INVESTIGATION OF THE FORCES IN THE FOREARM-HAND MODEL MUSCLES WITH VARIED ELBOW JOINT ANGLE

Faisal Saleh Abdalla[1,*] , Salah Hamad[2] and Ahmed Shletiet[3]
[1]College of Mechanical Engineering Technology–Benghazi, Dep. of General Science, Benghazi, Libya.
[2]Department of Mathematic, College of Education, Omer El- Mukhtar University, Al Bayda, Libya.
[3]Department of Mathematic, faculty of science, University of Ajdabiya, Ajdabiya, Libya.
[1]faisal@ceb.edu.ly, [2]Salahh92@gmail.com, [3]Ahmed.shletiet@uoa.edu.ly
[*]Corresponding Author: Faisal Saleh Abdalla

ABSTRACT

This paper aims to study muscles behavior and investigate the effect of varied joint angle on the muscles forces. Quadratic objective function of muscle forces was minimized to estimate muscles forces in the forearm-hand segment at four different elbow joint angles during carrying external load applied on hand performed on the sagittal plane. The forearm-hand model was investigated to study the influence of varied elbow angle on the load sharing of the forearm-hand model. Six muscles were selected as prime movers of the model and their forces were estimated using Lagrange multiplier method. At each elbow angle, the forces of the selected muscles were determined, during lifting a load, to be compared to each other with observing the influence of elbow angle. The findings showed that the minimized muscles forces were highly influenced by the change in elbow join angle. It was also found that differences between the loads sharing of the estimated muscles which are related to the change in the elbow angle. Once the elbow angle was 30 degrees, the estimated forces had the highest values among the other forces estimated with the other elbow angles whereas the elbow angle of 120 degrees the muscles had the lowest forces. Consequently, it is concluded that there is a significant relationship between the elbow angle and the muscle forces in the model. Moreover, the external load applied on hand is better being carried at elbow angle of 120 degrees. That indicates that the elbow joint angle of 120 degrees may be better than the other elbow joint angles.

Keywords: *Muscle force, elbow joint angle, optimization, load sharing.*

1. INTRODUCTION

A desired activity of human being can be done by many muscles which can be determined by an optimization technique. Optimization method has been a concern of many researchers to investigate the musculoskeletal system and estimate muscle forces [1-5] which is usually used to statically or dynamically minimize specific objective function using particular design variables. Static optimization method has much lower computational cost than dynamic optimization method, maybe for this reason, many researches use static optimization method [5-12] Hence, optimization technique is required to estimate muscle forces because of musculoskeletal system redundancy [1-4]. Many studies have been done utilizing static optimization criteria where they used muscle forces as design variables spanning different joints [1,10,13-16]. Nevertheless, the values of the muscle forces are influenced by several parameters which the researchers used in their optimization tasks. Several effects may influence muscle forces values estimated by an objective function which analytically solved by Lagrange multiplier method such as power raised to the design variables, external forces applied to the forearm, weight coefficients of design variables and moment arms of muscle forces [17]. However, only few studies examined the effect of the joint angle on muscle forces values during external applied load [10,18] who showed that elbow joint angle had a significant effect on muscle forces. [19] reported that elbow flexor muscles have been affected by varied elbow angle. [20] investigated the arm muscles while holding several objects with varied elbow joint angle to find that the determined forces in the lower arm muscles increase with the increase of elbow joint angle. Also, it has been shown that eccentric action of a muscle outcomes a larger decrease in force [21]. Nevertheless, estimation of muscle forces with varied joint angle have not been investigated using analytical method to show the effect of joint angle on muscle activation and the relationship between the joint angle and muscles activation has not been concerned. Therefore, the purpose of this study is to investigate the forces in the forearm-hand model and find out the effect of the varied elbow joint angle on the muscle forces estimated analytically via Lagrange multiplier method.

