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# FREQUENCY EFFECT ON SELECTED CHARACTERISTICS OF THE ELBOW JOINT CYCLIC MOVEMENTS

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**Abstract.** The subject of this thesis are relationships between quantities describing the behaviour of the human upper limb during cyclic movements in the elbow joint. Seventeen students took part in the experiment. The examined subjects' task consisted in performing cyclic flexion-extension movements in the elbow joint with the highest frequency within the range of movement placed symmetrically around the middle angle $\alpha_0 \approx 1.8$ rad.Movements were realised in 5 ranges with amplitudes $\alpha_m$ from 0.2 to 1.2 rad. The dependence of joint angle on time was measured and then angular velocity $\omega(t)$, angular acceleration $\varepsilon(t)$ and external power P(t) were calculated from the definition equations. The existence of a clear relationship (negative correlation) between amplitude and frequency of the forearm cyclic movements was found. Moreover, the strong resemblance of examined movements and harmonic oscillations was noted. It manifested itself in the character of observed kinematical dependencies and in the quantitative relations between them. Based on the above observation the dependencies of movement amplitude $\alpha_m$, angular velocity $\omega_m$, angular acceleration $\varepsilon_m$ and external power $P_m$ on movement frequency were determined and described using some simple equations. ***(Biol.Sport 23:195-208, 2006)***

*Key words:* Cyclic/periodic movements – Elbow joint – Frequency – Amplitude – Power

## Introduction

Periodic movements constitute a separate and specific category of motor tasks characterised by repetitiveness observed for example in kinematical values found in consecutive cycles. This feature manifests itself in many aspects of human motor activity, e.g. the whole locomotion is based on cyclic movements. As the skeletal muscle work is the main source of energy needed for realisation of conscious and

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controlled movements of body parts, the muscles energetic properties should have the decisive influence on dimension of the area, which determines limits of the elbow movement realisation ability. The maximal velocity of movement regarding a single joint is restricted by the power of muscles which actuate it. On the other hand, the mechanical power produced by muscles may be presented as product of the sum of the muscles torque $M_m$ and angular velocity $\omega$ during joint movement: $P_u=M_m\cdot\omega$. This dependence determines one of the restrictions limiting the maximal movement velocity in a joint. These limitations should be seen also in cyclic movements e.g.: in relations between maximal values of kinematic quantities describing it and the frequency. Partial confirmation of these suggestions is provided by studies examining: human locomotion (due to high external loads) [4,10], cycling (limited amplitude range) [5,6], or coordination (limited frequency band) [1,11].

The aim of this work is the determination of relationships between amplitude, maximal frequency and power produced in cyclic forearm movements. These relations expressed as quantitative dependencies between the aforementioned quantities delimit the range available for the elbow joint forearm free cyclic movements. The analysis of these dependencies may be the source of information about the cyclic movement control (with maximal intensity) as well as about the causes of restrictions for movements maximal frequency and their relations with its amplitude.

## Materials and Methods

Seventeen male students of the Academy of Physical Education in Wrocław aged 19 to 24 took part in the study. Their detailed characteristic is presented in Table 1.

**Table 1**
Characteristics of the subjects (n=17)

| Parameter | Mean | SD |
|---|---|---|
| Age (years) | 20.8 | 1.3 |
| Body mass (kg) | 75.5 | 4.4 |
| Body height (m) | 1.82 | 0.04 |
| Forearm moment of inertia ($kg\cdot m^2$)* | 0.083 | 0.0085 |

*for the transversal joint axis

The subject of this work is among the issues connected directly with muscles operation in cyclic movements with maximal intensity and special emphasis is placed on relations between kinematical parameters and movement frequency.

Examined subjects' task consisted in the performance of cyclic flexions and extensions of the right elbow joint. These movements were done with the maximal frequency around the joint angle central value $\alpha_0 \approx 1.8$ rad. The realisation of symmetric movements around this angle was possible due to the similar sizes of the flexion and extension ranges.

