Journal of Engineering Science and Technology
Vol. 13, No. 6 (2018) 1665 - 1676

A DYNAMIC VIRTUAL HAND MODEL FOR ESTIMATING JOINT TORQUES DURING THE WRIST AND FINGERS MOVEMENTS

KASIM SERBEST[1,*], MURAT CILLI[2], OSMAN ELDOGAN[1]

[1]Department of Mechatronics Engineering, Sakarya University, 54187, Sakarya, Turkey
[2]Faculty of Sport Sciences, Sakarya University, 54187, Sakarya, Turkey
*Corresponding Author: kserbest@sakarya.edu.tr

Abstract

Determining the dynamic properties of the joints of human limbs is a control and design parameter for humanoid mechanism, rehabilitation robots and orthotic and prosthetic devices. In other researches, some methods have been suggested for estimating joint torques of the hand such as mathematical models and simulation models. A 16 degree of freedom (DOF) dynamic simulation model of an average human hand is suggested in this study. Dynamic model of a human hand has been created by SimMechanics on MATLAB. Abduction/adduction and flexion/extension motions of the wrist and the fingers can be analysed using SimMechanics model by changing joint rotation. The model has been analyzed by inverse dynamics method using the video record of five healthy subjects (31.2 ±9.57 years) and the joint torques of the wrist and fingers have been calculated. The greatest torque of index finger with 0.0149 Nm occurs at the MCP joint during the cylindrical grip. The greatest wrist torque has been calculated as 0.225 Nm during motion of flexion/extension. Our results are similar to previous works. This simulation model can be used for estimating the joint torques at different motions of the hand without external devices and mathematical techniques.

Keywords: Biomechanical model, Joint torque, Virtual hand.

1. Introduction

Determining the dynamic properties of the joints of human limbs is a control and design parameter for humanoid mechanisms and assistive devices [1]. Several external devices measuring the joint torque of the human limbs are available [2]. However, they are bulky for a human hand and may cause inaccurate measurement. Besides, a few wearable devices monitoring the hand movements are also available [3]. These devices only measure the kinematic properties of the joint without torque

Greek Symbols

β	Angle between two segments (Fig. 3)
θ	Joint angle (Fig. 3)

Abbreviations

ADL	Activities of daily living
CAD	Computer aided design
CMC	Carpometacarpal
D	Digit
D.e	Distal end
DOF	Degrees of freedom
DIP	Distal interphalangeal
DP	Distal phalanx
IP	Interphalangeal
MCP	Metacarpophalangeal
MP	Middle phalanx
P.e	Proximal end
PIP	Proximal interphalangeal
PP	Proximal phalanx

and force. Additionally, some simulation models and mathematical techniques have been suggested analyzing the movement of the hand. Table 1 shows some previous research on mathematical and simulation models. Research in [4-6] are based on mathematical methods. Defining human movements requires a lot of DOFs. Thus, system of differential equation is needed when modelling human movements. Solving the equations can be challenging. Therefore, mathematical techniques can be difficult for some researchers who are interested in biomechanical analysis in different fields.

Research in [7] a bond graph method has been presented for only one joint of a finger. Creating a bond graph method for the hand including all joints is a challenging process. Research in [8, 9] have suggested simulation models for only kinematic analysis of the hand movement, but they are not able to calculate kinetic changes during movements such as force and torque of the joints.

Biomechanical studies may require interdisciplinary collaboration. Researchers from different fields of science such as physicians, physical therapist and sports scientists may be interested in biomechanical analysis, so there is a need for an uncomplicated analysis tools. We think that new methods should be developed for dynamic analysis of the hand movements because of difficulty of the mathematical techniques and limitation of the simulation models. MATLAB is a common software among scientists. Within this scope, we suggest a virtual hand model using MATLAB tools. SimMechanics tool is suitable for modeling of the human motion [10-12]. SimMechanics allows dynamic analysis of motions without the need for mathematical techniques.

The aim of this research is estimating the joint torques of fingers and the wrist in a MATLAB environment. Accordingly, an average adult human hand has been modelled as a 16 DOF dynamic structure. Hand movements both sagittal and frontal plane can be analysed with 16 DOF. Flexion/extension and abduction/adduction motions of the wrist and fingers for five subjects have been captured on a video camera. Then the virtual hand model has been simulated using the motion data on SimMechanics environment. Finally, finger joints and the wrist joint torques have been calculated. The torque data can be used for design parameter of a hand rehabilitation device. It can also be used for structural analysis of bones. Additionally, simulation results have been compared with other studies.

