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Biomechanical Analysis of Human Upper Limb

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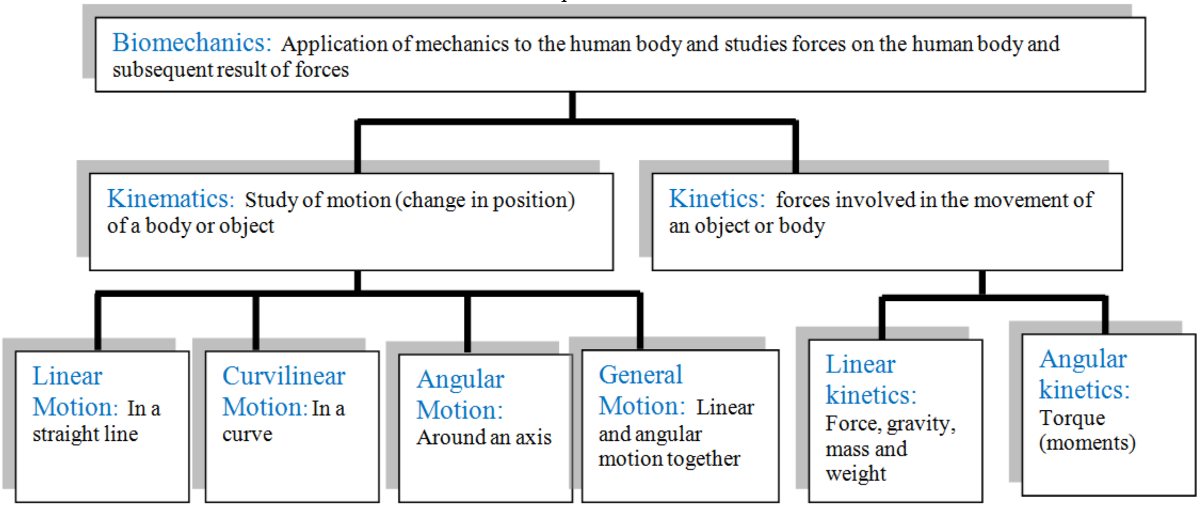
ABSTRACT: This paper presents Biomechanical Analysis of Human Upper Limb. Biomechanical analysis is done by kinematical analysis and static torque calculation. Kinematical analysis is carried out by Denavit and Hartenberg method (DH-method). Denavit Hartenberg method describes position and orientation of link from base to end effector. Static torque is calculated analytically as well as by MSC-Adams software. The design of human upper limb model in MSC-Adams software takes into account various biological properties such as density, mass, volume of each bone. Analytical static torque calculation, which requires values of center of mass from pivot joint, mass of each bone from point of rotation to end effector and force are calculated and the error between software output torque and analytically calculated torque is determined in this paper. With these findings selection of motor type, type of material for prosthetic arm etc becomes simpler when designing prosthetic human upper limb.

KEYWORDS: Biomechanics, Kinematics, DH-parameter, Torque, Density, Joint angle, Volume.

I.INTRODUCTION

Biomechanics is essentially the study of the way in which humans move. These findings are particularly important to the evolution of prosthetics as it aids in the creation of artificial limbs that can replicate human movement. This aspect is imperative when producing artificial limbs.

Biomechanics divided into two sub groups, kinematics and kinetics. Kinematics describes motion of object. Kinematics begins with the description of geometry of the system and initial condition of the known values of the position, velocity and or acceleration of various points that are a part of the system, then from geometrical arguments it can determine the position, the velocity and the acceleration of any part of the system. kinetics is concerned with the relation between motion and its causes like forces and torque.



Flow chart of Biomechanics

Anatomy of upper limb

Figure [1] shows the human upper limb. The upper limb consisting of various bones and joints. The size , shape and weight, type of joint of every bone is different. The study of anatomy of upper limb gives us idea about type of bone joint, volume, density and weight of bone. So there are several bones and joint explained below in detail.

Clavicle- Clavicle are a pair of long bones .the one end of bone is connected sternum while other to shoulder joint.

Shoulder joint-The most flexible joint in the entire human body, our shoulder joint is formed by the union of the humerus, the scapula, and the clavicle (or collarbone). Commonly thought of as a single joint, the shoulder is actually made up of two separate joints **-** the glenohumeral and acromioclavicular joints. These two joints work together to allow the arm both to circumduct in a large circle and to rotate around its axis at the shoulder.

Humerus-The humerus is the both the largest bone in the arm and the only bone in the upper arm. Many powerful muscles that manipulate the upper arm at the shoulder and the forearm at the elbow are anchored to the humerus. Movement of the humerus is essential to all of the varied activities of the arm, such as throwing, lifting, and writing.

