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FORCE – ANGLE AND FORCE – TIME CHARACTERISTICS OF HUMAN UPPER EXTREMITY MUSCLES

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Abstract. The object of this dissertation was to identify force – angle and force – time characteristics. These relationships were analysed for entire upper extremity and its large joints, which let determine connections between analysed characteristics created for entire biokinematic chain and its individual elements. The two experiments were involved in this research. In the first experiment the force characteristics of the shoulder, elbow and wrist during flexion and extension motion in a sagittale plane were tested. The measurements were made under isokinetic conditions at angular velocity ranging from 60 to 300 °/s. The values of force - time characteristic for extension movement of the entire upper extremity were achieved as the result of measurements made during the second experiment. The test equipment was the 3.08 m long physical pendulum having one degree of rotary freedom in relation to stationary, rigid base. The adjustable load was the moment of interia of pendulum changed in the range of 113 to 494 kgm^2.The research have shown that along with increase of load, the force generated by the groups of tested muscles and entire upper extremity increases. Along with increase of force, the angle and time required to get given force increases as well.

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Key words: Upper limb – Force - Angle - Isokinetics

Introduction

The muscles in human movement system are the biological „machines" which convert chemical energy being the final product of reaction between food and oxygen into a force and mechanical work. This muscles have the ability to change their length and generate force, that when transferred by bone levers may move body segments in relation to each other and then these segments may influence the environment generating reactive force [24].

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The strength and speed are considered to be one of basic features of and determine abilities to do a specific motion task. The following parameters are used for evaluating the force-velocity characteristic of human movement system: the angle, angular velocity and peak torque determined for given groups of muscles [1,2,8,21], maximum power [2], resultant muscular force in relation to an outside object, linear velocity, usable power [14], values of force and velocity measured at the maximum value of power [16], total work and total power [1].

The relationship between force generated by a muscle and velocity of shortening is a characteristic feature of the muscle and this problem has been the subject of research and analysis for many years. For the first time the F-v curve was described by A.V. Hill in 1938 [9] and is known as Hill characteristic equation according to which along with increase of load, the shortening velocity of isolated muscle decreases and assumes the shape of hyperbola. Subsequent research of multijoints biomechanical system have shown that the F-v curve may have the shape of straight line having a negative slope [3,7,12,13,14]. Also Taylor *et al.* [22] using the isokinetic dynamometer have shown the linear F-v curve for knee extensors for tested people practising endurance sports while the hyperbolic relation for those practising strength sports.

The relationship between force and motion velocity, and angle and time are not widely presented in literature. Especially the force as a function of angle is analysed mainly under static measurements [2,4,11]. The angular positions at which the maximum force was generated were determined with this relationship for each of joints. Dynamic analysis of force as a function of angle is mostly limited to single joints [10,19,20,22] or if it refers to the entire upper extremity the problem is limited to determining maximum angle which was achieved by biokinematic chain during motion [14,15,23]. Relations between force and time are mostly analysed under static conditions.

The object of this dissertation was to identify force – angle and force – time characteristics. These relationships were analysed for entire upper extremity and its large joints, which let determine connections between analysed characteristics created for entire biokinematic chain and its individual elements.

Materials and Methods

The group of 30 adult healthy men aged in 23±3 years with body mass 80±10 kg and height 1.80±0.14 m has taken part in this research. The two experiments were involved in this research.

Experiment I - „Biodex”: The essence of the first experiment was the measurement of force, in domain of time, generated by group of muscles controlling tested joint at target value (constant during given test) of angular velocity. The test equipment was BIODEX System 3, shown in the Fig. 1, consisting of:

- control panel connected with a computer
- test stand (dynamometer, armchair, attachments)

The control panel co-operates with WINDOWS 98 software. The dynamometer is fixed to the base that enables it to be set in each plane. Similarly, the armchair has adjustment that adapts it to test and given patient needs. Each of attachments which is fixed directly to dynamometer is used for testing given joint or type of movement.

Fig. 1
Biodex System 3

Each participant of the experiment was subjected to the same tests. The shoulder, elbow and wrist were tested during flexion and extension in a sagittale plane. It was used an isokinetic operating mode of the equipment which let record time functions of torque generated by tested group of muscles at fixed angular velocity.

