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Biomimetics of throwing at basketball

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Abstract. The paper deals with the inverse dynamics of a kinematic chain of the human upper limb when throwing the ball at the basketball, aiming to calculate the torques required to put in action the technical system. The kinematic chain respects the anthropometric features regarding the length and mass of body segments. The kinematic parameters of the motion were determined by measuring the angles of body segments during a succession of filmed pictures of a throw, and the interpolation of these values and determination of the interpolating polynomials for each independent geometric coordinate. Using the Lagrange equations, there were determined the variations with time of the required torques to put in motion the kinematic chain of the type of triple physical pendulum. The obtained values show, naturally, the fact that the biggest torque is that for mimetic articulation of the shoulder, being comparable with those obtained by the brachial biceps muscle of the analyzed human subject. Using the obtained data, there can be conceived the mimetic technical system, of robotic type, with application in sports, so that to perform the motion of ball throwing, from steady position, at the basket.

1. Introduction

Robots are used in sport both directly, by their participation at some sport contests, and indirectly, by developing some applications used in training or for recovery after an intense effort. Thus, as examples of direct participation at sportive activities, with begin from year 1997, there is organized the annual football competition exclusively destined to robots, entitled RoboCup [1], and from year 2004 there is organized an ample competition for more sports categories, for robots, entitled RobotChallenge [2]. The existence of these sportive competitions, some destined only for robots and others for robots and peoples [3], allowed to develop some applications used in sportive training, such as baseball, golf, tennis, target practice and so on, or destined to individuals with locomotive disabilities, for practicing sports. In the last case, there are known the prosthesis of superior or inferior limbs, used for running, bicycling, golf, ski or swimming [4], the prosthesis being adapted especially for a certain purpose [5].

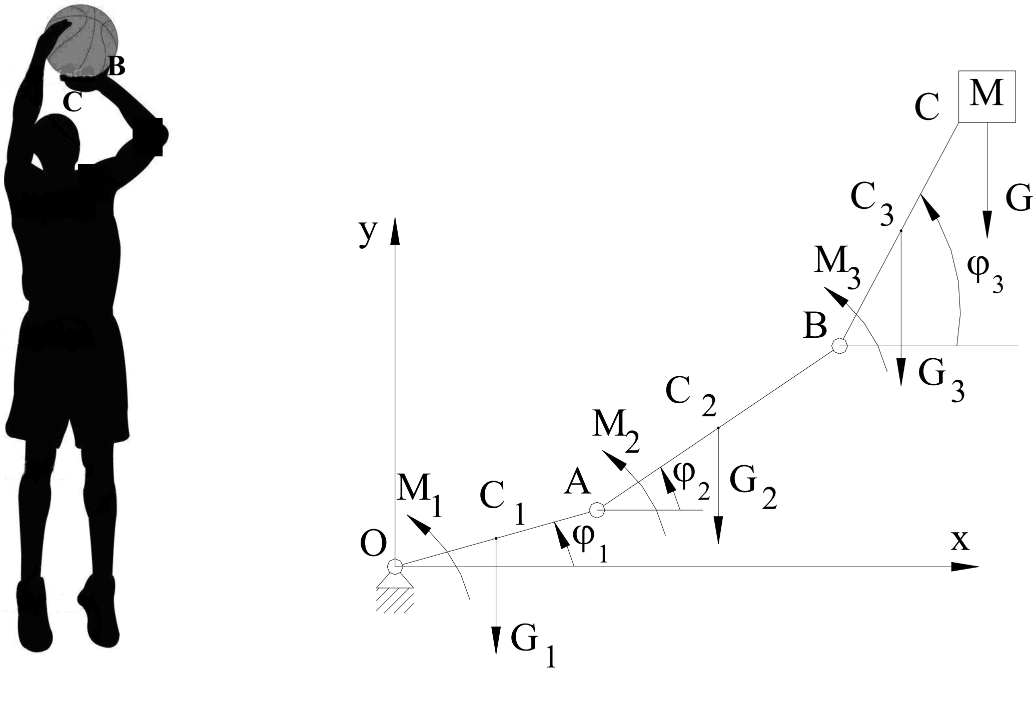
In basketball game, the first competition for robots was organized in 2012, in Long Beach, California, USA [6]. For throwing the ball at the basket, often there is used the principle of the ball gun, as technical solution for throwing mechanism. The use of some mechanisms imitating the kinematic chain of human superior limb, supposes to introduce many degrees of liberty, with consequences on the control of the motion. When throwing the ball, from the steady position, with one hand, only one kinematic chain of the human superior limb is active, the other one playing the role of support of the ball [7]. In the active kinematic chain, the main motions of the elements are of flexion and extension, but the arm has, supplementary, a secondary motion of abduction, for ball positioning.