The subjects performed movements with amplitude $\alpha_m$ within the following ranges $\alpha_{m1} \approx 0.2$ rad; $\alpha_{m2} \approx 0.4$ rad; $\alpha_{m3} \approx 0.6$ rad; $\alpha_{m4} \approx 0.8$ rad; $\alpha_{m5} \approx 1.2$ rad. The joint angle range was assessed approximately (subjects were shown the borders of allowed movement performance). Subjects were simultaneously informed that these borders have an approximate meaning only and therefore they should not try to reflect them during the experiment very precisely. Each subject presented 2 trials in each of the above mentioned amplitude ranges. This allowed determination of the individual amplitude-frequency characteristics $\alpha_m(f_m)$ defined by at least 5 points (but in practice usually 10 points).

Measurements were initiated in the so-called stable state of movements (after the end of transient processes in the initial phase of movement) i.e.: after a few seconds from its beginning. The dependency of joint angle on time $\alpha(t)$ was measured. Recordings were performed with the use of a potentiometric converter (attached to the moving forearm) characterised by linearity error of $\delta_N \leq 0.5\%$ and 12-bit A/D converter with sampling frequency of $f_s$=128Hz.

The subjects were sitting during the measurement with their arm abducted by 90° and stabilised. The forearm together with the hand was put on the horizontal lever whose rotation axis passed vertically through the elbow joint centre. Having such a limb organisation (with wrist joint immobilised) the forearm and hand could move in the horizontal plane around the transverse elbow joint axis. The moment of inertia of the lever amounted to 0.01 $kg \cdot m^2$, which was by one order of magnitude smaller than the moment of inertia of the forearm. It can be assumed then that the presence of the lever had no significal influence on the examined elbow joint movement what so ever.

The dependence of the elbow joint instantaneous angle position on time was the quantity registered directly. It was described by $\alpha(t)$ trajectory which displayed itself as a discrete relation: $\alpha_i(t_i)$ where i stands for the current sample number. Values of instantaneous angular velocity $\omega$; angular acceleration $\varepsilon$; kinetic energy Ek and external power $P_k$ were determined based on the above mentioned dependence. It was done using appropriate definition equations, which because of the joint angle α(t) measurement technique used assume the following discrete forms:

$$\omega(t)\overset{def}{=}\frac{d\alpha(t)}{dt}, \quad \text{i.e.} \quad \omega(t_i)\approx\frac{\alpha(t_{i+1})-\alpha(t_{i-1})}{t_{i+1}-t_{i-1}}$$

$$\varepsilon(t)\overset{def}{=}\frac{d\omega(t)}{dt}, \quad \text{i.e.} \quad \varepsilon(t_i)\approx\frac{\omega(t_{i+1})-\omega(t_{i-1})}{t_{i+1}-t_{i-1}}$$

$$E_k(t)=\tfrac{1}{2}I\omega^2, \quad \text{i.e.} \quad E_k(t_i)\approx\tfrac{1}{2}I\omega^2(t_i)$$

$$P_k(t)\overset{def}{=}\frac{dE_k(t)}{dt}, \quad \text{i.e.} \quad P_k(t_i)\approx\frac{E_k(t_{i+1})-E_k(t_{i-1})}{t_{i+1}-t_{i-1}}$$

## Results and Discussion

Fig. 1 presents the exemplary time dependencies of kinematical quantities registered during one flexion-extension cycle of elbow joint realised by one of the examined subjects (8) for 2 extreme and 1 middle value of movement amplitudes. Trajectories corresponding to small amplitude movement resemble quite faithfully the analogous dependencies observed for harmonic oscillations. However, the higher was the forearm movement amplitude the less clear this resemblance was. This especially applies to the angular acceleration and to a somewhat lesser extent, the angular velocity. Such effect could be elicited by the non-linear characteristic of tendon-muscle arrangement involved in limb movement, for example: asymmetry of joints flexors in relation to extensors which is presented in Fig. 1 as asymmetry of the angular acceleration which respect to the movement direction. The analogical effect was registered by Mirkovand *et al.* [7] and Nagasaki [8], where such asymmetry occurred in movements with low frequency.

