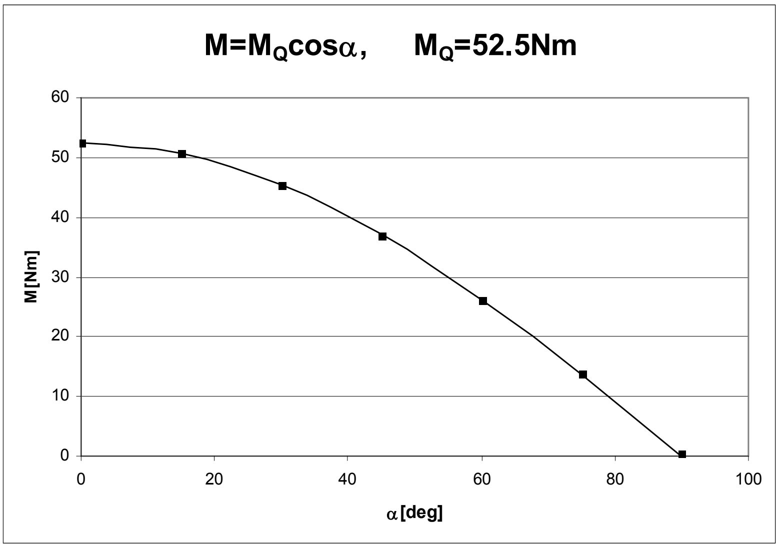
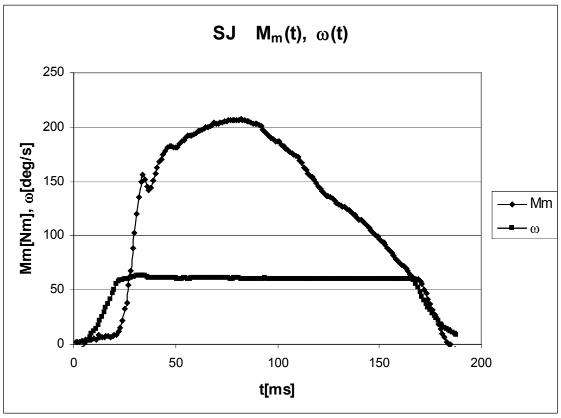
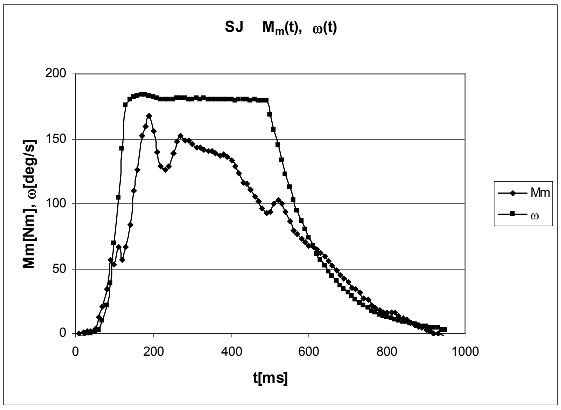


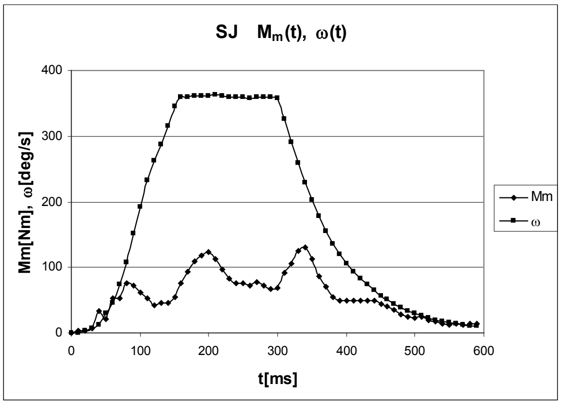

Fig. 2. The influence of the angular position of the lever arm on the indications of the Biodex dynamometer under static conditions. Indications of the dynamometer (■) loaded with torque $M = M_Q{\cdot}\cos\alpha$ (solid line)