Table 1. Some previous researches about human hand: Mathematical techniques and simulation models. Y; yes, N; no, Ref.; reference.

Ref.	Method	DOF	Muscles	Kinetics
[4]	Computer model using a non-linear optimizing mathematical equations for the index finger	4	Y	Y
[5]	Excursion model using a non-linear optimization for the index finger	3	Y	Y
[6]	Dynamic equations using the Newton - Euler formulation by Hollerbach with CyberGlove for the index finger	4	N	Y
[7]	Bond graph method using Hill's 4 element muscle model for two segments of a finger	1	Y	Y
[8]	CAD model using the Denavit - Hartenberg method for the hand	25	N	N
[9]	Computer model using the Denavit - Hartenberg method with optical tracking system for the hand	23	N	N

2. Material and Methods

2.1. Dynamic model of the hand

The hand located on the distal end of the upper extremity has three parts: the wrist, the metacarpus and the digits (D). The palm and five digits or fingers make up the hand. Phalanges, metacarpals and carpal bones are three parts of bones in the human hand. Figure 1 shows the biomechanical model of the hand in our study. Proximal, middle and distal phalanges compose the bones of the digits 2-5 (index, middle, ring finger and pinky). A distal phalanx, a proximal phalanx and a metacarpal bone compose the digit 1 (thumb). Metacarpals and carpal bones make up the palm. The wrist segment connects the forearm and the hand. The wrist joint is located between the radius and the carpal bones [13]. Digits 2-5 have three joints: distal interphalangeal (DIP), proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints [14]. Digit 1 has a carpometacarpal (CMC), a metacarpophalangeal (MCP), an interphalangeal (IP) joint. All IP joints (total of nine) are hinge joint which have only one DOF capable of flexion/extension movement. A CMC and five MCP joints are saddle joints which have two DOFs capable of both abduction/adduction and flexion/extension movement [6, 15]. The wrist joint has two DOFs with abduction/adduction and flexion/extension [14].

The dynamic structure of the hand has been modelled as a link-segment model using open chair structure. The model consists of 16 revolute joints and 16 solid limbs. Changing rotation axis of the CMC joints, MCP joints and the wrist joint can perform movements of the hand in sagittal and frontal plane. Thus it can be used to analyse abduction/adduction movements besides flexion/extension.

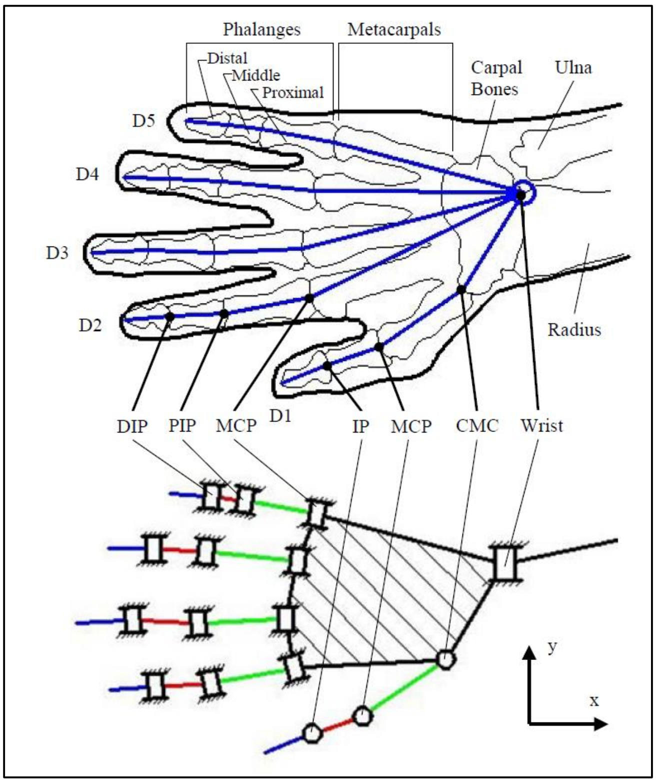


Fig. 1. The biomechanical model of the human hand in frontal plane.