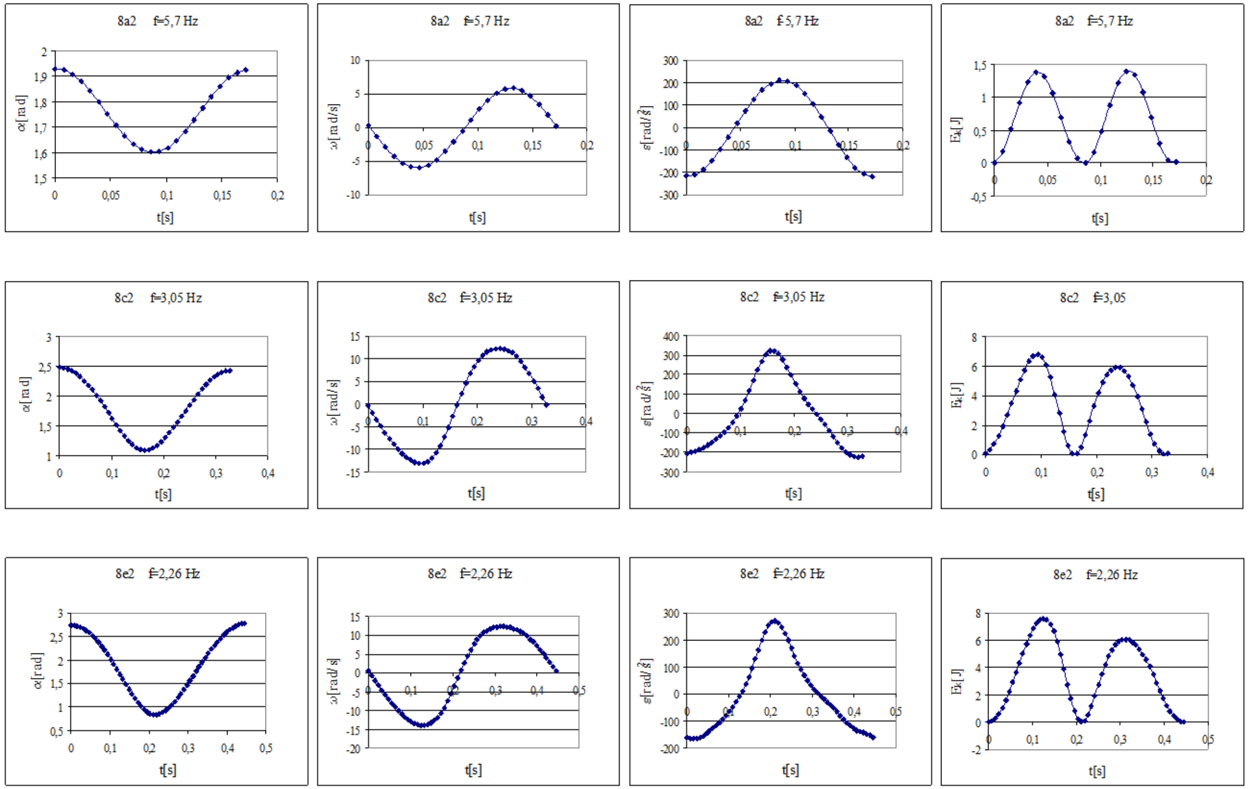

**Fig. 1**
Exemplary time histories of: joint angle α; angular velocity ω; angular acceleration ε; kinetic energy $E_k$ in the forearm cyclic movements realised by subject 8 for three movement frequencies