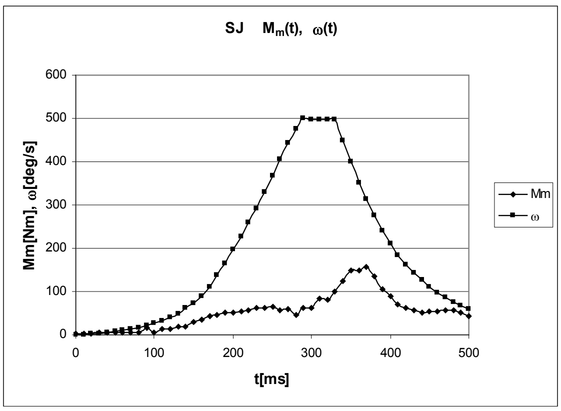

| Biodex report | | Biodex raw draw |
|---|---|---|
| Peak torque | 206.5 Nm | 207.5 Nm |
| AVG peak torque | 204.4 Nm | 203.5 Nm |
| AVG power | 119.4 W | 161.3 W |
| Velocity | 60 deg/s | 60.4 deg/s |




| Biodex report | | Biodex raw data |
|---|---|---|
| Peak torque | 149.6 Nm | 167.9 Nm |
| AVG peak torque | 148.4 Nm | 158.6 Nm |
| AVG power | 158.7 W | 408.8 W |
| Velocity | 180 deg/s | 180.6 deg/s |




| Biodex report | | Biodex raw data |
|---|---|---|
| Peak torque | 108.4 Nm | 124.1 Nm |
| AVG peak torque | 106.8 Nm | 122 Nm |
| AVG power | 145 W | 589 W |
| Velocity | 360 deg/s | 360.4 deg/s |




| Biodex report | | Biodex raw data |
|---|---|---|
| Peak torque | 133.2 Nm | 98.7 Nm |
| AVG peak torque | 129.4 Nm | 83.2 Nm |
| AVG power | 164.7 W | 599.9 W |
| Velocity | 500 deg/s | 497.8 deg/s |

Fig. 3. Selected torques produced by extensor muscles of the knee joint and angular velocity determined on the basis of the raw data recorded during the isokinetic tests (SJ: subject's initials). The tables include numerical values provided in the Biodex report and determined during the isokinetic phase on the basis of the raw data

$M = Q \cdot r \cdot \cos\alpha$. The dependence of the indications of the dynamometer and the values of the torque applied on the angle $\alpha$ is shown in figure 2. The relative difference between the indication of the dynamometer and the torque applied did not exceed 0.9% in this test. The results of both static tests are satisfactory. Indications of the dynamometer lay within the error range declared by the manufacturer (torque: $\delta = \pm 1\%$, angle: ±1 deg), and thus can be considered accurate. This level of accuracy is sufficient for measuring parameters describing human movement activity, which are characterised by significant dispersion and relatively poor repeatability.

The Biodex System 3 is capable of directly recording the following parameters: time (accuracy of 10 ms), the torque applied to the lever arm and angular position of the lever arm. Other parameters, i.e. power, force and those parameters which are provided in the Biodex report, are calculated indirectly also taking into account the information entered by the operator (e.g., body mass, body height). In this study, we decided to analyse only the results obtained from direct measurements (angle, angular velocity, torque) and power.

Isokinetic tests should be performed at the velocity of movement in a joint being constant and equal to the desired value in the whole range of the movement. However, it is evident that the above condition can only be partly fulfilled. Target velocity of movement in a joint can be achieved only after overcoming the inertia of the moving segment of the body and of the measuring device, as well as friction and the resistance to motion of the limb fixed to the lever arm of the dynamometer. Thus, the above-mentioned condition can be fulfilled only in the central part of the range of movement, and consequently the results of the measurements presented in the test report should refer to this phase of movement only. The results of isokinetic tests performed on flexor and extensor muscles of the knee joint were analysed initially. Example material as well as the results of these analyses are shown in figure 3. These results are questionable as the difference between the results provided in the Biodex report and raw data collected from the same device was significant. Its value was more than 10% in the case of torque measured at high velocity, 25% in the case of power measured at a velocity of 60 deg/s and more than 100% at a velocity greater than 180 deg/s. An explanation for this situation is difficult to find, hindered even more by failure of the manufacturer to provide accurate definitions of the parameters used and descriptions of methods by which they were determined.