2.2. Anthropometric data of the hand

Anthropometric data of an adult human hand has been taken from other researches [16-19] and SolidWorks software. The thumb (D1) has been described as a cylindrical bar. MP of D 2-5 have been modelled as a conical bar. Proximal and distal phalanges of digits 2-5 have been described as a cylindrical bar. The center of mass of the all phalanx has been assumed to be on their midpoint. The palm has been modelled as a prismatic solid limb from MCP joints of D2-5 and CMC joint of D1 to the wrist joint. The center of mass of it has been determined by SolidWorks. The moment of inertia tensor has been determined by SolidWorks using the center of mass of the all hand part. Table 2 shows the anthropometric data of the digits (fingers) and Table 3 shows the anthropometric data of the palm.

2.3. MATLAB model

The dynamic model of the adult human hand has been created with SimMechanics block diagrams in MATLAB. Figure 2 shows SimMechanics structure of the model. Block diagrams consist of a ground block, a machine environment block, body blocks, joint blocks, joint actuator blocks, joint sensor blocks and signal (motion, torque) input/output blocks. Ground block is immobile point of mechanism. Machine environment block presents mechanical settings. Body blocks specified mass, inertia tensor and coordinate systems. Joint blocks provide relative motions between bodies. Each joint has been defined as a revolute joint with one DOF. The revolute joint can perform one of the movements of flexion/extension or abduction/adduction. The rotation axis of this joint can be changed. Thus, flexion/extension and abduction/adduction movements can be analysed separately. Joints are actuated by joint actuator blocks using motion data. The joint torque is measured by joint sensor blocks. Motion data with angular displacement, velocity and acceleration for all joints have been read from MATLAB Workspace and the calculated joint torque data has been written to the MATLAB Workspace. The axis definition is suitable for SimMechanics coordinate system.

Table 2. Anthropometric data of the digits.

Segment	**Length (cm)**	**Diameter (cm)**		**Mass (g)**	**Moment of Inertia (g•cm^2)**
		P.e.	**D.e.**		
D1 DP	3.26	2.06	2.06	11.72	I_{xx}= 6.219 I_{yy}=I_{zz}= 13.49
D1 PP	2.01	2.06	2.06	7.23	I_{xx}= 3.384 I_{yy}=I_{zz}= 4.351
D1 metacarpal	6.42	2.06	2.06	23.08	I_{xx}= 12.24 I_{yy}=I_{zz}= 85.42
D2 DP	2.69	1.64	1.64	6.13	I_{xx}= 2.061 $_{yy}$=I_{zz}= 4.728
D2 MP	2.18	1.64	1.97	6.03	I_{xx}=2.492 I_{yy}=I_{zz}= 3.615
D2 PP	5.68	1.97	1.97	19.27	I_{xx}= 9.349 I_{yy}=I_{zz}= 59.82
D3 DP	2.69	1.65	1.65	6.20	I_{xx}= 2.112 I_{yy}=I_{zz}= 4.798
D3 MP	2.57	1.65	2.0	7.27	I_{xx}= 3.076 I_{yy}=I_{zz}= 5.504
D3 PP	5.22	2.0	2.0	17.69	I_{xx}= 8.847 I_{yy}=I_{zz}= 44.60
D4 DP	2.78	1.54	1.54	5.58	I_{xx}= 1.656 I_{yy}=I_{zz}= 4.427
D4 MP	2.35	1.54	1.87	5.80	I_{xx}= 2.143 I_{yy}=I_{zz}= 3.718
D4 PP	5.06	1.87	1.87	14.99	I_{xx}= 6.554 I_{yy}=I_{zz}= 35.27
D5 DP	2.55	1.40	1.40	4.23	I_{xx}= 1.038 I_{yy}=I_{zz}= 2.814
D5 MP	1.69	1.40	1.65	3.34	I_{xx}= 0.981 I_{yy}=I_{zz}= 1.279
D5 PP	3.96	1.65	1.65	9.13	I_{xx}= 3.109 I_{yy}=I_{zz}= 13.49

Table 3. Anthropometric data of the palm.