If there are taken into account the inferior limbs and the body, then the number of independent kinematic parameters increases from 4, for the active kinematic chain of the human superior limb, up to 8, by adding the rotation angles of the foot, thigh, shank and body. Such approach, from kinematic point of view, using experimental methods, is presented in previously cited work [7]. Considering only the kinematic chain of the active superior limb, in flexion motion, when throwing the ball to the basket, may be associated to a triple pendulum, with 3 degrees of mobility. An approach regarding the oscillations of triple pendulum belongs to classical mechanics, but the problem of using some actuators to drive a propelling system, formed by rigid bars, with imitating the human superior limb in flexion motion during ball throwing, implies limitations and specific calculus. For a triple pendulum, the problems to be solved refer to various random motions that elements may have [8, 9], prediction of these motions [10], feedback control of the desired motion and Mielnikov method to predict the random motion [11], the shape of potential surfaces from the dynamic equilibrium equations [12] or particular situations such as cushioned motions of the pendulum [13].

The present paper aims to determine the motor torques necessary to drive the motion in sagittal plane of a kinematic chain of triple pendulum kind, used for throwing the ball at basket.

2. Equations of dynamic model

The motion equations were written for the kinematic chain of the active upper limb, when throwing the ball at the basket, as can be observed in figure 1. This kinematic chain, formed by arm, forearm and hand can be compared with a triple physical pedulum for which the independent motion parameters have known limits, given by the flexion angles during the throw.



a. b.

Figure 1. Direct throw at the basket (a) and the active kinematic chain (b)

The independent geometric parameters were denoted with φ_1,φ_2 and φ_3, representing the flexion angles of the arm, forearm and respectively the hand.

The Lagrange equations of second kind for the 3 degrees of mobility are:

$$\frac{d}{dt}\left(\frac{\partial E_c}{\partial \dot{q}_k}\right)-\frac{\partial E_c}{\partial q_k}=Q_k\,, \tag{1}$$

where: k=1,2,3; $q_k = \varphi_k$ (see figure 1); E_c= kinetic energy,

$$Q_k = \overline{Q_k} + \frac{\partial U}{\partial q_k}, \tag{2}$$

where: $U = -E_p$; Ep=potential energy; $\overline{Q_1} = M_1 - M_2$; $\overline{Q_2} = M_2 - M_3$; $\overline{Q_3} = M_3$; M_k=motor torques from rotation joints O, A and B.

The kinetic energy may be written as:

$$E_c = E_{c1} + E_{c2} + E_{c3} + E_{cM}, \tag{3}$$

where:

$$E_{c1} = \frac{m_1 \cdot l_1^2 \cdot \omega_1^2}{6}, \tag{4}$$

$$E_{c2} = \omega_1^2 \cdot \left\{ \frac{m_2 \cdot l_1^2}{2} + \frac{m_2 \cdot l_2^2}{6} + \frac{m_2 \cdot l_1 \cdot l_2 \cdot \cos(\varphi_1 - \varphi_2)}{2} \right\} + \omega_2^2 \cdot \frac{m_2 \cdot l_2^2}{6}, \tag{5}$$

$$\begin{aligned} E_{c3} = {} & \omega_1^2 \cdot \left\{ \frac{m_3 \cdot l_1^2}{2} + \frac{m_3 \cdot l_2^2}{2} + \frac{m_3 \cdot l_3^2}{6} + m_3 \cdot l_1 \cdot l_2 \cdot \cos(\varphi_1 - \varphi_2) \right\} + \omega_1^2 \cdot \{ \frac{m_3 \cdot l_1 \cdot l_3 \cdot \cos(\varphi_1 - \varphi_3)}{2} + \\ & + \frac{m_3 \cdot l_2 \cdot l_3 \cdot \cos(\varphi_2 - \varphi_3)}{2} \} + \omega_2^2 \cdot \left\{ \frac{m_3 \cdot l_2^2}{2} + \frac{m_3 \cdot l_3^2}{6} + \frac{m_3 \cdot l_2 \cdot l_3 \cdot \cos(\varphi_2 - \varphi_3)}{2} \right\} + \omega_3^2 \cdot \frac{m_3 \cdot l_3^2}{6} \end{aligned}, \tag{6}$$