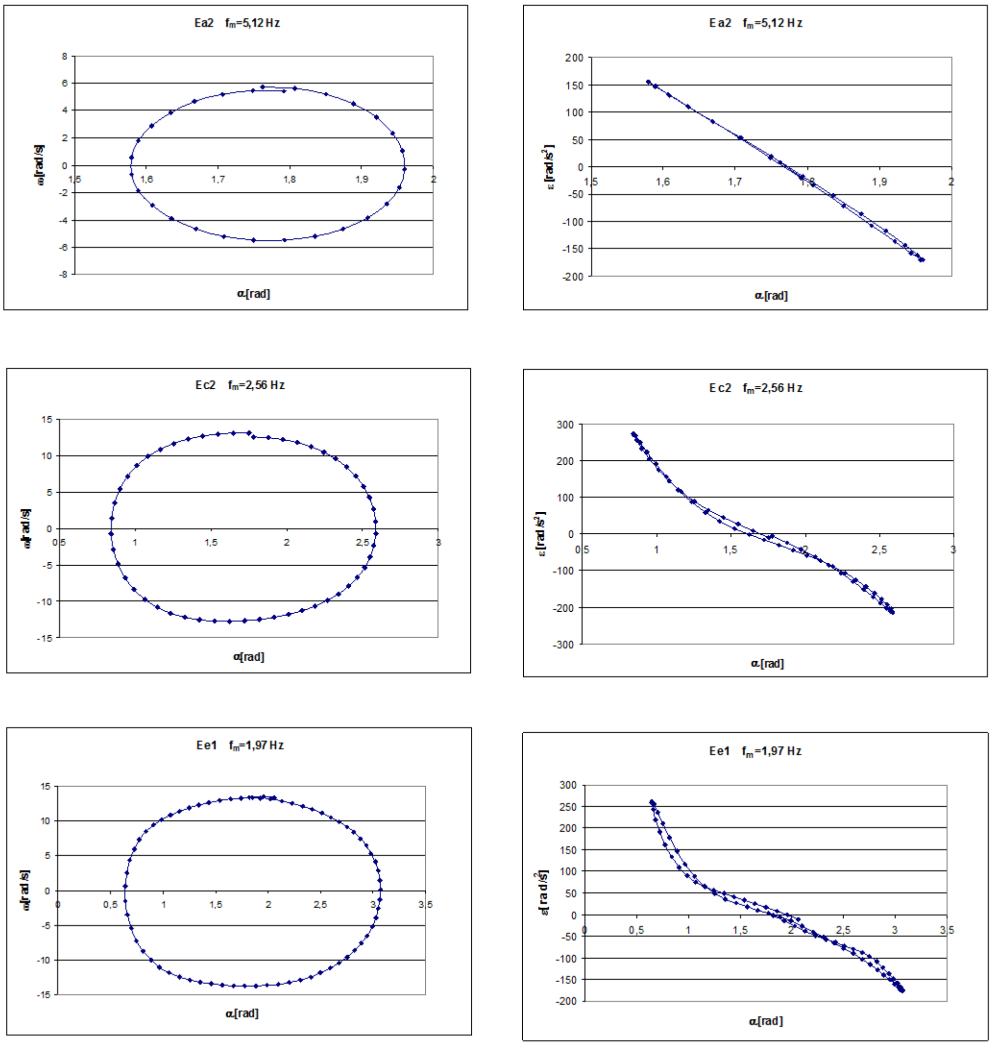

**Fig. 2**
Typical ω(α) and ε(α) dependencies found in cyclic movements of the elbow joint registered for three frequencies ($f_m$)

Characteristics of ω(α) and ε(α) presented in Fig. 2 show more clearly the extent and character of the earlier described observations. The ε=f(α) curve slope pictures the relationship between angular acceleration value ε and forearm deviation from position $\alpha_0$. The acceleration is elicited by the moment of force component (which is in phase with acceleration) which can be named as useful moment: $M_u=I\cdot\varepsilon$. It follows from dependencies presented in Fig. 2 that the useful moment value displays a close to linear (although with negative slope) relation with the joint angle deviation ($\alpha$- $\alpha_0$) which allows to state that $\varepsilon$=-c($\alpha_m$)·($\alpha$- $\alpha_0$) that is $M_u$=-I·c($\alpha_m$)·($\alpha$-$\alpha_0$). The I·c($\alpha_m$) product stands for the stiffness present during the joint movement. Such stiffness is connected with the amplitude (frequency as well) of the realised movement and increases along with the frequency but decreases when the amplitude increases. Additionally, this stiffness seems to attain higher values in the area of joint angles below 1 rad. i.e: for limb flexed more than by the middle angle $\alpha_0$. Discussed stiffness is not only the effect of passive deformation of tissues but may also partly come from the active muscles which may suggest that the role of extensors in cyclic movements is bigger than that of flexors. Gottlieb and Agarwal [2] stated that the stiffness in the elbow joint shows non-linear character, it is dependent on the deformation degree and falls along with its increase. Taking into consideration the above fact, it should be expected that the slope of $\varepsilon(\alpha)$ curves presented in Fig. 2 should decrease in the vicinity of extreme values of the joint angle and not increase as it is shown especially in the joint flexing area. Such phenomenon may be explained on the basis of the stiffness of the muscle-tendon complex and muscle activation dependence [2,12]. This would mean that the joint angle range under discussion is characterised by the increase of extensors activations which would result in providing of some mechanical energy needed for the loss supplementation and continuation of the movement in the limb.