Wrist width (cm)	6.22
Palm witdh on MCP of D2-5 (cm)	8.41
The length from wrist to MCP of D2 (cm)	7.18
The length from wrist to MCP of D3 (cm)	8.13
The length from wrist to MCP of D4 (cm)	7.48
The length from wrist to MCP of D5 (cm)	7.09
Tickness (cm)	3.02
Mass (g)	181.0
Moment of Inertia (g•cm^2)	I_{xx}=945.9 I_{xy}= I_{yx}=53.60 I_{yy}=995.9 I_{zz}=1666 I_{xz}= I_{yz}= I_{zx}= I_{zy}=0

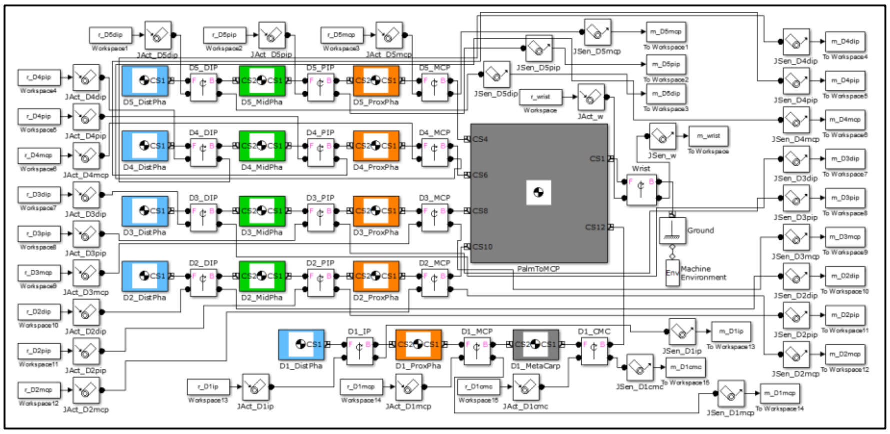


Fig. 2. SimMechanics structure of the dynamic hand model.

2.4. Motion analysis and simulation of the model

The movement of all joints must be known clearly because of inverse dynamics analysis for simulations. Two males and three females volunteer (mean age: 31.2 ± 9.57, right handed) participated in the study. Four different movements of the hand have been selected. They are flexion/extension movement of the fingers during cylindrical grip, abduction/adduction movement of the fingers, flexion/extension movement of the wrist and abduction/adduction movement of the wrist. These movements are often performed in activities of daily living (ADL). We use combination of these movements in some significant ADL such as grasping, opening a jar, brushing teeth, knocking at a door and handwriting.

Analyzing for flexion/extension of the fingers, passive reflective markers have been placed on subjects' hand. Markers were attached on the five anatomical landmarks (the wrist joints, joints of MCP, PIP, DIP and the distal end of the distal phalanx) for each digits [20]. Subjects gripped a 42 millimeters diameter object with self-selected speed by their dominant hand. Then they got the fingers initial position. The object was fixed on a desk, so the weight of the object did not affect the subjects' hand. Analyzing for abduction/adduction of the fingers, subjects performed abduction movement first with same marker placement. Then they performed adduction movement of fingers.

Analyzing for the wrist motion, the markers have been placed on MCP joint of D3, the ulnar styloid, the approximate midpoint of forearm. Subjects performed the motion of the wrist like extension first, secondly flexion, lastly neutral (initial) position. Analyzing for abduction/adduction of the wrist, subjects performed abduction first. Then they performed adduction movement of the wrist. Their fingers were a straight position during wrist movements.

Subjects have been monitored using a video camera (320x240 pixels resolution, 25 frames per second). Captured data of the markers has been obtained through image processing methods in MATLAB. The angle between two adjacent parts (such as between palm and forearm, between MP and DP, etc.) has been calculated by Eq. (1).

$$\beta = \cos^{-1} [(u \bullet v) / (|u| \bullet |v|)] \quad (1)$$

where v, u are vectors of the adjacent parts, β is angle between two parts. Figure 3 shows representation of the joint angle. Then angular velocities (ω) and angular accelerations (α) of the all joints are calculated by derivation like Eq. (2).

$$\omega = \dot{\theta}, \alpha = \ddot{\theta} \tag{2}$$

Motions of the wrist and fingers have been simulated by SimMechanics using the movement data. Figure 4 shows simulation views of these different motions. Inverse dynamics mode has been selected for simulations. The type is fixed-step and the solver is discrete. Thus, joint torques of the wrist and fingers have been calculated.