2. METHODOLOGY

Quadratic objective function of muscle forces was statically minimized to estimate the forces in the investigated muscles of forearm-hand model and study the effect of change in elbow joint angle on the muscle forces. The muscles assumed to be active during carrying external load applied on hand in the sagittal plane. The muscle forces were estimated using Lagrange multiplier method at different degrees of elbow joint angles under static conditions. The angles at the elbow joint are measured between the vertical upper arm and the free segment of forearm-hand segment. Four different elbow angles were considered as positions to the forearm-hand model to be studied and investigate the muscles which was minimized at each position of the angles which were taken as 30, 60, 90, and 120 degrees. In this study, the model was investigated to study the effect of change in elbow joint angle on the load sharing of the modeled muscles and only six muscles are assumed to be investigated which considered as the prime movers of the forearm-hand segment. The muscles are biceps (bic), brachialis (bra), brachioradialis (brd) and flexor carpi radialis (FCR) muscles which work as flexors and triceps (tri) and anconeus (anc) muscles functioning as extensors (F_1=bic force , F_2=tri force, F_3=bra force, F_4=brd force, F_5=FCR force, F_6=anc force). The muscle forces were taken as design variables of the objective function to analytically investigate the biomechanical model such that the upper arm was in vertical position whereas the forearm-hand segment was in free motion and the external load applied on hand. The objective function of muscle forces was minimized when the external load was applied on the hand. At each position of the elbow angle the forces in the examined muscles were minimized using the Lagrange multiplier method and the effect of the change in elbow angle was considered. The method of Lagrange multiplier was used to estimate the muscle forces at the selected angles of elbow joint when the external load of 15 kg was applied on hand to be carried by hand of a subject weight of 70 kg. The length of forearm-hand segment is approximately 30 cm and the center of mass is assumed to be the geometrical center of the forearm-hand segment.
Moment arm values of muscle forces were taken from Murray et al. (1995) which are listed in table 1 to be used in the model and estimate the muscle forces.

TABLE (1). Biceps moment arm (r_1), triceps moment arm (r_2), brachialis moment arm (r_3), Brachioradialis moment arm (r_4), FCR moment arm (r_5), and anconeus moment arm (r_6).

Angle	r_1	r_2	r_3	r_4	r_5	r_6
30 degrees	2.8	-2.4	1.6	3.0	0.1	-0.6
60 degrees	4.2	-2.2	2.4	5.2	0.2	-0.6
90 degrees	4.6	-2.0	2.9	6.5	0.2	-0.6
120 degrees	4.2	-1.8	3.0	7.2	0.1	-0.7

2.1 MATHEMATICAL FORMULATION

The quadratic objective function $Z(F_i)$ is formulized as following:

$$Z = min \sum_{i=1}^{6} q_i \cdot F_i^2 \quad (1)$$

subject

$$\sum_{i=1}^{6} r_{ij} \cdot F_i - M_{ext} = 0 \quad (2)$$

where $M_{ext} = s_j \cdot P + t_j \cdot l_{ext}$

The optimization problem was minimized and can be analytically solved using the Lagrange multiplier method to show how each muscle shares in the activity of carrying the applied external load. The objective function is minimized and can provide the values of muscle forces, during the activity, via Lagrange multiplier method. Lagrange multiplier method has been used to define the necessary conditions for the quadratic objective function constrained by the equilibrium moment equation and estimate the unknown muscle forces. Depending on the equations of objective function and the equilibrium moment equation, Lagrangian equation can be made as following:

$$L = \sum_{i=1}^{6} q_i \cdot F_i^2 - \lambda\left(\sum_{i=1}^{6} r_{ij} \cdot F_i - M_{ext}\right) \quad (3)$$

The minimized muscle forces can be determined when deriving the equations (3) with respect to the forces in the muscles, as design variable, and Lagrange multiplier parameter and set to zero as shown in the following equations:

$$\frac{\partial L}{\partial F_i} = 2q_iF_i - \lambda r_{ij}$$

$$\frac{\partial L}{\partial \lambda} = \sum_{i=1}^{i=6} r_{ij} \cdot F_i - M_{ext}$$

Where: Z is the minimized objective function, i is the index of the muscle forces, j is the index of the joint elbow angle, q_i are the weight coefficients, F_i is the i-th muscle force and M_{ext} is the moment of external applied load and the forearm-hand segment. P is the weight of the forearm-hand segment. l_{ext} is the external applied load. L is the Lagrangian equation. r_{ij} is moment arm for the i-th muscle and the j-th angle. s_j is the moment arm of the segment weight at the j-th angle. t_j is the moment arm of the external load applied at the hand. λ is the Lagrange multiplier. The muscle forces of this model can be obtained at the selected elbow joint angles to be tabulated and plotted to show the muscle forces pattern and the differences in the muscles' contribution and how they have been influenced with the varied elbow joint angle.