The averaged dependence between maximal movement amplitude $\alpha_m$ and its frequency $f_m$ is presented in Fig. 3. The characteristic shown in this figure marks the limit of the movement area with possible parameters combination: amplitude and frequency. This curve has a distinct hyperbolic character and its shape is in agreement with the one obtained by Beck [1] in limited amplitude movements realised in part of the joint movement range. Post *et al.* [11] observed that forearm movement amplitude decreased twice by the frequency increase from 0.75 to 2.25 Hz. Similar though linear dependence was noted by Martin and Spirduso [6] while examining the relation between pedalling frequency and the crank length.

The relationship between the forearm movement amplitude and its frequency is presented and described with the following equation (solid line in Fig. 3):

$$\alpha_m(f_m) = \frac{3.16}{f_m} - 0.347; \qquad R^2 = 0.977 \qquad (1)$$

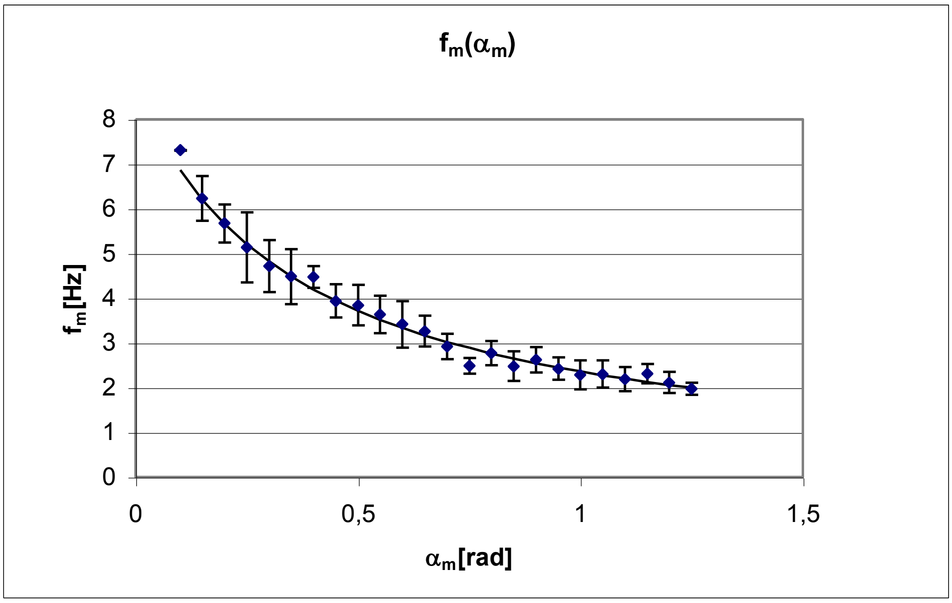

**Fig. 3**
Averaged (17 subjects) dependency between frequency and amplitude in the forearm elbow joint cyclic movements

The maximal external power and movement frequency dependence is presented in Fig. 4. The external power is represented here by the derivative – with respect to time – of external mechanical energy i.e.: kinetic energy associated with the forearm movement. The dependencies presented in Fig. 4 regard the so called “positive power” that is the one observed in the phase of acceleration of flexion or extension. Maximal positive power values determined experimentally are presented against the background of the curve:

$$P_m = \tfrac{1}{2} I\omega_m \cdot \varepsilon_m = \tfrac{1}{2} I\alpha_m^2 (2\pi f_m)^3 \qquad (2)$$

picturing the relation between the maximal rate of kinetic energy changes and the frequency for analogous harmonic oscillations.