$$\begin{aligned} E_{cM} = {} & \frac{M \cdot \omega_1^2}{2} \cdot \left\{ l_1^2 + l_2^2 + l_3^2 + 2 \cdot l_1 \cdot l_2 \cdot \cos(\varphi_1 - \varphi_2) \right\} + \frac{M \cdot \omega_1^2}{2} \cdot \{ 2 \cdot l_1 \cdot l_3 \cdot \cos(\varphi_1 - \varphi_3) + \\ & + 2 \cdot l_2 \cdot l_3 \cdot \cos(\varphi_2 - \varphi_3) \} + \frac{M \cdot \omega_2^2}{2} \cdot \left\{ l_2^2 + l_3^2 + 2 \cdot l_2 \cdot l_3 \cdot \cos(\varphi_2 - \varphi_3) \right\} + \frac{M \cdot \omega_3^2 \cdot l_3^2}{2} \end{aligned} \tag{7}$$

The potential energy may be written as:

$$E_p = E_{p1} + E_{p2} + E_{p3} + E_{pM}, \tag{8}$$

that is:

$$\begin{aligned} E_p = {} & \left[\frac{m_1 \cdot l_1}{2} + m_2 \cdot l_1 + m_3 \cdot l_1 + M \cdot l_1 \right] \cdot g \cdot \sin(\varphi_1) + \left[\frac{m_2 \cdot l_2}{2} + m_3 \cdot l_2 + M \cdot l_2 \right] \cdot g \cdot \sin(\varphi_2) + \\ & + \left[\frac{m_3 \cdot l_3}{2} + M \cdot l_3 \right] \cdot g \cdot \sin(\varphi_3) \end{aligned}. \tag{9}$$

The Lagrange equation of second kind for the first degree of mobility is:

$$\varepsilon_1 \cdot A_1 + \omega_1^2 \cdot B_1 + \omega_1 \cdot \omega_2 \cdot C_1 + \omega_1 \cdot \omega_3 \cdot D_1 + E_1 = M_1 - M_2, \tag{10}$$

where:

$$\begin{aligned} A_1 = {} & \frac{m_1 \cdot l_1^2}{3} + m_2 \cdot \left\{ l_1^2 + \frac{l_2^2}{3} + l_1 \cdot l_2 \cdot \cos(\varphi_1 - \varphi_2) \right\} + m_3 \cdot \left\{ l_1^2 + l_2^2 + \frac{l_3^2}{3} + 2 \cdot l_1 \cdot l_2 \cdot \cos(\varphi_1 - \varphi_2) \right\} + \\ & + m_3 \cdot \left\{ l_1 \cdot l_3 \cdot \cos(\varphi_1 - \varphi_3) + l_2 \cdot l_3 \cdot \cos(\varphi_2 - \varphi_3) \right\} + M \cdot \left\{ l_1^2 + l_2^2 + l_3^2 + 2 \cdot l_1 \cdot l_2 \cdot \cos(\varphi_1 - \varphi_2) \right\} + \\ & + M \cdot \left\{ 2 \cdot l_1 \cdot l_3 \cdot \cos(\varphi_1 - \varphi_3) + 2 \cdot l_2 \cdot l_3 \cdot \cos(\varphi_2 - \varphi_3) \right\} \end{aligned}, \tag{11}$$

$$\begin{aligned} B_1 = {} & -\frac{m_2 \cdot l_1 \cdot l_2 \cdot \sin(\varphi_1 - \varphi_2)}{2} + m_3 \cdot l_1 \cdot \left\{ -l_2 \cdot \sin(\varphi_1 - \varphi_2) - \frac{l_3}{2} \cdot \sin(\varphi_1 - \varphi_3) \right\} + \\ & + M \cdot l_1 \cdot \left\{ -l_2 \cdot \sin(\varphi_1 - \varphi_2) - l_3 \cdot \sin(\varphi_1 - \varphi_3) \right\} \end{aligned}, \tag{12}$$