2.2 BIOMECHANICAL MODEL

Human forearm and hand segments were modeled in the sagittal plane and the two segments were linked by the wrist joint to be considered as one rigid body. The model is supposed to be free of the body at the elbow joint and local coordinate system of OXY plane was assumed to be attached to the model and located at the elbow joint center as origin point. The elbow joint angle is considered to be the angle between the vertical upper arm and the forearm-hand segment. Four angles were selected as 30, 60, 90 and 120 degrees and investigated to estimate the forces in the muscles. The gravity forces on the modeled segment which is assumed to be concentrated at the geometrical center of the forearm-hand segment. The weight of the forearm-hand body and the external applied load exert clockwise moments about the elbow joint, and the flexor muscles act in counterclockwise direction.

3. RESULTS

The forces in forearm-hand muscles were estimated, under static condition, using Lagrange multiplier method at varied elbow joint angle. The investigation of the forearm-hand muscles had been carried out with different joint angles and external load applied at the hand center which connected to the forearm as one rigid body. The muscle forces are presented in Table 2 to show the activity level in each investigated muscle in the model. The table shows that all the selected muscles were active during carrying external load throughout all the investigated elbow angles. Brd muscle produced the largest force and then the bic muscle to be followed by the tri and bra muscles whereas anc and FCR muscles showed weak contribution compared to the other muscles. This level of contribution of each muscle was comparable to each other throughout the estimation even though with change of elbow angle.
Table 2, the estimated muscle forces at the four selected elbow joint angles and the considered muscles:

F_1=bic, F_2=tri, F_3=bra, F_4=brd, F_5=FCR, F_6=anc.

Angle (degrees)	**F_1**	**F_2**	**F_3**	**F_4**	**F_5**	**F_6**	**Total load**
30	326	279	186	394	12	70	1267
60	248	130	142	307	12	35	874
90	211	92	133	298	9	27	770
120	95	41	0	231	2	16	385

Lagrange multiplier method was used to solve optimization problem to determine the muscle forces at four different position of the lower arm with the elbow joint angles: 30, 60, 90, and 120 degrees. The results showed that there is a significant influence on the estimated muscle forces with the change in the elbow angle. This change in the elbow angle was approximately has similar effect on each determined muscle. The influence of the change in the angle was also obvious and clearly noticed in the load sharing of the estimated muscles. The muscles had higher forces with elbow angle of 30 degrees and got decreased with elbow joint extension to become the smallest with the degree of 120 degrees when the external load was applied and lift.

The relationship between the elbow joint angle and the load sharing of the selected muscles was plotted to show the effect of elbow angle on the load sharing in forearm-hand segment. As seen in figure 1, it shows that the muscle load sharing is clearly influenced by the change in the elbow joint angle where the forces in the investigated muscles were entirely affected. The figure revealed that with increase of the elbow joint angle the load sharing of the selected muscles decrease.