Elbow joint-The elbow joint is a complex hinge joint formed between the distal end of the humerus in the upper arm and the proximal ends of the ulna and radius in the forearm. The elbow allows for the flexion and extension of the forearm relative to the upper arm, as well as rotation of the forearm and wrist.

Radius-The radius is the more lateral and slightly shorter of the two forearm bones. It is found on the thumb side of the forearm and rotates to allow the hand to pivot at the wrist. Several muscles of the arm and forearm have origins and insertions on the radius to provide motion to the upper limb. These movements are essential to many everyday tasks such as writing, drawing, and throwing a ball.

Ulna-The ulna is the longer, larger and more medial of the lower arm bones. Many muscles in the arm and forearm attach to the ulna to perform movements of the arm, hand and wrist. Movement of the ulna is essential to such everyday functions as throwing a ball and driving a car.

Hand and wrist-The bones of the hand and wrist provide the body with support and flexibility to manipulate objects in many different ways. Each hand contains 27 distinct bones that give the hand an incredible range and precision of motion. The forearm's ulna and radius support the many muscles that manipulate the bones of the hand and wrist. Rotation of the radius around the ulna results in the supination and pronation of the hand. These bones also form the flexible wrist joint with the proximal row of the carpals There are eight small carpal bones in the wrist that are firmly bound in two rows of four bones each. The mass that results from these bones is called the carpus. The carpus is rounded on its proximal end, where it articulates with the ulna and radius at the wrist. The carpus is slightly concave on the palmnar side, forming a canal known as the carpal tunnel through which tendons, ligaments, and nerves extend into the palm. Its distal surface articulates with the metacarpal bones, which are joined to the carpus by the palmnar carpometacarpal ligaments.[5]

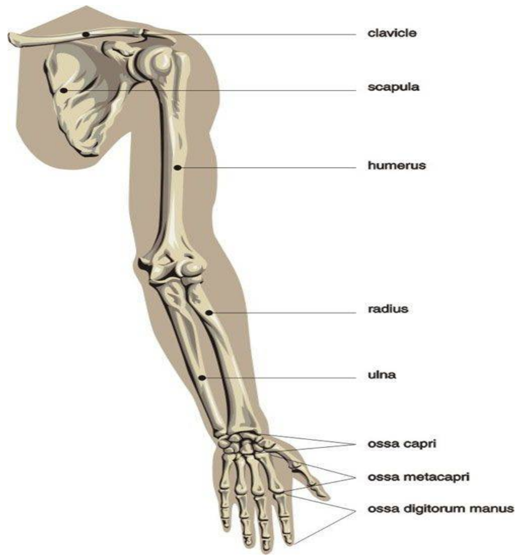


Fig 1: Human hand

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Degree of freedom - It is the number of inputs (number of independent coordinates) required to describe the configuration or position of all the links of the mechanism, with respect to the fixed link at any given instant. The arm considered as 7 degree of freedom model. The clavicle is considered as fix joint. Shoulder joint is known a spherical joint which is having three degree of freedom. The elbow joint is type of revolute joint and has one degree of freedom. The wrist joint has three degree of freedom.

Kinematical analysis using Denavit-Hartenberg method

The kinematics is concerned with the relationship between the individual joints of the robot manipulator and the position and orientation of the tool or end-effector. The forward kinematics is to determine the position and orientation of the end-effector, given the values for the joint variables of the robot. The joint variables are the angles between the links in the case of revolute or rotational joints, and the link extension in the case of prismatic or sliding joints. There are four transformation parameters of DH- parameters[2][12] shown in figure [2]

- θ : A rotation about the *z*-axis.
- **d** : The distance along the *z*-axis during each transformation from old z value to new z' value.
- a : The length of each common normal (Link length L_n).
- α : The angle between two successive *z*-axes i.e angle between old z to new z' value.

So the general DH-parameter equation can be written as,

$$ {}^{n-1}_{n}T = Trans_{z_{n-1}(d_n)} * Rot_{z_{n-1}}(\theta_n) * Trans_{x_n}(a_n) * Rot_{x_n}(\alpha_n) $$