$$C_1 = m_2 \cdot l_1 \cdot l_2 \cdot \sin(\varphi_1 - \varphi_2) + m_3 \cdot l_2 \cdot \left\{2 \cdot l_1 \cdot \sin\left(\varphi_1 - \varphi_2\right) - l_3 \cdot \sin\left(\varphi_2 - \varphi_3\right)\right\} + \\ +2 \cdot M \cdot l_2 \cdot \left\{l_1 \cdot \sin\left(\varphi_1 - \varphi_2\right) - l_3 \cdot \sin\left(\varphi_2 - \varphi_3\right)\right\}, \tag{13}$$

$$D_1 = m_3 \cdot l_3 \cdot \left\{l_1 \cdot \sin\left(\varphi_1 - \varphi_3\right) + l_2 \cdot \sin\left(\varphi_2 - \varphi_3\right)\right\} + 2 \cdot M \cdot l_3 \cdot \left\{l_1 \cdot \sin\left(\varphi_1 - \varphi_3\right) + l_2 \cdot \sin\left(\varphi_2 - \varphi_3\right)\right\}, \tag{14}$$

$$E_1 = \left[\frac{m_1}{2} + m_2 + m_3 + M\right] \cdot g \cdot l_1 \cdot \cos\left(\varphi_1\right). \tag{15}$$

The Lagrange equation of second kind for the second degree of mobility is:

$$\varepsilon_2 \cdot A_2 + \omega_1^2 \cdot B_2 + \omega_2^{\ 2} \cdot C_2 + \omega_2 \cdot \omega_3 \cdot D_2 + E_2 = M_2 - M_3. \tag{16}$$

where:

$$A_2 = \frac{m_2 \cdot l_2^2}{3} + m_3 \cdot \left\{l_2^2 + \frac{l_3^2}{3} + l_2 \cdot l_3 \cdot \cos\left(\varphi_2 - \varphi_3\right)\right\} + M \cdot \left\{l_2^2 + l_3^2 + 2 \cdot l_2 \cdot l_3 \cdot \cos\left(\varphi_2 - \varphi_3\right)\right\}, \tag{17}$$

$$B_2 = -\frac{m_2 \cdot l_1 \cdot l_2 \cdot \sin(\varphi_1 - \varphi_2)}{2} - m_3 \cdot l_2 \cdot \left\{l_1 \cdot \sin\left(\varphi_1 - \varphi_2\right) - \frac{l_3}{2} \cdot \sin\left(\varphi_2 - \varphi_3\right)\right\} - \\ -M \cdot l_2 \cdot \left\{l_1 \cdot \sin\left(\varphi_1 - \varphi_2\right) - l_3 \cdot \sin\left(\varphi_2 - \varphi_3\right)\right\}, \tag{18}$$

$$C_2 = -\frac{m_3 \cdot l_2 \cdot l_3}{2} \sin\left(\varphi_2 - \varphi_3\right) - M \cdot l_2 \cdot l_3 \cdot \sin\left(\varphi_2 - \varphi_3\right), \tag{19}$$

$$D_2 = m_3 \cdot l_2 \cdot l_3 \cdot \sin\left(\varphi_2 - \varphi_3\right) + 2 \cdot M \cdot l_2 \cdot l_3 \cdot \sin\left(\varphi_2 - \varphi_3\right), \tag{20}$$

$$E_2 = \left[\frac{m_2}{2} + m_3 + M\right] \cdot g \cdot l_2 \cdot \cos\left(\varphi_2\right). \tag{21}$$

The Lagrange equation of second kind for the third degree of mobility is:

$$\varepsilon_3 \cdot A_3 + \omega_1^2 \cdot B_3 + \omega_2^{\ 2} \cdot C_3 + D_3 = M_3, \tag{22}$$

where:

$$A_3 = l_3^2 \cdot \left[\frac{m_3}{3} + M\right], \tag{23}$$

$$B_3 = -\frac{m_3 \cdot l_3}{2} \cdot \left\{l_1 \cdot \sin\left(\varphi_1 - \varphi_3\right) + l_2 \cdot \sin\left(\varphi_2 - \varphi_3\right)\right\} - M \cdot l_3 \cdot \left\{l_1 \cdot \sin\left(\varphi_1 - \varphi_3\right) + l_2 \cdot \sin\left(\varphi_2 - \varphi_3\right)\right\}, \tag{24}$$

$$C_3 = -\frac{m_3 \cdot l_2 \cdot l_3}{2} \sin\left(\varphi_2 - \varphi_3\right) - M \cdot l_2 \cdot l_3 \cdot \sin\left(\varphi_2 - \varphi_3\right), \tag{25}$$

$$D_3 = \left[\frac{m_3}{2} + M\right] \cdot g \cdot l_3 \cdot \cos\left(\varphi_3\right). \tag{26}$$

From equations (10), (16) and (22) are determined the necessary torques for the actuators to obtain the desired motion.