For the purposes of this experiment the following values of angular velocity were established for each joint:

- shoulder, elbow: 60, 120, 180, 240, 300 °/s
- wrist: 90, 120, 180, 240, 300 °/s (at angular velocity equal to 60 °/s the load of tested joint was too high)

Before each test the armchair and dynamometer and suitable attachment were positioned according to guidelines given in an instruction this way so that a tip of dynamometer was an extension of axis of rotation in joint under test. The predominant limb was tested. Each time the range of movement was determined. The initial position for the shoulder was retroflexion up to 45º, i.e. -45º (the assumed position of the limb along the axis of trunk was 0º), the elbow was extended up to the maximum, and the wrist was bent up to 70º.

In case of shoulder and wrist a handle of attachment was overhand gripped. During the test of elbow the forearm in relation to arm was in „zero" position while the attachment was gripped, and angle of elbow was about 60º.

The trunk of tested person was stabilised with belts intersecting on the chest and fixed to the armchair. Additionally, the arm during the test of elbow and the forearm during the test of wrist were fixed to a special support so that movement of neighbouring joint was eliminated.

The tests was preceded by verbal guidelines applying to way of performing the task and three submaximum and three maximum forces applied to the lever [19]. Each tested person did three tests separated with two-minute breaks. It was obligatory to generate in each movement the maximum muscular force within as short time period as possible at each set value of velocity.

Experiment II - „Pendulum": The time functions of resultant force generated by the entire upper extremity extensors in relation to an outside object were achieved as the result of measurements done during this experiment. The test equipment was the 3.08 m long physical pendulum, shown in the Fig. 2, considered as a rigid mass having one degree of rotary freedom in relation to stationary base. The adjustable load was the moment of interia of pendulum changed in the range of 113 to 494 kgm^2, which affected motion velocity.

The force acting on the end of pendulum was registered with a tensometric dynamometer having measuring range from 0 to 1000 N in which relationship between measured value and voltage signal is linear. The analogue signals from force gauges were processed by 12-bit A/D converter connected to a computer and then sampled and digitised [15].

Each participant of the experiment sat down in the armchair placed in relation to pendulum this way so that before test the participant's arm was situated along axis of trunk, an angle between forearm and arm was 90° in elbow and forearm was in „zero" position in relation to the arm. The trunk of tested person was stabilised in relation to the backrest with belts in order to eliminate movements in joints of shoulder girdle. The construction of armchair backrest prevented upper limb from making sweeping movements.

The participant's task was to push the pendulum with his upper extremity in sagittale plane with maximum force and within as short time period as in order to give it as high velocity as possible irrespective of load. Three tests separated with 2-min breaks have been carried out at each of three known loads. The tests were preceded by verbal guidelines and two test pushes after each change of load.

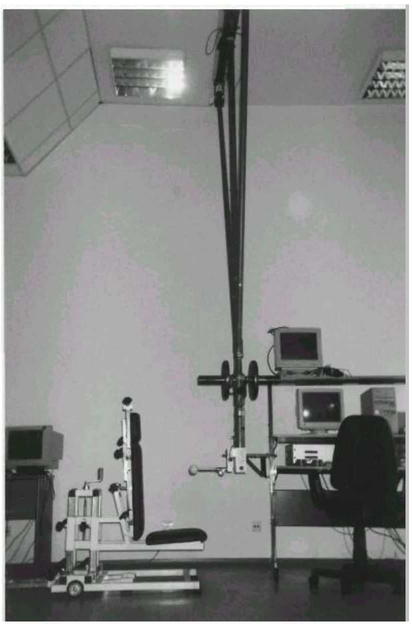

Fig. 2
Physical pendulum

The following muscle groups were only taken into consideration while results of the first experimental research were systemised:

- shoulder flexors (SF)
- elbow extensors(EE)
- wrist flexors and extensors (WF, WE)

It was done like that because only above-mentioned groups of muscles were engaged during the second experiment i.e. in extension motion the entire upper extremity.

For each tested group of muscles the readout of peak torque values (Mm [Nm]) for each of set loads as well value of the angle of the joint corresponding to such torque value (α [°]), and time (t [s]) needed to generate the peak torque was done.

The maximum force values for entire upper extremity (FP [N]) achieved by each participant of tests at each set load (moment of interia of pendulum) were measured during the second experiment. The readout of values of deflection angle of pendulum (αP [°]), and time (tP [s]) required to generate the maximum force was also done during this experiment.

The values of force, velocity, time and angle for each of given joint and for entire upper extremity were averaged for each load (Table 1 and Table 2). Standard deviation for each above-mentioned average value was calculated. The percentage difference between maximum and minimum values of angle and time for each analysed movement was also calculated (Fig. 3).