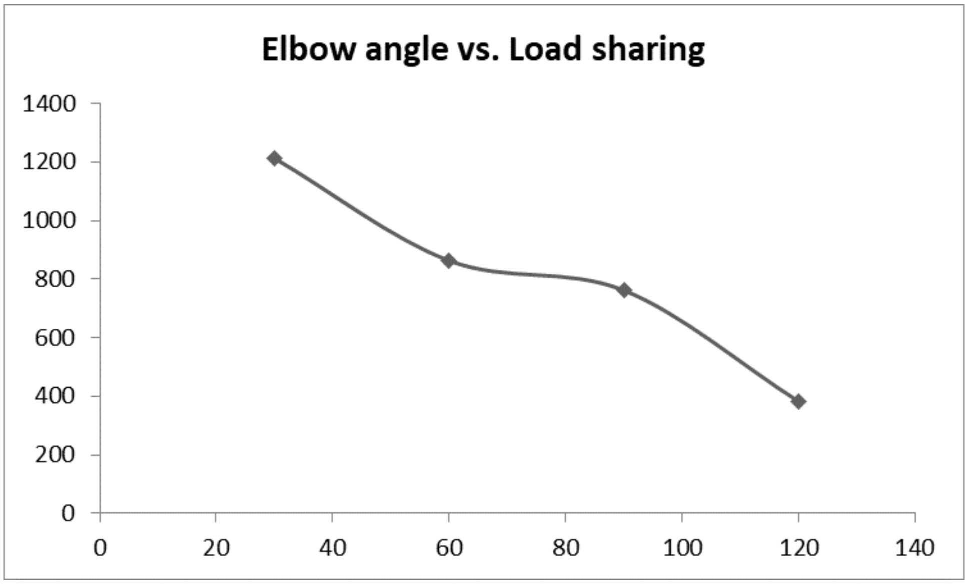

Figure 1

4. DISCUSSION

The purpose of this paper was to examine the effect of change in elbow joint angle on muscle forces in the forearm-hand segment. The muscle forces estimated analytically using Lagrange multiplier method. The estimated forces in the forearm-hand muscles were significantly influenced by varied elbow joint angle which necessitated also investigating the elbow angle and finding a relationship between the muscle forces and the elbow angle. The total contribution of muscle actions during lifting the external load applied on hand is significantly influenced by the change in elbow joint angle which clearly seen in figure 1.

The results indicate that the load carried by hand was heavier when the elbow angle was 30 degrees, in other words, the muscles produced larger forces to carry the external load. Once the elbow joint extended, the muscles produced smaller forces when carrying the external load. Among all estimated muscle forces, the muscles produced the lowest level with elbow angle of 120 degrees that means muscles needed less effort to carry the load applied on hand. The change of elbow joint angle causes change in the moment arms of the investigated muscles which in turn influence the results of the estimated muscle forces. However, the force of each muscle had approximately similar

change with change in elbow angle which shows decreasing contribution of each muscle, during lifting the external applied load, when the elbow angle get extended. In figure 1, the relationship showed extending elbow angle and a result of regular decreasing muscle forces. Consequently, elbow angle is recommended to be nearly 120 degrees when carrying load by hand.

5. CONCLUSIONS

The muscle forces in the forearm-hand model were statically determined during lifting a load applied on hand with considering the effect of the change in the elbow joint**-** angle which clearly influenced the estimated forces in the muscles. A relationship between the elbow angle and the estimated muscle forces was clearly noticed in figure 3.1. The figure showed that the sharing load of the investigated muscles have forces at elbow angle of 120 degrees less than the muscle forces which estimated in case of 30, 60 and 90 degrees. This can provide indication that the optimal angle according to this study is to carry the external load applied on hand with elbow joint angle of 120 degrees compared to the other investigated angles.

6. REFERENCES

[1]. Seireg, A. & Arvikar, R. J. 1973. A mathematical model for evaluation of forces in lower extremeties of the musculo-skeletal system. Journal of Biomechanics. 6 (3), 313–26 (1973).

[2]. Penrod, D.D., Davy, D.T. & Singh, D.P. 1974. An optimization approach to tendon force analysis. Journal of Biomechanics. 7, 123-129 (1974).

[3]. R. D. Crowninshield. Use of optimization techniques to predict muscle forces. Journal of Biomechanical Engineering, 100, pp. 88-92 (1978).

[4]. H. Hatze. A complete set of control equations for the human musculoskeletal system. Journal of Biomechanics, 10, pp. 799-805 (1977).

[5]. Kian, Azadeh, Claudio Pizzolato, Mark Halaki, Karen Ginn, David Lloyd, Darren Reed, and David Ackland. "Static optimization underestimates antagonist muscle activity at the glenohumeral joint: A musculoskeletal modeling study." Journal of biomechanics 97, 109348 (2019).