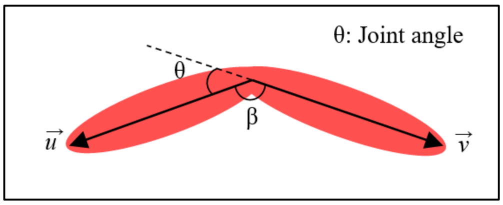


Fig. 3. Presentation of the joint angle between two adjacent parts.

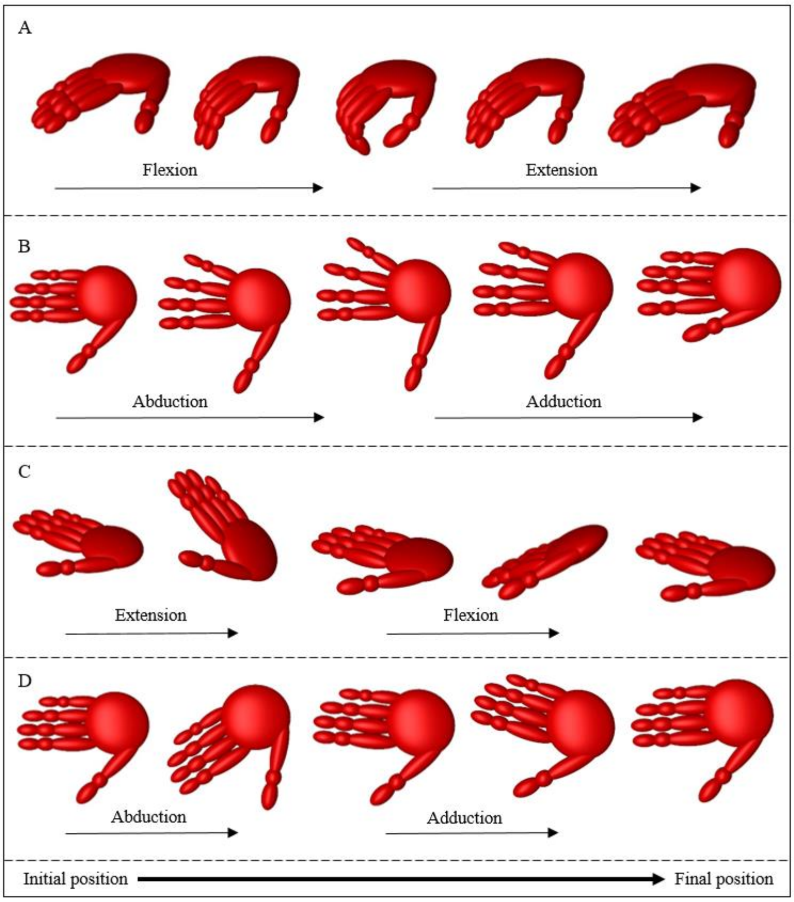
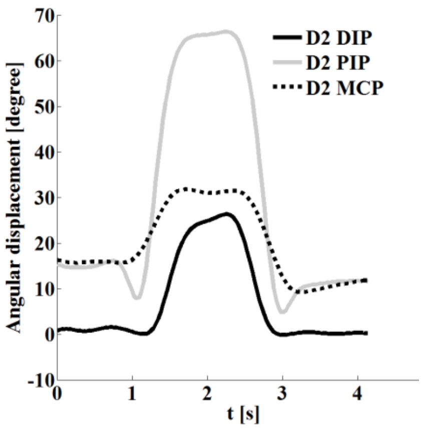


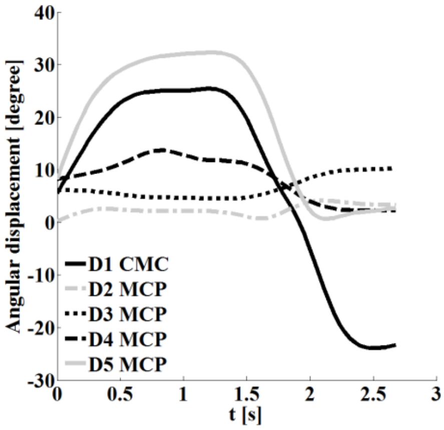
Fig. 4. Movements of the virtual hand. A; Cylindrical grip, B; abduction/adduction of the fingers, C; flexion/ extension of the wrist, D; abduction/adduction of the wrist.