Results and Discussion

The force-velocity characteristics determined for entire upper extremity and its large joints shows that the higher load is the bigger force generated by system is [1,6,10,19,22]. The moment of inertia of pendulum was the load for entire upper extremity while for individual joints the load was an angular velocity which showed inversely proportional relationship to obtained values of force (Table 1 and Table 2).

Table 1
Mean values (±SD) of the force (FP), the angle (αP) and the time (tP) for the entire upper extremity in relation to the given load – the moment of interia of pendulum (a=113, b=283, c=494 kgm^2)

	a	b	c
FP [N]	224.68 (36.17)*	271.37 (47.00)*	303.39 (53.02)
αP [°]	1.42 (1.12)	1.90 (1.14)*	1.88 (1.32)
tP [s]	0.54 (0.12)*	0.62 (0.09)*	0.68 (0.10)

*The essential statistical values of average differences calculated with T-Student test for p<0.5 between consecutive values

Table 2
Mean values (±SD) of the peak torque (Mm), the angle (α) and the time (t) for shoulder flexors (SF), elbow extensors (EE), wrist flexors and extensors (WF, WE) in relation to the given load – the motion velocity (ω_{1-5} = 60 – 300°/s)

	Angular velocity				
Muscle group	60 (90**)°/s	120°/s	180°/s	240°/s	300°/s
SF					
Mm [Nm]	86.86.(10.4)*	78.30 (9.30)*	71.85 (9.24)*	67.60 (9.04)*	63.39 (8.78)
α [°]	33.91(56.34)*	51.33 (52.57)	57.24 (55.59)*	83.44 (0.22)	91.98 (49.18)
t [s]	1.23 (0.90)*	0.78 (0.43)	0.74 (0.77)	0.59 (0.22)	0.54 (0.18)
EE					
Mm [Nm]	75.66 (9.87)*	71.33 (9.22)*	68.58 (9.82)*	65.03 (9.57)*	59.47 (9.71)
α [°]	48.49 (10.79)*	34.42 (23.23)*	26.87 (35.20)	24.51 (46.39)	22.22 (56.25)
t [s]	1.26 (0.23)*	0.78 (0.18) *	0.59 (0.13)*	0.48 (0.11)*	0.41 (0.08)
WF					
Mm [Nm]	18.23 (4.29)*	17.12 (4.08)*	16.23 (3.96)*	15.37 (3.81)*	14.56 (3.75)
α [°]	19.22 (47.86)	18.40 (32.97)	17.90 (34.91)*	8.78 (48.77)	8.42 (57.91)
t [s]	0.61 (0.33)*	0.48 (0.25)*	0.37 (0.13)	0.37 (0.14)*	0.33 (0.10)
WE					
Mm [Nm]	10.85 (2.23)*	10.22 (2.12)*	9.59 (1.99)*	9.09 (1.76)*	8.70 (1.73)
α [°]	14.23 (27.12)	15.92 (33.98)*	5.32 (41.50)	-4.03 (52.61)*	-16.28(59.92)
t [s]	0.65 (0.28)*	0.45 (0.22)	0.39 (0.18)	0.37 (0.14)	0.37 (0.12)

*The essential statistical values of average differences calculated with T-Student test for p<0.5 between consecutive values
**ω = 90º/s applies to wrist (WF and WE)

The values of force and angle showed roughly proportional relationship. An angle means a deflection of pendulum for measurements applying to entire upper extremity or the angle between neighbouring segments joined together with the joint under test at which the torque reached its maximum value. It means that the higher value of force (torque) is the bigger angle at which this value was achieved is. Such results were obtained for entire upper extremity, elbow extensors and wrist flexors and extensors. Average increase of angle for muscles complex mentioned above is 48% (calculated between maximum and minimum value of angle for analysed movement). The smallest increase is noticed for the entire upper extremity extensors, and for remaining muscular groups the values are even and amount approximately to 50% (Fig. 3). The increase of angle along with the force is not constant. At high loads (high values of force) the stabilisation and slow decrease of its value was noticed (Tables 1 and 2). Similar results were obtained by Marginson and Eston [17] for elbow extensors who initially also noticed increase of value of the angle in the joint along with increase of generated forced and then its stabilisation and slow decrease.

Only shoulder flexors showed that the relationship between value of peak torque and an angle at which this value is achieved is inversely proportional. Along with increase of torque, the average decrease of angle (calculated between maximum and minimum values) was 63% (Fig. 3).