3. Numerical results

For numerical simulation there was considered a sportsman with the height of 2.01 [m] and the mass of 99.5 [kg], that being the medium values emphasized by NBA for the american basketball players. With the anthropometrical coefficients [14], there were calculated the lengths and the masses of body segments arm, forearm and hand, assimilated as elements of the triple pendulum and given in table 1. The lengths and the weights of elements of the triple pendulum were considered being equal with the lengths and the weights of the body segments of the upper limb for the analyzed athlete.

Determining angles of the triple pendulum's elements representing throwing in the direct free kick, was performed using the videorecording, decomposition in sequential images and the angular position measurement of each segment 's body upper limb actively using specialized software, as seen in figure 2.

The vectorial field of flexion angles can be determined experimental, by the videorecording at normal speed or at more speed , so the number of images highlighted in unit time can be greater.

Table 1. Anthropometric size measurements of the upper limb

	Arm	Forearm	Hand
Length of body segment [m]	0.377	0.291	0.217
Weight of segment [kg]	2.786	1.592	0.597

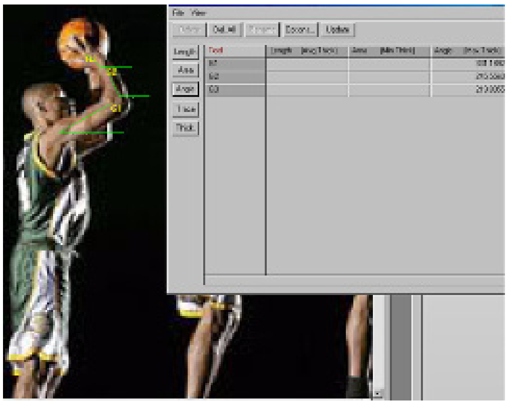


Figure 2. A videorecording image sequence and the angles' measurement

Using previously determined angular values, were determined the interpolation polynomials of fourth degree, so that, by derivation of these polynomials, the angular accelerations and velocities, required in inverse dynamics analysis were calculated. The degree of polynomial interpolation is determined so as to better approximate the points representing the angles of flexion. The graphs of the angles variation for the arm, forearm and hand, during the throwing, are shown in figures 3, 4 and 5.