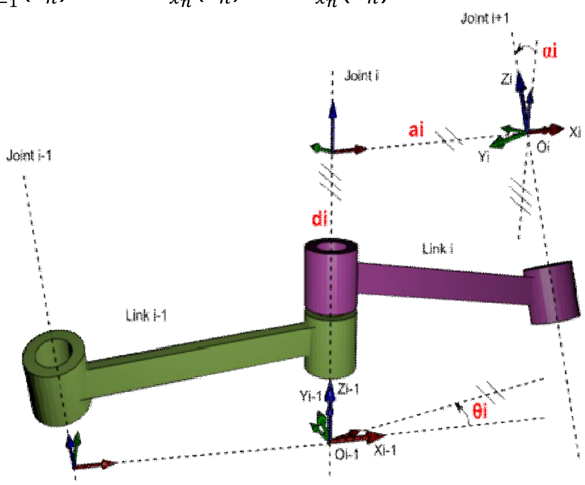

Figure 1 : DH-parameter

Example : Planar Elbow Manipulator[11]

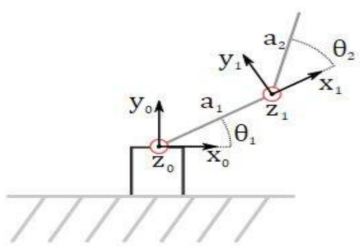

Fig 3: Two link planar elbow

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joint	a_i	d_i	α_i	θ_i
1	a_1	0	0	θ_1
2	a_2	0	0	θ_2

$$T_i = \begin{bmatrix} cos\theta_i & -\sin\theta_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_i & -\cos\theta_i \sin\alpha_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^1_0T = \begin{bmatrix} cos\theta_1 & -\sin\theta_1 & 0 & a_1 \cos\theta_1 \\ \sin\theta_1 & \cos\theta_1 & 0 & a_1 \sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad ^2_1T = \begin{bmatrix} cos\theta_2 & -\sin\theta_2 & 0 & a_2 \cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & a_2 \sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_0^2 = {}^1_0T\,{}^2_1T = \begin{bmatrix} cos(\theta_1+\theta_2) & -\sin(\theta_1+\theta_2) & 0 & a_1 \cos\theta_1 + a_2 \cos(\theta_1+\theta_2) \\ \sin(\theta_1+\theta_2) & \cos(\theta_1+\theta_2) & 0 & a_1 \sin\theta_1 + a_2 \sin(\theta_1+\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure [3] shows example of two link planar elbow manipulator. The general DH-parameter matrix for elbow manipulator is taken as T_i . a_1 and $a_2$are the two links of planar elbow . d_i is the displacement along z axis and it is zero because there is no displacement along z axis . α_i is angle between two successive z axis i.e z to z' and it is zero because there is change angle from z to any z' value. To find out the end effector value we need to put all four dh parameter in T_i matrix to calculate transformation from ^1_0T and ^2_1T one by one. By multiplying matrix ^1_0T and ^2_1T , we will have the position and orientation of the end effector of planar elbow manipulator in matrix T_0^2. In T_0^2 matrix a_{11} to a_{33} 3*3 matrix gives us the idea about orientation and $a_{14,}a_{24,}a_{34}$ gives us the idea about position of end effector with respect to base.

Arm kinematical model

The arm kinematic model in Figure[4] is assigned with its corresponding link frames where the *Zi* axes is parallel to the rotational axis of the joint and the *Xi* axes is perpendicular to the plane containing *Zi* and *Zi+1*. The DH-Parameter[4] tabulated in Table I is then substituted into the *4 x 4* homogeneous transformation matrixes in (1) . The end effectors position and orientation expressed with respect to the previous link can be transformed and expressed in the base coordinate through sequential transformation as shown by equation (2)[1][3]

$$A_i = \begin{bmatrix} cos\theta_i & -\sin\theta_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\theta_i \cos\alpha_i & -\cos\theta_i \sin\alpha_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{... (1)}$$

$$^E_0T = {}^1_0T\ {}^2_1T\ {}^3_2T\ {}^4_3T\ {}^5_4T\ {}^6_5T\ {}^7_6T\ {}^E_7T \quad \text{.... (2)}$$

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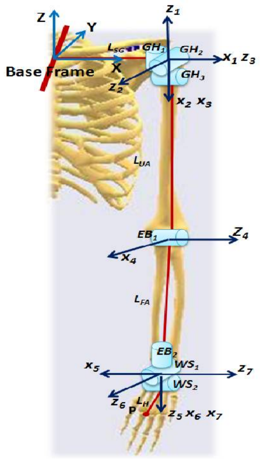