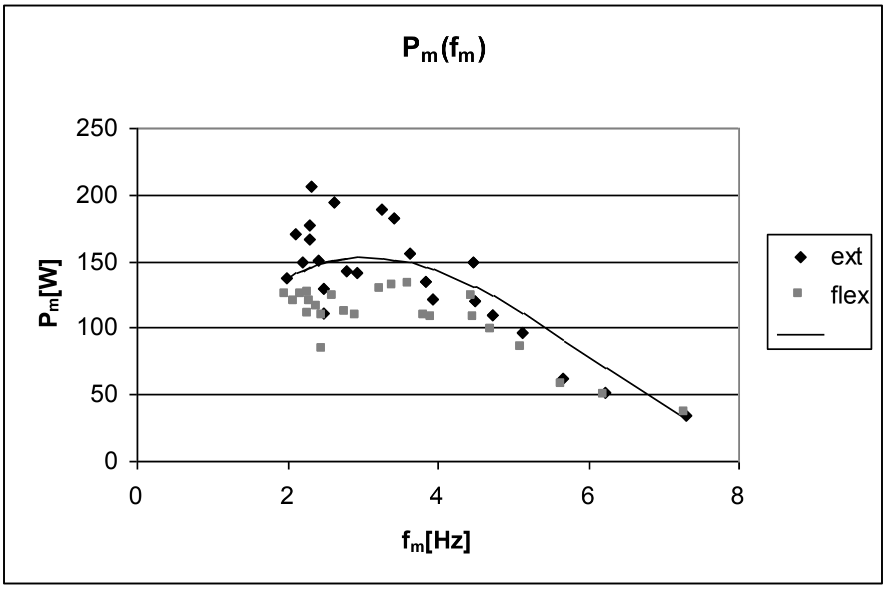

**Fig. 4**
Maximal external power (averaged for the examined group) in relation to the cyclic elbow joint movement frequency

The external power determined on the basis of kinetic energy changes may have two sources: 1) recuperation of internal potential elastic energy accumulated in earlier deformed tissues being a source of joint stiffness; 2) metabolic energy transferred as a result of muscles activity. Kinetic energy observed in the forearm cyclic movement during one cycle attained its maximal value twice. It occurred during the joint angle middle value $\alpha_0$ crossing. It can be stated then that the value of the elastic potential energy equals zero in this area. Therefore $E_{km}$ is equal to the total mechanical energy engaged in the limb movement. A part of this energy undergoes a double change into the potential energy during one cycle and the other part corresponding to energy loss must be supplied by working muscles. As a conclusion, the one cycle energetic cost can not be identified with the sum of external mechanical energy change, which formula is widely used for the calculation of useful work in human body movements. This formula is completely useless as regards cyclic movement [9] and its applications may lead to erroneous results.

A similar consideration applies to the external power. The curve presented in Fig. 4 and described by equation (2) should not be interpreted as characteristic of muscle power engaged in the movement. It shows the rate of change of the potential energy and the energy delivered by muscles into kinetic energy. This rate depends on power produced by working muscles, stiffness, damping in the joint and inertia of the mobile part of the limb.

The joint movement velocity caused by the muscle contraction depends on the muscle-tendon shortening velocity considering the transition from linear change of the tendon-muscle length to the rotational movement of bone lever. Hence, the maximal velocity of the joint movement is dependent on the maximal muscle shortening velocity. In reality, the joint movement velocity caused by concentric muscle contraction may attain somewhat different value than that following from the current contraction velocity of the muscle belly. This is because tendons which transport the muscles velocity to the bone lever may also get lengthened or shortened which in conclusion generates smaller or higher velocity of muscle attachments approach than the contraction velocity of muscle belly.

In such actions, usually realised in the form of stretch-shortening or cyclic movement with high intensity, we may expect that the summing of the tendon shortening velocity and the belly shortening velocity will be clearly visible and as a result muscle-tendon shortening (observed between the muscle attachment points) in the concentric phase may be significantly higher then that of the muscle belly [3]. In such a situation the joint movement velocity will attain higher value than that resulting from the shortening velocity of the contractile part of the muscle alone.

The dependence of the maximal angular velocity on frequency was presented in Fig. 5. The above dependence has a linear and decreasing character. The highest velocities (amounting to 19 rad·s$^{-1}$) were registered in movements performed with the lowest frequencies and the highest amplitudes. For the maximal movement frequencies (approximately 7 Hz) the velocity fell to about 4 rad·s$^{-1}$. The solid line in Fig. 5 represents the relationship between the maximal angular velocity and the frequency for harmonic oscillations with amplitude described by the formula (2):

$$\omega_m(f_m) = 2\pi f_m \cdot \alpha_m(f_m) = 2\pi \cdot (3{,}16 - 0{,}347 \cdot f_m) \qquad (3)$$