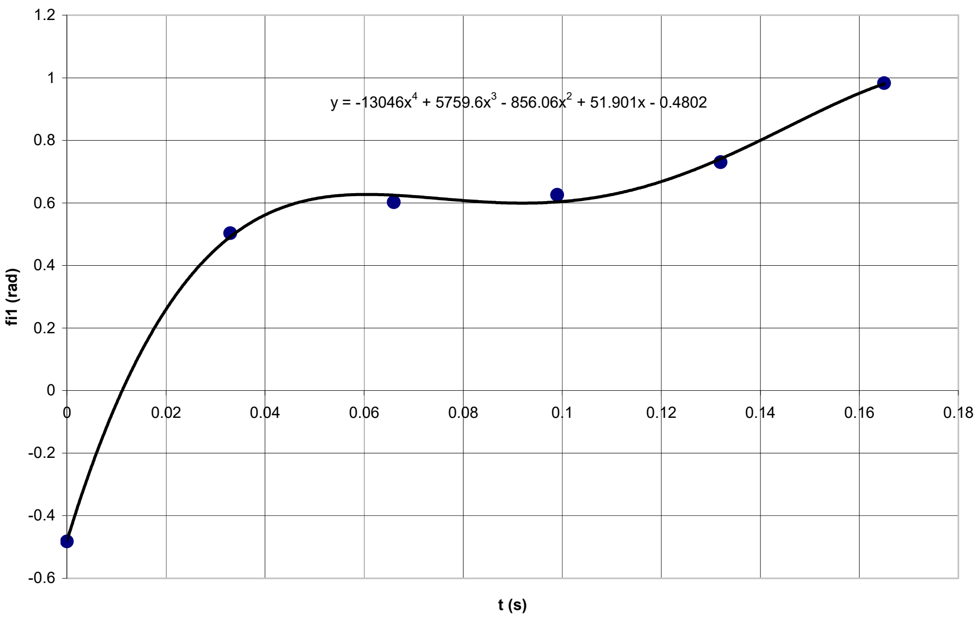


Figure 3. Arm's flexion angle's variation during the throwing

The mass of the ball, required in dynamic equilibrium equations, is between 567 and 650 grams for the men's basketball game and between 510 and 567 grams for the female's basketball game. In the effectuated calculations, the value of 600 grams was chosen, corresponding to the men's basketball game.