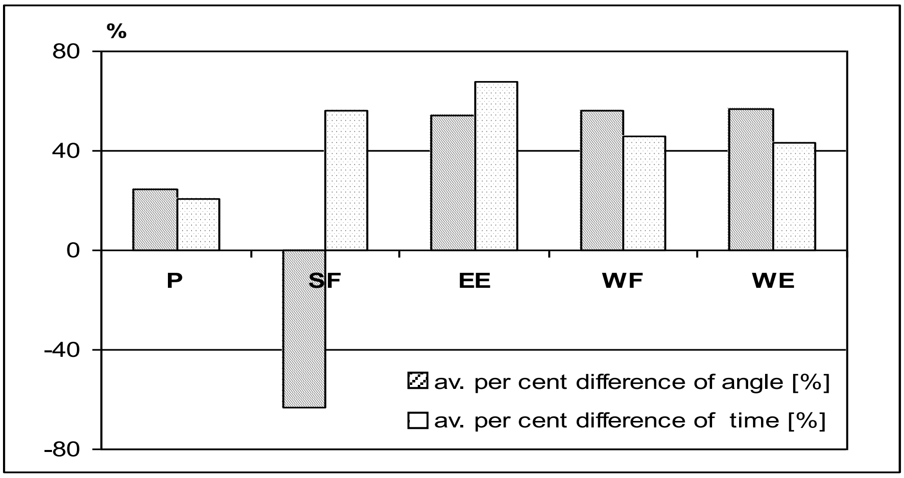

Fig. 3
Mean percentage difference between maximum and minimum values of angle and time for each analysed movement (entire upper extremity extensors (P), shoulder flexors (SF), elbow extensors (EE) and wrist flexors and extensors (WF, WE)

It results from the peculiarity of flexion movement in the shoulder. The initial position used during tests for this movement was retroflexion up to 45º, (i.e.-45º). The peak torque in statics (ω=0º/s) is provided at the angle of joint from -45º to–15º (optimum position is -30º, the others are influenced with 5% error) and beyond these values the torque decreases in the linear way along with change of angle [4,5]. In static measurements the maximum obtainable torque is generated very nearly to initial position of analysed movement and the higher velocity of the movement is (lower load) the lower torques are obtained, and also, due to direction of the movement, angular values corresponding to them are higher. Similar results were obtained by Mayer *et al*. [18] who, among other things, tested flexion movement in the shoulder under conditions of concentric, isometric and eccentric work. They showed that values of angle in the shoulder, for which peak torque was obtained, are higher for concentric measurements than for isometric ones. The concentric measurements were done by the authors of quoted research under isometric conditions using the same values of angular velocity applied in this dissertation as the load. However, they do not assign angular values to given loads but give only entire range of theirs (91-31º), which is comparable to results obtained in this dissertation (92-33º).

On the other hand results obtained by Bober and Hay are considerably different [4]. They determined angular values of joints corresponding to the peak torque under both static and dynamic conditions. Dynamic measurements were done with isokinetic dynamometer and applied load equal to 1 rad/s (approximately 60º/s). For this load the peak torque of flexion movement in the shoulder was obtained by them at the angle form -42º to -17º, and for extending of the elbow at the angle from 62 to 101º. The differences which were observed might be caused by different measuring equipment which was used for tests and different conditions under which measurements were done (during test on the elbow the forearm in relation to the shoulder was in supination, while during tests carried by myself the "zero" position was applied).

It can be observed, while force-time relationship is characterised, that longer time is required to generate higher values of force (Table 1 and 2). Such results were obtained for all tested muscular groups and entire upper extremity. Average increase of time period between minimum and maximum values of force was 46.7%. The smallest increase, i.e. 20.6%, was noticed for entire upper extremity, and the highest, i.e. 67.5%, was noticed for elbow extensors. (Fig. 3). Time needed to generate the maximum force extends along with the increase of load but it is not an even increase.

Precise knowledge of force characteristics of the upper extremity and its large joints may be used in physiotherapy and physiology of sport in order to evaluate state of health and physical condition of a human organism, and influence of different forms of training on level of force parameters of muscles. The characteristics of multijoint biomechanical systems can also be used in ergonomics for designing and selecting tools for work or sports equipment suitable for given person.

Conclusions

Support that view that along with increase of load of tested groups of muscles and entire upper extremity the value of generated force rises.

The increase of force is accompanied by enlargement of time needed to generate this force and also increase of angle of the joint and deflection angle of pendulum at which given force was generated (only the group of shoulder flexors is characterised by decrease of value of the angle along with increase of force.

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