3. Results and Discussion

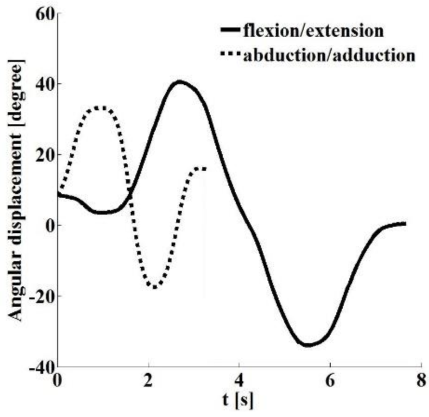
Angular displacements of the finger joints and the wrist during different movement are shown in Fig. 5. At the left side, angular displacement of the index finger is shown during cylindrical grip. Movements of other fingers are similar to the index finger. The greatest angular displacement is at the PIP joint of the index finger as about 65° during cylindrical grip. At the middle side, angular displacement of fingers which has two DOFs joints (CMC and MCP) are shown. The thumb and the pinky have the biggest angular displacement during abduction/adduction movement. At the right side, angular displacement of the wrist during abduction/adduction and flexion/extension movements are shown. The continuous line refers to flexion/extension movement of the wrist and the dashed line refers to abduction/adduction movements of the wrist. Positive angle mean the extension of the wrist and negative angle mean flexion of the wrist for continuous line. In dashed line, the positive ones describe abduction of the wrist and the negative ones describe adduction of the wrist. Range of motion (ROM) of the flexion/extension is more than ROM of the abduction/adduction. It is an expected result for the wrist joint.



(a) Flexion/extension of the index finger



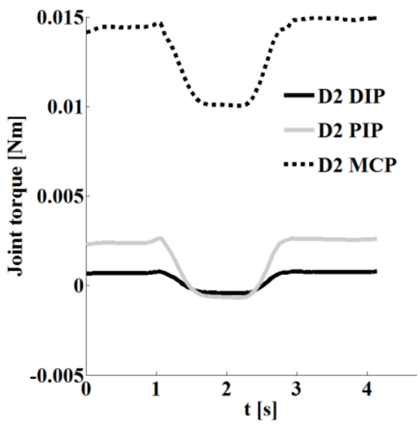
(b) Abduction/adduction of fingers



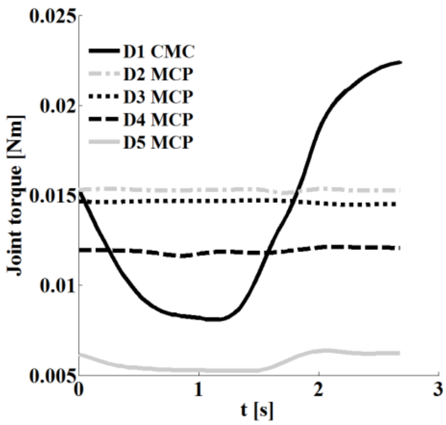
(c) Wrist movements

Fig. 5. Angular displacement of joints.

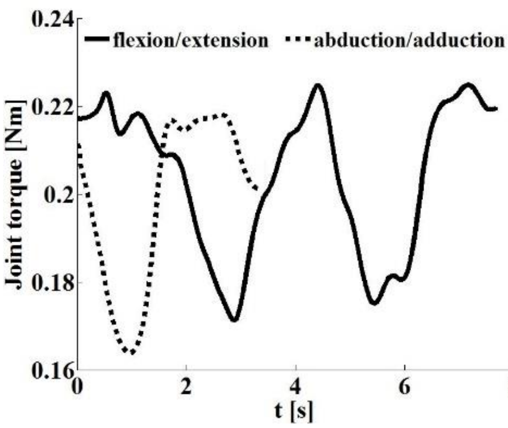
The joint torques has been calculated using SimMechanics as a result of the simulation. The joint torques is summarized in Fig. 6. At the left side, the greatest torque 0.0149 Nm occurs at the MCP joint of the index finger. The torques of the DIP and the PIP joint are much smaller than the MCP joint. It is an expected result because MCP joint is affected by total finger weight. The force of gravity contribute positively to the flexion of the fingers. In this way, the joint torque is decreased during the movement of flexion. The torques of other joints are similar to joints of the index finger. At the middle, it is shown that the torques changing during abduction/adduction movement of the fingers. The most significant torques occurs at the CMC joint and MCP joints of D2-5. The maximum torque of the CMC joint is calculated as 0.022 Nm. The comparison of the wrist torques is shown at the right side. The maximum torque of the flexion/extension movement is about 0.225 Nm and the abduction/adduction movement is about 0.218 Nm. Table 4 shows a summary of the maximum calculated joint torques for fingers and the wrist.