The $M_m(t)$ and $\omega(t)$ curves shown in figure 3 point to another source of possible errors of indications of the dynamometer. It consists in disturbances resulting from transient states (decaying vibrations in the system) occurring when the velocity stabilisation system is being switched on and off. The first transient state (switching on) affects the characteristic $M_m(t)$ during the isokinetic phase and is potentially more dangerous. The second transient state is mentioned in the Biodex System Software Operation Manual and has been detected in previous studies [3]. This transient state occurs after the end of the isokinetic phase, and thus seems to be less important, provided that the observations and measurements are carried out during this phase only. The effects of non-stationary states disappear after about 150 ms. This is comparable to the duration of the isokinetic phase observed for the extensor muscles of the knee joint (one of the strongest muscle groups of the human musculoskeletal system) at a velocity of about 240–300 deg/s. Therefore, the tests performed on this muscle group at a velocity greater than 240–300 deg/s are fully affected by the non-stationary states. The tests on weaker muscle groups will be affected at lower movement velocities. This means that the results of the tests performed at relatively higher velocities can be affected by significant errors. It is worth noting the effectiveness of the velocity stabilisation system, its stable work and small error ($\delta < 1\%$).

The muscular torque characteristic $M_m$, as a function of the velocity of movement $\omega$ in a joint, is also questionable. The characteristic is a counterpart of the classic Hill's curve but measured under in vivo conditions. In the concentric action, this relation is usually represented by a shifted hyperbola which crosses the two axes of the coordinate system (velocity–torque) at two points corresponding to the maximum value of muscular torque (static conditions, $\omega = 0$) and the maximum velocity of free movement in a joint ($\omega = \omega_{\max}$, $M_m = 0$). This property of the muscular drive is indisputable as it derives from the laws of thermodynamics. Such a shape of the torque–velocity relation has the following effect. The maximum effective power produced by muscles equals zero at both ends of the range of movement velocities in the concentric action and reaches its maximum value in the central part of the range. Extensor muscles of the knee joint develop their maximum power at movement velocity equal to about 30% of the maximum extension velocity of the joint which is about 210 deg/s [13].

Modern technologies make it possible to measure the relation $M_m(\omega)$ in the lower and central parts of the range of movement velocities. The missing part of the