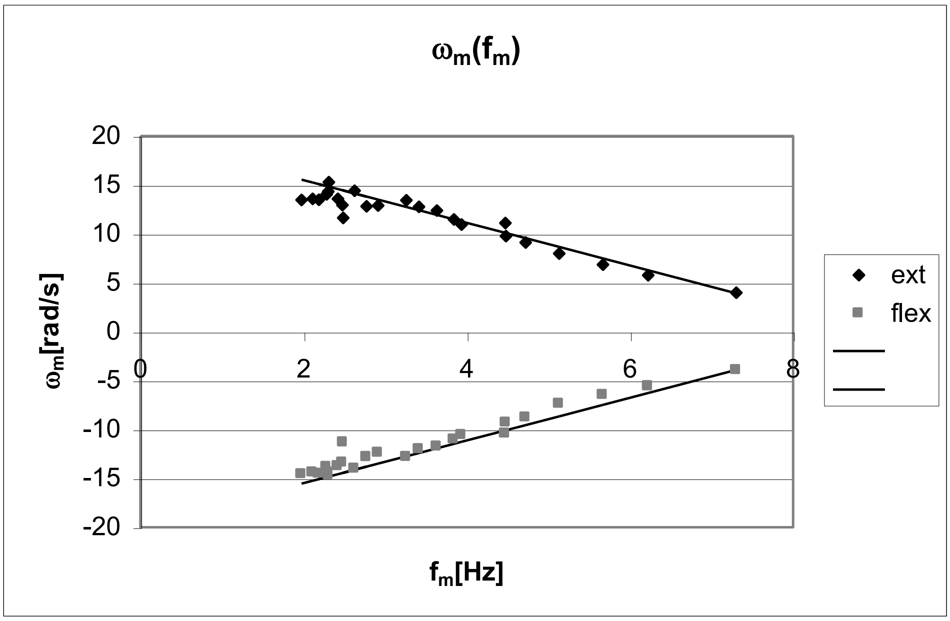

**Fig. 5**
Relationship of the maximal angular velocity $\omega_m$ (during extension: ext and flexion: flex) and frequency for the cyclic forearm movements. Averaged characteristic for 17 subjects

The similarity of the dependence (3) and empirical characteristics $\omega_m(f_m)$ proves the significant resemblance of the examined forearm movements and harmonic oscillations. Similar observations are shown in Fig. 6 by means of the relationship between the maximal value of angular acceleration and the movement frequency. The solid line in the diagram shows the dependence $\varepsilon_m(f_m)$ for the analogous harmonic oscillations described by the following dependence:

$$\varepsilon_m(f_m) = 4\pi^2 \cdot f_m^{\ 2} \cdot \alpha_m(f_m) = 4\pi^2 \cdot f_m \cdot (3.16 - 0.347 \cdot f_m) \qquad (4)$$

Worth mentioning is the fact that the significant similarity with harmonic oscillations can be also noticed in produced accelerations $\varepsilon_m$. The main exception is for the low frequency and high amplitude movements but mainly in regard to accelerations caused by extending moment of force, which is related to nonlinearity of ε (α) dependence shown in Fig. 2. Such an effect can be observed in the stiffness increase during the elbow joint flexion for joint angles smaller than 1.2 rad. On the other hand, this phenomenon may have a purely mechanical background. This is because the contact of external arm and forearm surfaces located near the joint may occur for the small values of joint angle during the elbow flexion. The smaller is the angle the bigger is the area of such a contact. Also the extent of tissue deformation in this area is bigger. Such deformations may cause non-linear increase of the joint stiffness.