[6]. Heintz, S. & Gutierrez-Farewik, E.M. Static optimization of muscle forces during gait in comparison to EMG-to-force processing approach. Gait & Posture. 26, 279–288 (2007).

[7]. Jinha A., Ait-Haddou R., Kaya M. & Herzog,W. A task-specific validation of homogeneous non-linear optimisation approaches. Journal of Theoretical Biology. 259, 695–700 (2009).

[8]. Seth A. & Pandy M. G. A neuromusculoskeletal tracking method for estimating individual muscle forces human movement. Journal of Biomechanics. 40, 356 –366 (2007).

[9]. Barakat, Christopher, Renato Barroso, Michael Alvarez, Jacob Rauch, Nicholas Miller, Anton Bou-Sliman, and Eduardo O. De Souza. "The effects of varying glenohumeral joint angle on acute volume load, muscle activation, swelling, and echo-intensity on the biceps brachii in resistance-trained individuals." Sports 7, no. 9, 204 (2019).

[10]. Correa, Jorge Hernán Restrepo; Arellano, Juan Luis Hernández. Distribution of handgrip force in the forearm muscles through static optimization. International Journal of Combinatorial Optimization Problems & Informatics, Vol. 11 Issue 1, p76-87. 12p (2020).

[11]. Catelli, Danilo S., KC Geoffrey Ng, Mariska Wesseling, Erik Kowalski, Ilse Jonkers, Paul E. Beaulé, and Mario Lamontagne. "Hip muscle forces and contact loading during squatting after cam-type FAI surgery." JBJS 102, no. Suppl 2, 34-42 (2020).

[12]. Roelker, Sarah A., Elena J. Caruthers, Rachel K. Hall, Nicholas C. Pelz, Ajit MW Chaudhari, and Robert A. Siston. "Effects of optimization technique on simulated muscle activations and forces." Journal of Applied Biomechanics 36, no. 4, 259-278 (2020).

[13]. Pedotti, A., Krishnan, V. & Stark, L. Optimization of muscleforce sequencing in human locomotion. Mathematical Biosciences. 38, 57–76 (1978).

[14]. Heller, M. O., Bergmann, G., Deuretzbacher, G., D¨urselen, L., Pohl, M., Claes, L., Haas, N. P. & Duda, G. N. Musculo-skeletal loading conditions at the hip during walking and stair climbing. Journal of Biomechanics. 34 (7) 883–93 (2001).

[15]. Abdalla, Faisal Saleh, and azmin sham rambely. "static optimization of muscles forces of lower arm during lifting a load." no. paper id, 591(2010).

[16]. Abdalla, Faisal Saleh, and Azmin Sham Rambely. "Predicting the safe load on backpacker’s arm using Lagrange multipliers method." In AIP Conference Proceedings, vol. 1614, no. 1, pp. 948 954. American Institute of Physics, (2014).

[17]. Raikova, R. A model of the flexion–extension motion in the elbow joint some problems concerning muscle forces modelling and computation. Journal of Biomechanics. 29, 763–772 (1996).

[18]. Emer P. Doheny, Madeleine M. Lowery, David P. FitzPatrick, Mark J. O’Malley, 2008. Effect of elbow joint angle on force–EMG relationships in human elbow flexor and extensor muscles. Journal of Electromyography and Kinesiology. 18(5), 760-770.

[19]. Kasprisin, J. E., and M. D. Grabiner. "Joint angle-dependence of elbow flexor activation levels during isometric and isokinetic maximum voluntary contractions." Clinical Biomechanics 15, no. 10 743-749, (2000).

[20]. Kulkarni, Tushar, and Rashmi Uddanwadiker. "Modeling of muscle force at varied joint angles of the human arm and estimation of gripping force using surface emg." Mol. Cellular Biomechanics 13, no. 2, 87-104 (2016).

[21]. Nosaka, Kazunori, and K. E. I. Sakamoto. "Effect of elbow joint angle on the magnitude of muscle damage to the elbow flexors." Medicine and science in sports and exercise 33, no. 1, 22-29 (2001).