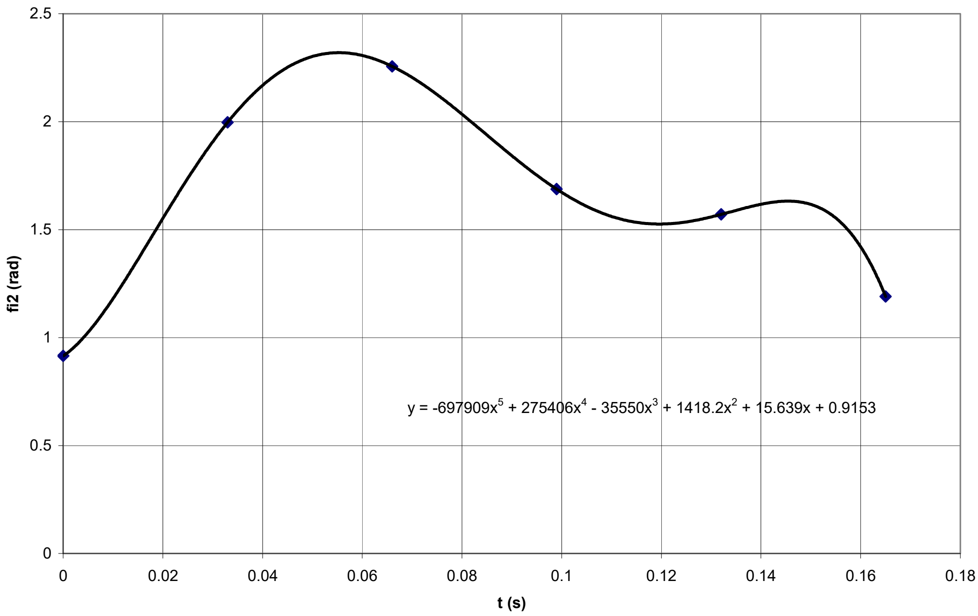


Figure 4. Forearm's flexion angle's variation during the throwing

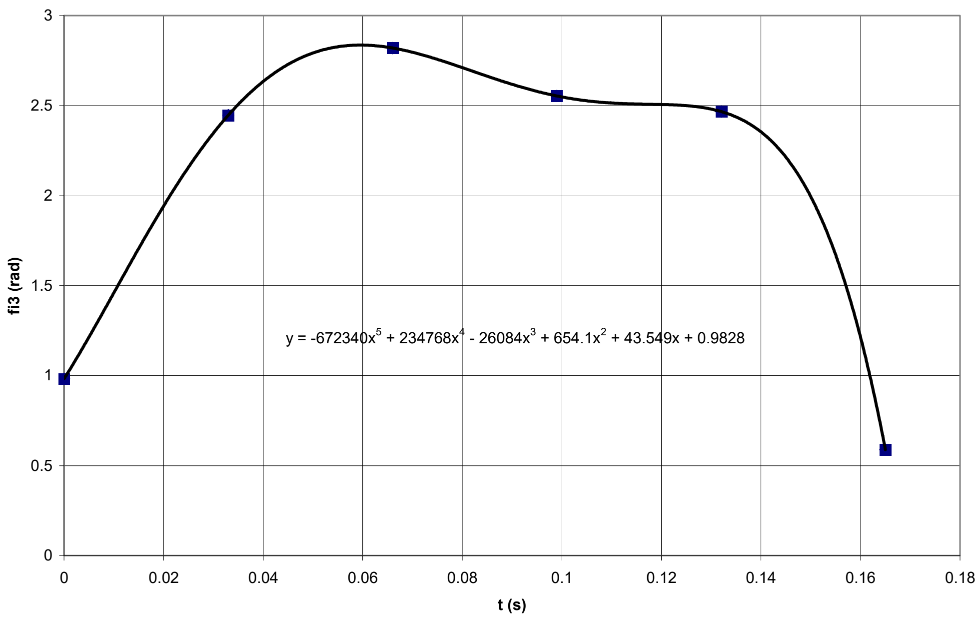


Figure 5. Hand's flexion angle's variation during the throwing

Using equations (10), (16) and (22), there were determined the values of the actuators' necessary moments, during the movement of throwing for the mimetic kinematic chain analyzed. The variation graphs of the torques M_1, M_2 and M_3 are represented in figure 6 and the numerical values corresponding to the times of motion sequences are given in table 2. The highest values for the torques analyzed are for the elements representing the arm and forearm.

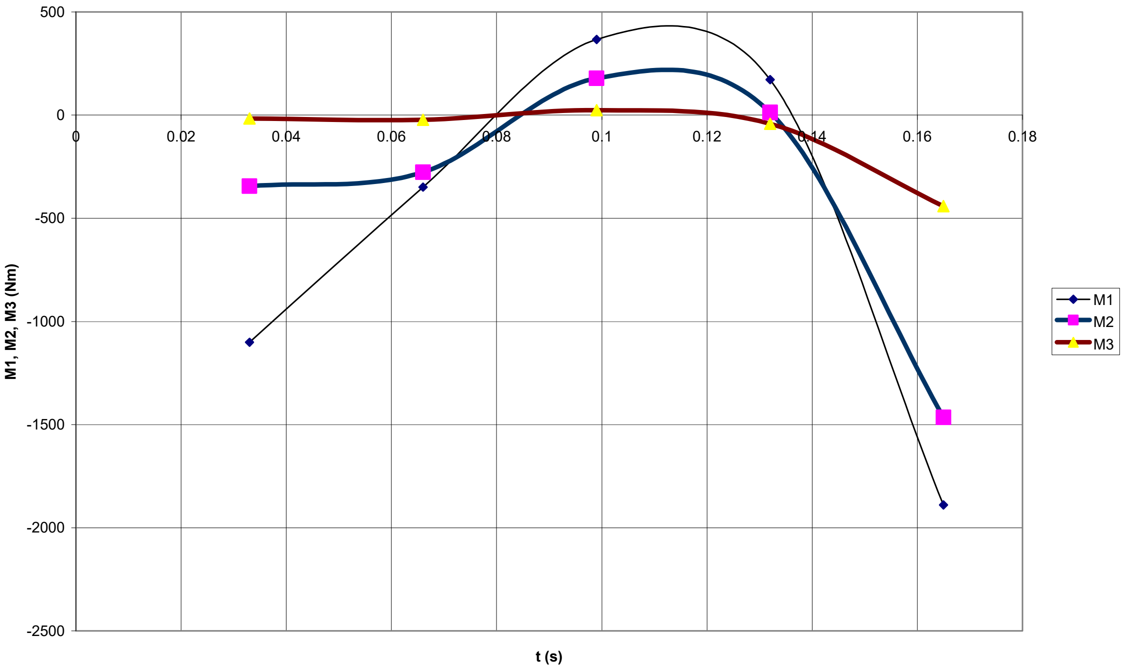


Figure 6. The variation of rotation torques of pendulum elements during the throw

Table 2. The sequential values of rotation torques

t [s]	M_1 [Nm]	M_2 [Nm]	M_3 [Nm]
0.033	-1100.7	-344.375	-16.2316
0.066	-348.579	-276.445	-22.397
0.099	366.2647	178.6089	24.14808
0.132	172.3826	13.2179	-41.5272
0.165	-1889.21	-1464.32	-441.553

The values from table 2 are comparable with the torques of muscle forces, highlighted in literature [14]. Knowing the maximum angular speed of each element, we can thus determine the necessary power of driving for these elements.

4. Discussions and conclusions

The human upper limb was modelled like a triple pendulum and the dynamic model was solved for obtaining the values of torques in articulations of shoulder, elbow and hand.

The obtained values of the torques are comparable with those obtained by the brachial biceps muscle of the analyzed human subject.

The study performed in the paper can be useful to conceive the mimetic technical system, of robotic type, with application in sports, so that to perform the motion of ball throwing, from steady position, at the basket.

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