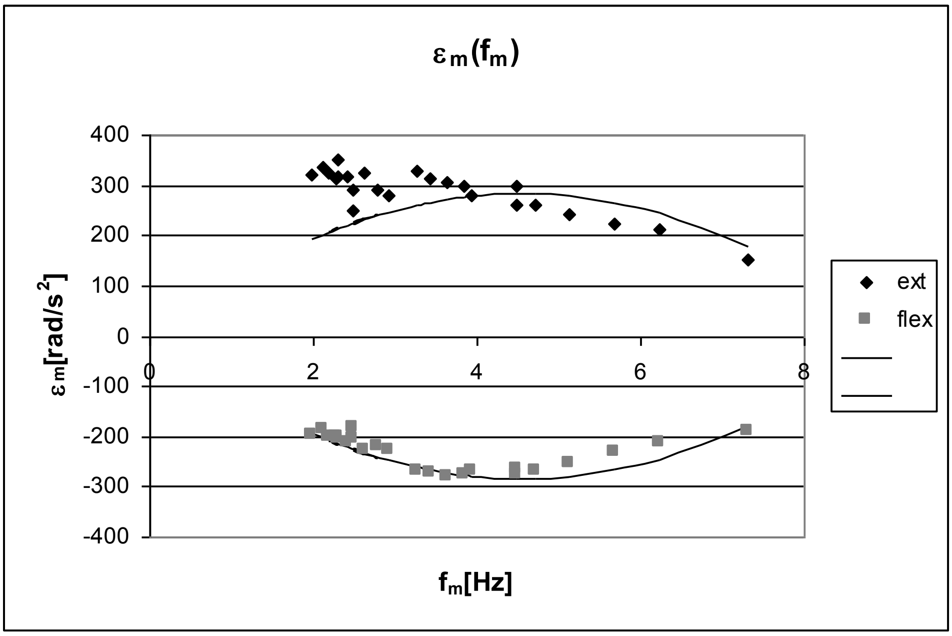

**Fig. 6**
Dependence of extension (ext) and flexion (flex) angular acceleration amplitude on frequency ($f_m$) in forearm cyclic movements

## Conclusions

Basic quantities characterising cyclic movements in joints (as in all phenomena repeatable in time) are: amplitude and movement frequency. Existence of explicit relation between the amplitude and frequency was found by considering the cyclic movements realised in the elbow joint. This relationship has a character of inverse proportionality that can be described by a hyperbole. Such relation was observed in each examined subject and consequently on average for the whole studied group. In the light of the abovementioned fact, it should be accepted that this dependence is typical and presents a significant and specific characteristics of the muscle system responsible for the realisation of the mentioned movements. Moreover, it is coherent with the basic skeletal muscle characteristic described with Hill's curve, which shows that maximal velocity of muscles shortening (and also the power produced by them) is restricted. Therefore, in order to increase movement frequency (while velocity cannot be increased) the amplitude must be decreased.

Taking into consideration the above facts a hypothesis arises that similar type of amplitude-frequency dependence will occur in other joints as well and also in complex movements involving more joints.

The considerable similarity to harmonic oscillations arises after the analysis of dependencies of quantities describing the examined movements. Firstly, the angular acceleration $\varepsilon$ observed in the movement is in anti-phase to the limb angular position described by the ($\alpha$- $\alpha_0$) coordinate. Secondly, the relationship of the angular acceleration value and joint angle has a linear character (for small amplitude movements) like in the case of harmonic oscillations.

Relations of registered amplitudes: angular displacement $\alpha_m$; angular velocity $\varepsilon_m$; angular acceleration $\varepsilon_m$ and instantaneous power $P_m$ with the frequency are faithfully described by relations relevant to harmonic oscillations, hence by simple formulas. Linearity of $\varepsilon = f(\alpha)$ characteristic deteriorates along with the movement amplitude increase although to such an extent only that the use of this simple description is not definitely excluded..

The above observations allow to state that the useful component of the moment of force actuating the joint (responsible for the angular acceleration) evaluated by $M_u=I\cdot\varepsilon$ is (for the small amplitudes of movements $\alpha_m<0.5$ rad especially) proportional to the ($\alpha$- $\alpha_0$) angle representing the deviation of limb from the central (neutral) position. The sense of this moment is opposite to the limb angle deflection, hence it is characterised by the moment of force produced by the joint equivalent stiffness K: $M_u=-K\cdot(\alpha-\alpha_0)$. The movement frequency $f_m$ evoked by such a moment of force depends on the stiffness K and limb inertia I:

$$f_m = \frac{1}{2\pi}\sqrt{\frac{K}{I}}$$

Therefore, the frequency change may be realised by changing the equivalent joint stiffness K, which may be brought about by proper muscle activation. This may require simultaneous antagonistic muscles activity (coactivation), especially in the case of movements with relatively high frequencies. Such pattern of muscular activity might seem inexpedient, however it could allow a rational explanation of the so-called antagonistic muscles co-contraction observed in some motor acts.

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