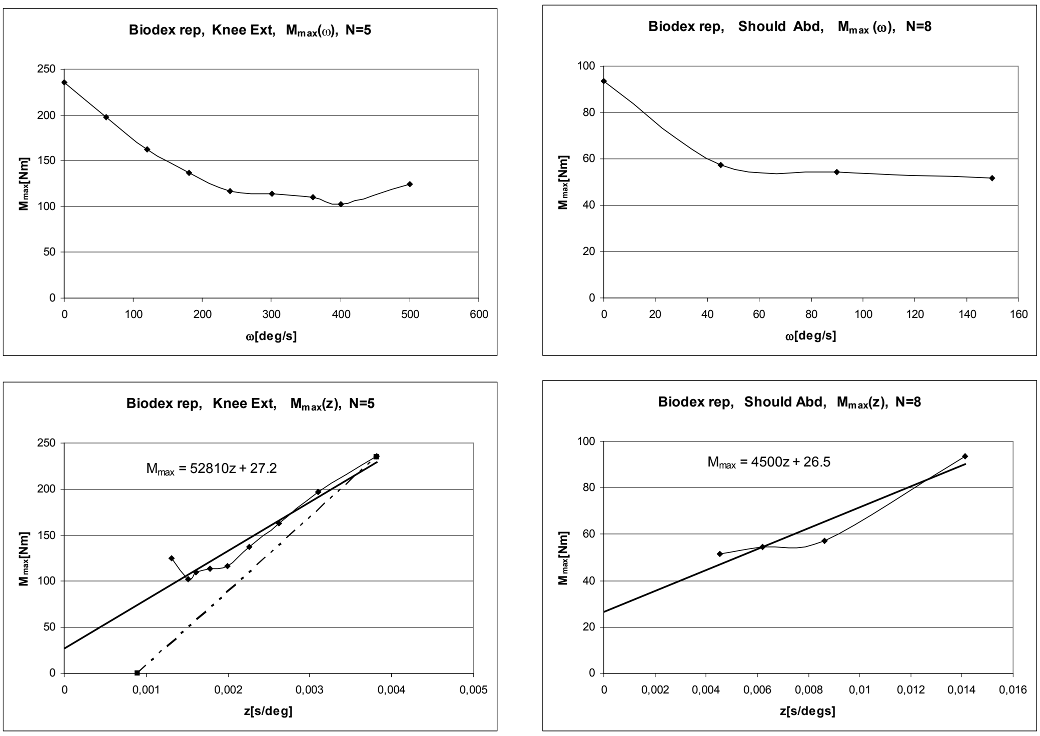



Fig. 4. Averaged (for $N = 5$ and $N = 8$ subjects) relations $M_{\max}(\omega)$ determined on the basis of the Biodex report for extensor muscles of the knee joint (left column) and abductor muscles of the arm (right column). The results of the approximation of 'hyperbola' $M_{\max}(\omega)$ by a straight line equation $M_{\max}(z)$, $z = 1/(\omega + b)$ are presented below. The predicted shape of $M_{\max}(\omega)$ determined in accordance with the laws of thermodynamics and knowledge of the musculoskeletal system is shown using a broken line

characteristic $M_m(\omega)$ is obtained by extrapolation of this part of the characteristic, which is determined empirically and described by a hyperbola equation. The results are shown in figure 4.

If we make a replacement $z = 1/(\omega + b)$, then the hyperbola described by Hill's equation $(M_{\max} + a) \cdot(\omega + b) = c$ will transform into the equation of a straight line as follows: $M_{\max} = c/(\omega + b) - a = c \cdot z - a$. This is a simple way to verify the hypothesis of the 'hyperbolic nature' of the relation $M_{\max}(\omega)$. It is proven by checking whether the relation $M_{\max}(z)$ is linear or close to linear. Moreover, the above procedure considerably facilitates the description of the empirical characteristic $M_{\max}(\omega)$, which consists in deriving an equation of a straight line. The shapes of the maximum muscular torque (figure 4) determined on the basis of the data provided in the Biodex report were found to have a hyperbolic character. Therefore, their form was in conformity with general knowledge of the properties of skeletal muscles under dynamic conditions. However, the position of the above-mentioned curves was in contrast to this knowledge. They should clearly cross the $\omega$-axis at least close to a point representing the maximum velocity of movement in a joint, which is about 17 rad/s in the case of the extension movement in the knee joint [14]. Extrapolation of the relations describing empirical characteristics determined using the Biodex dynamometer (both individual and averaged) suggests that the tested muscle groups are capable of developing a torque of 20–30 Nm at an infinitely high velocity of movement in a joint ($1/\omega \to 0$)! The shape of the relation $M_{\max}(z)$ determined for extensor muscles of the knee joint was in conformity with both general knowledge and expectations. This is shown in figure 4 as a broken line in the bottom left diagram.