Figure 4: Kinematical model of arm

The DH parameter for human arm is given in table [1].The shoulder joint consisting of three revolute joints as GH_1, GH2, GH3 where rotation is replicated by GH_1, adduction-abduction replicated by GH_2 and flexion-extension replicated by GH_3. EB_1 and EB_2 are two revolute joints of elbow. The humeroulnar articulation allowed the ulna to rotate with respect to the humerus causes forearm flexion-extension replicated by EB_1 while the forearm pronation-supination (EB_2) is due to the rotation of the radius about the ulna longitudinal axis. The WS_1 and WS_2 are two revolute joints. The hand is connected to the arm by the wrist articulation which controls the hand orientation and provides strength for gripping. The wrist comprised of eight small bones called carpus which allowed the hand adduction-abduction replicates by WS_1 and flexion-extension replicates by WS_2. The mechanical function of the wrist joint is represented by 2 revolute joint is depicted in figure. The end effector of the arm model is located at point P, which is the center of mass of the palm. L_{UA} is the link length of Humerus. L_{FA} and L_H are link length of fore arm and hand respectively.L_{SG} is the link length of clavicle bone.[1]

TABLE I.		DH PARAMETERS FOR HUMAN ARM			
Joint	**i**	α_{i-1}	a_{i-1}	d_i	Θ_i
GH_1	**1**	**0**	**L_{SG}**	**0**	**Θ_1**
GH_2	**2**	**90**	**0**	**0**	**Θ_2**
GH_3	**3**	**-90**	**0**	**0**	**Θ_3**
EB_1	**4**	**0**	**L_{UA}**	**0**	**Θ_4**
EB_2	**5**	**-90**	**0**	**L_{FA}**	**Θ_5**
WS_1	**6**	**90**	**0**	**0**	**Θ_6**
WS_2	**7**	**-90**	**0**	**0**	**Θ_7**
P	**E**	**0**	**L_H**	**0**	**0**

Table 1: DH parameter of human upper limb

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Software model of human upper limb

The human upper limb can be represented by kinematical chain that consists of links which is connected with different joint. Due to the high complexity and high degrees of freedom, the model of the hand is separated from the arm. So the hand is represented by gripper in this model shown in figure [5]. The model is consisting of 7 Dof kinematical chain. Parts of model consisting of Clavicle, Humerus, Fore arm, gripper[10]. The density of compact bones is same and it is given in Kg/m^3. Mass and volume is dependent on geometry and shape of each part (link).

The software model of human upper limb is designed in MSC-Adams student license version software. The model is designed on the basis of markers, parts (links), geometry.

Markers are used wherever a unique location needs to be defined. For example:

- The location of a part's center of mass.
- The reference point for defining where graphical entities are anchored.
- The axes about which part mass moments of inertia are specified.
- Directions for constraints.
- Directions for force application.

Parts defines bodies(rigid or flexible) that can move relative to other bodies and have properties like Mass, Inertia, Initial location and orientation, torque etc. Graphics is used to enhance the visualization of parts using properties such as Length, Radius, Width[8] etc.

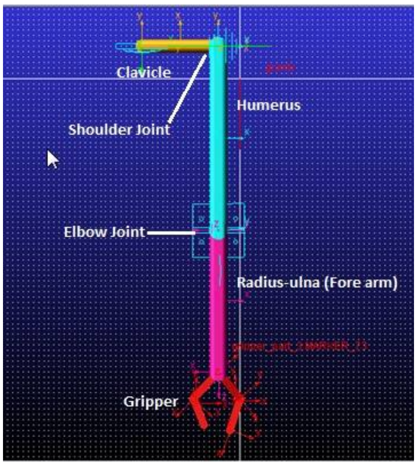

Fig 5: Human upper limb model

Calculation of static torque

Calculation of static torque is dependent on several thing like Link length, Density, Mass, Volume, Center of mass etc . All these value of designed software human upper limb model is given in table no [2].

The center of mass [6] from pivot joint is calculated as

$$CM = \frac{m_1 x_{1+} m_2 x_2 + m_n x_n}{m_1 + m_2 + m_n}$$

Width, Length, Height is used to calculate volume of each link. The value of torque [9] is calculated as

Torque = Force * CM distance from joint*mass of links * gravity

The center of mass from shoulder to gripper and elbow to gripper is calculated and it is 360.36mm, 185.77mm respectively. The masses of links from shoulder to gripper and elbow to grippers are 1.6988 and 0.8908. The density [13] of all bones taken as 1900 kg/m^3 (density of compact bone is 1900 kg/m^3).

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Sr.no	Parts	Density	Mass	Volume
		(Kg/m^3)	Kg	m^3
1	Clavicle	1900	0.1720	$9.099*10^{4}$
2	Humerus	1900	0.8082	$4.253*10^{5}$
3	Fore Arm	1900	0.6350	$3.342*10^{5}$
4	Gripper Part-1	1900	0.0697	$3.670*10^{4}$
5	Gripper Part-2	1900	0.0595	$2.944*10^{4}$
6	Gripper Part-3	1900	0.0663	$3.490*10^{4}$
7	Gripper Part-4	1900	0.0639	$3.367*10^{4}$

Table 2 : Human upper limb model parameters

Software torque analysis of human upper limb model

Simulation of upper limb model is shown in figure [6]. In this figure the shoulder joint is rotated from 0^0 to 30^0 and elbow joint from 0^0 to 60^0. The static toque calculation is shown below.