(a) Flexion/extension of the index finger



(b) Abduction/adduction of fingers



(c) Wrist movements

Fig. 6. Calculated joint torques.

Table. 4. The maximum calculated joint torques for fingers and the wrist.

Segment/Joint		Maximum joint torques [Nm]	
		Flexion/Extension	Abduction/Adduction
D1	IP	0.0014	0.0017
	MCP	0.0036	0.0046
	CMC	0.0175	0.0224
D2	DIP	0.000785	0.000814
	PIP	0.0027	0.0028
	MCP	0.0149	0.0154
D3	DIP	0.000798	0.000818
	PIP	0.0032	0.0033
	MCP	0.0143	0.0147
D4	DIP	0.000749	0.000765
	PIP	0.0027	0.0027
	MCP	0.0117	0.0121
D5	DIP	0.000512	0.000547
	PIP	0.0014	0.0016
	MCP	0.0061	0.0064
Wrist		0.225	0.218

In a research, analysing of repetitive fingers and wrist movements [6], MCP joint torques have been determined less than 0.03 Nm during a 4-second motion. They calculated very little changes at the PIP and DIP torques. Figure 7 shows a comparison between our results and their results. Our findings are similar to that research. Although our model is simpler than study in [6], the results are similar. We think simplicity is the advantage of our model.

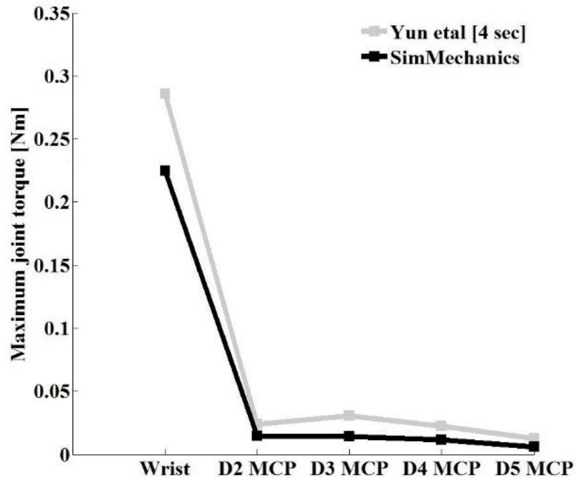


Fig. 7. Comparison of Yun et al. and SimMechanics results during flexion/extension movement.

In other previous research [21], it has found that most of ADL have been performed with 40° on both flexion and extension movements of the wrist. It has supported our wrist movement measurement.

4. Conclusion

In this research a dynamic model of the average human hand has been suggested to estimate the joint torques. The model has a simple structure. Thus, dynamical analysis can be done easily without mathematical background. Cylindrical grip movements and abduction/adduction movements of the fingers, abduction/adduction movements and flexion/extension movements of the wrist have been simulated using MATLAB tools. It is clear that dynamics changes of the joints can be calculated using SimMechanics tools without bulky measurement devices and mathematical equations. The energy and the force also can be determined using other SimMechanics tools. Besides, customized analysis for individual anthropometric data can be done by changing the parameters of SimMechanics blocks. SimMechanics model of the hand has some limitations. Body in SimMechanics is solid form but human limbs are viscoelastic form. Therefore results have some margin of error.

The future work is adding the muscles to the simulation model. Thus we can calculate the muscle force. On the other hand, we plan to use the torque and motion data for development of a hand assistive and rehabilitation device. We are working on designing a novel actuator mechanism according to the motion and the torque data. Additionally, the calculated torques can be used for structural analysis of bones.

Acknowledgments

This study has been supported by The Scientific and Technological Research Council of Turkey (TUBITAK) with project No. 115M622. Author Serbest special thanks to The Scientific and Technological Research Council of Turkey BIDEB.