Why does such a significant discrepancy exist? It seems implausible that it is due only to the errors connected with determining torque at higher movement velocities as mentioned above. This possibility is excluded by the relation $M_{\max}(z)$, which is close to linear (in the whole range of velocities). It is also proven by similar shapes of the characteristics of flexor and extensor muscles of the knee joint (figure 5) determined on the basis of the raw data. They suggest that the torque measured in the whole range of the velocities tested is affected by an error. This is indirectly proven by the shape of the characteristics of power shown in figure 6. All three curves represent the relation between muscular power and the velocity of knee

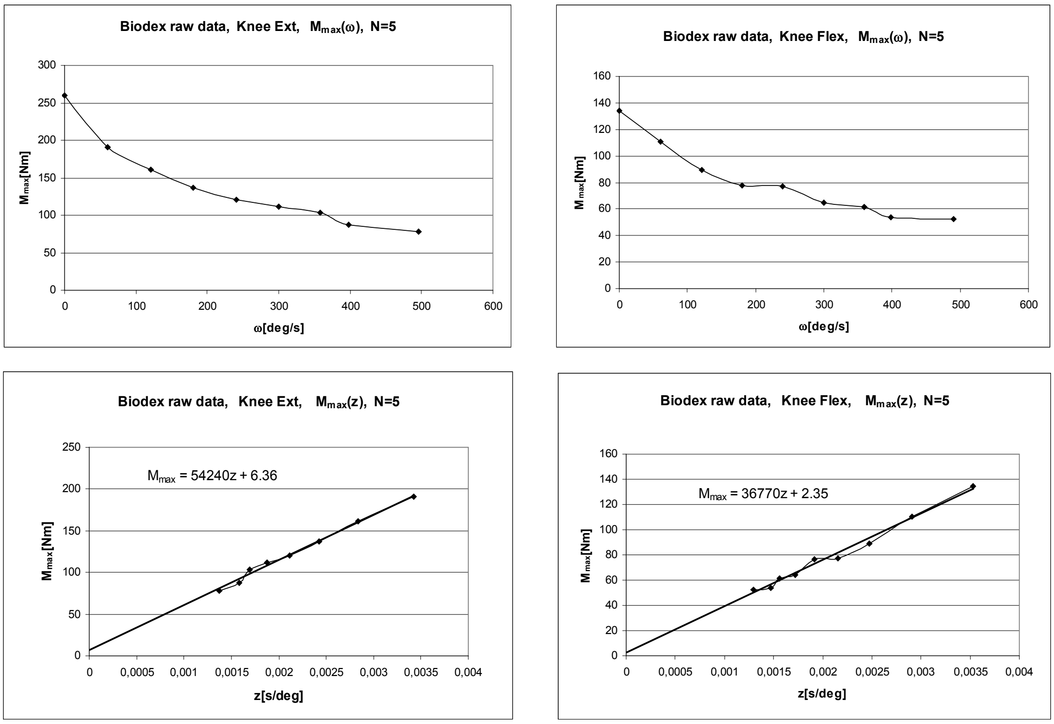



Fig. 5. Averaged relations $M_{max}(\omega)$ and the corresponding characteristics $M_{max}(z)$, $z = 1/(\omega + b)$, determined for flexor (right column) and extensor (left column) muscles of the knee joint (five subjects were tested). The straight line (bottom diagrams) is a linear approximation of empirical data. Its equation is placed next to the line