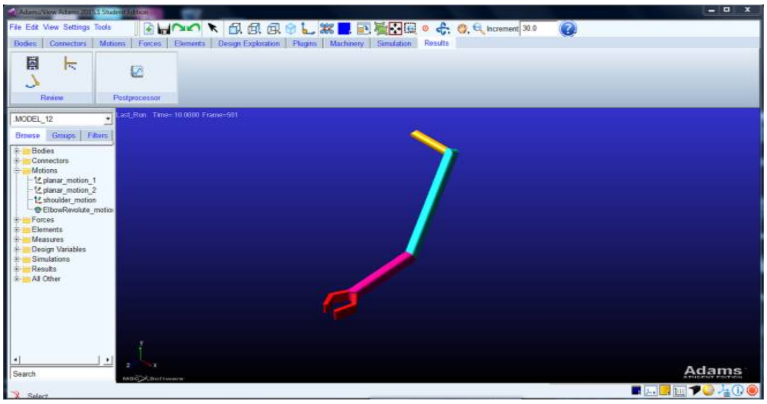

Figure 6: software model of upper limb

Analytical calculation of the torque from 0^o to 30^o at shoulder and 00 to 60^o at elbow is calculated as

Analytically calculated Torque (At shoulder) = sin 30 * 360.36 * 1.6988 * 9.81

Torque = 3792 N-mm

Figure 7: Torque from 0^0 to 30^0 at shoulder

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Fig 7 shows software simulated output torque which is 3801N-mm. The error between analytical calculation and software simulated torque calculation is found to be 0.237%

Analytically calculated Torque (At Elbow) = sin 60 * 185.77 * 0.8908 * 9.81
Torque = 1623 N-mm

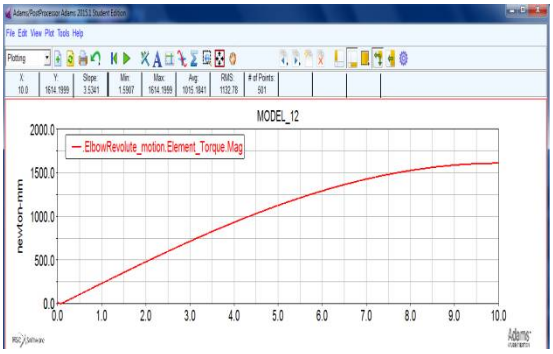

Figure 8: Torque from 0^0 to 60^0 at elbow

Fig 8 shows software simulated output torque which is 1614N-mm. The error between analytical calculation and software simulated torque calculation is found to be 0.557%

III.RESULTS AND DISCUSSIONS

Torque and angles at joints

The arm designed in software is rotated from initial position to various angles. The rotated arm produces torque at joints and it is calculated by software. This torque is also calculated by analytical method as done above. Following table [3] gives the comparison between software simulated torque and analytically calculated torque. Results show closer agreement between analytical and software result and maximum error is only 1 percent.

Sr.no	Revolution	Angle of Rotation	Analytically torque value(N-mm)	Software torque value(N-mm)	Error percentage %
1	Only at Elbow	From 0^0 to 50^0	1238	1225	1.060
2	Only at Elbow	From 0^0 to 120^0	1405	1408	0.216
3	Only at Shoulder	From 0^0 to 70^0	5637	5630	0.124
4	At shoulder and At Elbow at same time	From 0^0 to 30^0 From 0^0 to 60^0	3792 1623	3801 1614	0.237 0.557

Table 3: comparison of analytical and software output torque

Application

The forces at joints can be reviewed and hence can select appropriate bearing. Also Torques acting at the joints can be found and hence an appropriate motor can be used based on the operating speed and torque requirements. All the mass properties, geometries, speed etc changed and their effects can be evaluated as per requirement.

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IV.CONCLUSIONS

Biomechanics of upper limb is combined study of biological properties of limb and mechanical analysis of limb. Biological properties include mass, volume, density of limb whereas mechanical analysis includes kinematical analysis of limb which is study of motion of limb. This paper focus on finding torque requirements using Adams software and validating the results of software through mathematical modelling i.e kinematical analysis. Using this approach one can finalize the selection of appropriate drive and material selection for proper functioning of mechanical or prosthetic hand.

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