References

1. Olinski, M.; Lewandowski, B.; and Gronowicz, A. (2015). Type synthesis and preliminary design of supporting lower limbs' rehabilitation. *Acta Bioeng Biomech*, 17(1), 117-127.
2. Esteki, A.; and Mansour, J.M. (1996). An experimentally based nonlinear viscoelastic model of joint passive moment. *Journal of Biomechanics*, 29(4), 443-450.
3. Fujiwara, E.; Onaga, C.Y.; Santos, M.F.S.; Schenkel, E.A.; and Suzuki, C.K. (2014). Design of a glove-based optical fiber sensor for applications in biomechatronics. *Proceedings of the 5th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics*, Sao Paulo, 786-790.
4. Fok, K.S.; and Chou S.M. (2010). Development of a finger biomechanical model and its considerations. *Journal of Biomechanics*, 43(4), 701-713.

5. Sancho-Bru, J.L.; Perez-Gonzalez, A.; Vergara-Monedero, M.; and Giurintano, D. (2001). A 3-D dynamic model of human finger for studying free movements. *Journal of Biomechanics*, 34(11), 1491-1500.
6. Yun, M.H.; Eoh, H.J.; and Cho, J. (2002). A two-dimensional dynamic finger modeling for the analysis of repetitive finger flexion and extension. *International Journal of Industrial Ergonomics*, 29(4); 231-248.
7. Vaz, A.; Singh, K.; and Dauphin-Tanguy, G. (2015). Bond graph model of extensor mechanism of finger based on hook-string mechanism. *Mechanism and Machine Theory*, 91, 187-208.
8. Pena-Pitarch, E.; Falguera, N.T.; and Yang, J.J. (2014). Virtual human hand: model and kinematics. *Computer Methods in Biomechanics and Biomedical Engineering*, 17(5), 568-579.
9. Veber, M.; and Bajd, T. (2006). Assessment of human hand kinematics. *Proceedings of the IEEE EMBS International Conference on Robotics and Automation*, Orlando, 2966-2971.
10. Serbest, K.; Cilli, M.; and Eldogan, O. (2015). Biomechanical effects of daily physical activities on the lower limb. *Acta Orthopaedica et Traumatologica Turcica*, 49(1), 85-90.
11. Jamshidi, N.; Rostami, M.; Najarian, S.; Menhaj, M.B.; Saadatnia, M.; and Firooz, S. (2009). Modelling of human walking to optimize the function of ankle-foot orthosis in Guillan-Barre patients with drop foot. *Singapore Medical Journal*, 50(4), 412-417.
12. Daumas, B.; Xu, W.L.; and Bronlund, J. (2005). Jaw mechanism modelling and simulation. *Mechanism and Machine Theory*, 40, 821-833.
13. Drake, R.L.; Vogl, W.; Mitchell, A.W.M. (2004). *Gray's anatomy for students*. Churchill Livingstone Elsevier.
14. Nordin, M.; and Frankel, V.M. (2012). *Basic biomechanics of the musculoskeletal system*. Lippincott Williams & Wilkins.
15. Buchholz, B.; and Armstrong, T.J. (1992). A kinematic model of the human hand to evaluate its prehensile capabilities. *Journal of Biomechanics*, 25(2), 149-162.
16. Garret, J.W. (1970). *Anthropometry of the hands of male air force flight personnel*. DTIC Document.
17. Garret, J.W. (1970). *Anthropometry of the air force female hand*. DTIC Document.
18. Greiner, T.M. (1991). *Hand snthropometry of U.S. army personnel*. Technical Report.
19. Chandler, R.F.; Clauser, C.E.; McConville, J.T.; Reynolds, H.M.; and Young J.W. (1975). *Investigation of inertial properties of the human body*. Aerospace Medical Research Laboratory.
20. Miyata, N.; Kouchi, M.; Kurihara, T.; and Mochimaru, M. (2004). Modeling of human hand link structure from optical motion capture data. *Proceedings of the International Conference on Intelligent Robots and Systems*, Sendai, 2129-2135.
21. Ryu, J.; Cooney, W.P.; Askew, L.J.; An, K.; and Chao, E.Y.S. (1991). Functional ranges of motion of the wrist joint. *Journal of Hand Surgery*, 16(3), 409-419.