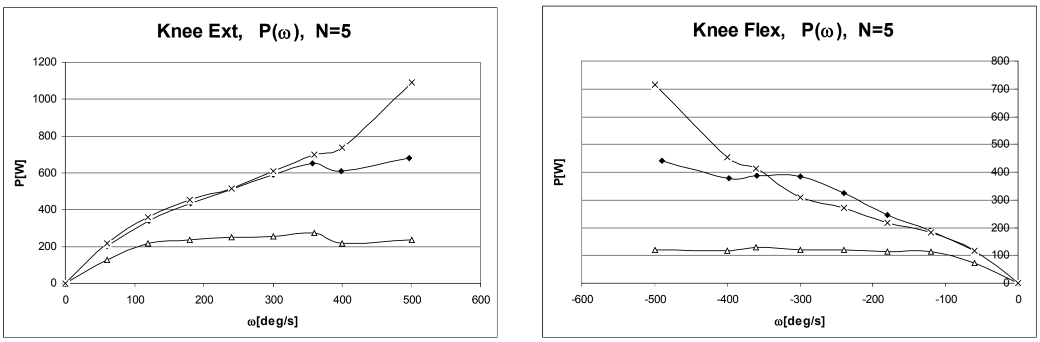



Fig. 6. Characteristics of power (averaged values, five subjects) as a function of movement velocity determined for flexor (right column) and extensor (left column) muscles of the knee joint. Symbol Δ represents mean power (data exported from the Biodex report), symbol ♦ represents maximum power $P_{max} = M_{max} \cdot \omega$ determined on the basis of the raw data, and symbol × represents maximum power determined from the same relation but on the basis of $M_{max}$ provided in the Biodex report

flexion and knee extension. Each curve was determined in a different way, but on the basis of indications of the Biodex dynamometer. The three curves represent the following types of power: mean power (data exported from the Biodex report), maximum power during the isokinetic phase determined from the relation $P_{max} = M_{max} \cdot \omega$ on the basis of the raw data, and maximum power determined from the same relation but on the basis of $M_{max}$ and $\omega$ provided in the Biodex report. It can be seen from figure 6 that all the curves tend to slope upwards in the whole range of movement velocities. This is questionable as the maximum power produced by skeletal muscles in the concentric action rises with increasing movement velocity until the velocity reaches about one-third of its maximum value and then the maximum power falls. The value at which the maximum power starts to fall is about 4 rad/s (about 230 deg/s) for extensor muscles of the knee joint [13] in the case of maximum velocity of free extension movement in the knee joint of about 12–15 rad/s [15]. Therefore, the relations of maximum power as a function of movement velocity determined with use of the Biodex dynamometer are also open to question. Their shapes suggest that muscles of the limb tested are not the only source of energy involved in its movement. This additional energy and power seem to be hidden, but their presence is evident if we analyse the results of tests. They can be an undesired effect of the compensation system of a dynamometer's own resistance to motion. This can be proven by short-lasting and impulsive disturbances of significant value which are sometimes present during measurements of torque when the direction of movement of the lever arm of the dynamometer is changed.

Is it true that the Biodex System 3 does not determine the characteristics of human skeletal muscles, but rather the characteristics of muscles supported by a motor whose parameters are unknown to the user? The answer to the question asked in the Introduction relating to the functions and possible use of the Biodex dynamometer is not obvious. Static tests proved that indications of the dynamometer lay within the error range specified by the manufacturer, which can be considered sufficient for measurements on biological subjects. Therefore, the Biodex System 3 allows valid measurements of muscular torque under static conditions to be performed and the results obtained can be used in scientific analyses. However, the results of dynamic tests performed under isokinetic conditions are definitely open to question. This particularly refers to measurements performed at relatively high movement velocities ($\omega$ > 240 deg/s), where the results provided in the Biodex report were significantly different from the results calculated on the basis of the raw data. Transient states in the velocity control system seriously affecting the torques can be one of the reasons for these discrepancies. The characteristics of torque and velocity, as well as power and velocity, are also questionable. They are determined on the basis of indications of the dynamometer, and seem to suggest that human skeletal muscles are capable of reaching infinitely high values of effective power. Therefore, numerical values of parameters determined under dynamic conditions with the use of the Biodex dynamometer should neither be treated as valid nor used in scientific analyses.

In summary, the Biodex System 3 is fairly useful if we consider it as a training device with several testing functions providing numerical values of some conventional parameters, which can be used to assess the progress of training and rehabilitation. However, in contrast to the names of these parameters, they cannot be treated as physical quantities which have their accurate definitions and are determined in accordance therewith. This seems to be in conformity with the intention of the manufacturer of the Biodex dynamometer, as no information is provided about the accurate definitions of the parameters used and descriptions of the methods by which they were determined.

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