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Modeling of Muscle Force at Varied Joint Angles of the Human Arm and Estimation of Gripping Force Using Surface EMG

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Abstract: This paper aims to determine the force required for holding the objects by human hand. A static analysis is performed on mathematical modelsto obtain holding force considering lower arm as class three lever and by varying the joint angles.Three mathematical models are discussed to quantify the force required to hold any object, for different weight of the object and the joint angles.

Anoninvasive experimentation using surface electromyogram was performed to determine the forces required by human hand for the same objects used in the mathematical modeling.Twenty-one male subjects participated in this test and were asked to hold different objects. EMG signals were recorded and converted into grip force in Newton.The EMG to Force conversion was accomplished by the equation derived from the Hills model.

The experimentation revealed that subjects in the age group of 20-50 years generated more grip force as compared to those above the age of fifty years.The values of muscle force obtained from the experimentation are optimum values which depend upon the nature of the gripping habits subjects are used to. Whereas, in the case of mathematical models yielded maximum force required to sustain the weight placed on the hand considering it as a mechanical system.

The study revealed an average gripping force of 85 Newton required to hold the objects weighing between 0.015 kg to 1.18 kg used in the experimentation. The mathematical model resulted in an average of 162 Newton muscle force to hold the object having similar weights.

Keywords: Holding force, grip force, surface EMG, arm biomechanics, muscle strength.

1 Introduction

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Biomechanics principals are used for studying the responses of the human body to the external loads and the stresses induced in the body. In a biomechanical analysis, the body segments are assumed to be rigid links that rotate about joint centers. Static analysis involvesthestudy ofthebody at rest, calculation of composition and resolution of forces, moments and torques such that body remains in static equilibrium[Fariborz and Tayyari. (1997)]. Muscle strength is an ability of a muscle to generate tension, the nerve stimulation triggers the process for the generation of muscular forces for the mechanical work.

Grip or holding strength of the human hand is the force required to grip any object. The human hand is used to grip objects at various positions which require different grips strengths. Gripping action is performed with the fingers and the process involves the participation of flexure and forearm muscles above and below the elbow. It requires adequate muscular force to be generated to hold the object as per desired requirements.

2 Literature Study

Various approaches were developed by researchers to scientifically establish the relation of the muscle activity with the grip strength. Researchers S Shimizu et al. (1997), R Baranski et al. (2014) used a sensor glove to measures grasping force and its distribution in human grasping motion [Shimizu *et al*][Martin-Martin and Cuesta-Vargas. (2014)] and their study revealed the sensitive location was brachioradialis. They found signals from flexor carpi ulnaris and flexor carpi radialis were weaker and stronger signal was produced by flexor digitorum superficialis which is the strongest flexor of the hand [Baranski and Kozupa. (2014)]. L. Claudon et al. (1998) developed a relationship to evaluate the grip force using the EMG of the flexor digitorum superficialis (FDS) and of the extensor digitorium according to the flexion-extension wrist angle and to the pronation-supination forearm angle [Claudon. (1998)]. R. Liu et al (2002) found the value of exerting grip force was between 604 N and 635 N [Roman-Liu and Tokarski.(2002)]. A. Ashour et al. (2014) investigated the relationship between myoelectric activities of wrist flexors-extensors and hand grip strength. Their study supported the idea of a linear and direct relationship between isometric muscle force and RMS EMG signals[Ashour(2014)]. A. Oyong et al. (2010), investigated simulated annealing (SA) to obtain an optimum model that maps EMG into estimated joint torque [Oyong, Parasuraman, Jauw.(2010)]. F Bai et al. (2013) predicted force/torque exerted by the muscles under dynamic muscle contractions based on continuous wavelet transform and artificial neural networks approaches [Bai and Chew. (2013)]. R Tibold et al. (2015), tested the ability of different artificial neural networks to predict EMG activities of arm muscles while human subjects made free movements of the arm or grasped and moved objects of different weights and dimensions [Tibold and Fuglevand.(2015)]. Shahrul NaimSide et al. (2012) explained the relationship between forearm EMG, handgrip force, and wrist angle simultaneously [Sidek and Mohideen, (2012); Ngeo, Tamei, Shibata. (2014)]. There is need to study the effect of joint angles and weight ofanobject on the gripping force considering the weight of the body segments which forms the objective of this research.

3 Methods

To analyze holding and gripping forces we have followed two approaches, first mathematical modeling and second as experimental validation using surface electromyography.

3.1 Mathematical modeling

A human arm is divided into two parts arm and forearm. Muscles are also classified as extrinsic and intrinsic muscles, these perform specific activity. Extrinsic muscles are located in an anterior and posterior compartment of the forearm, they control crude grip and produce forceful grip where as intrinsic muscles present within the hand are responsible for the fine motor function of the hand. The shoulder muscles include the deltoid andpectoralis major, which rotate the shoulder and move the arm toward and away from the center of the body. The muscles of the upper arm include thebiceps and triceps. This information about the muscles is helpful inthemodelingthe muscular system as lever mechanism mathematically.

Any object under the grasping action imposes forces and stresses on the body muscles. The holding of an object is a two-dimensional task. To conduct two-dimensional static analysis information related to the forces acting on the body, their directions, body posture, body segment parameters are required. External forces are usually the weight of the object being held or forces generated due to lifting, lowering push-pull tasks. For postural analysis, external forces might be negligible or zero. The body segment parameters are taken as standard data. Three sets of models are analyzed, neglecting the weight of body segments, considering the weight of body segments atafixed joint angle and withtheweight of the body segment taking various joint angle into account.

3.1.1 Method I: Neglecting the weight of body segments:

Assuming lower arm as a rigid body at a right angle with the upper arm. The body segment weight of lower arm or the weight of lever is neglected. A mathematical model can be developed for the force supplied by the biceps to hold an object having weight 'W_O' kg. It is possible to find the force supplied by the biceps if we sum the torques about the pivot point at the joint. Fig. 1 depicts free body diagram of an arm.

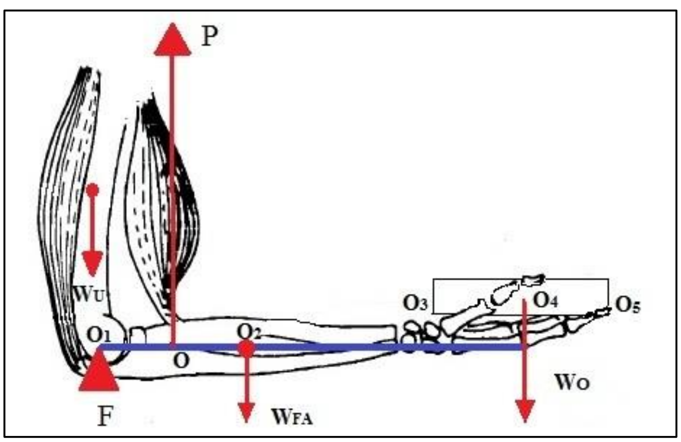

Figure1: Forearm as class III lever

There are two torques acting on the joint due to weight W_O,which is equal to $O_1O_4W_O$ acting clockwise and another one due to the force P produced by muscles which act counterclockwise havingamagnitude of O_1OP, consider bicep insertion at point O.

For the arm to be in equilibrium position ;

$$O_1O\,P - O_1O_4W_O = 0 \tag{1}$$

Equation (3.1) can also be written as ;

$$P = \left(\frac{O_1O_4}{O_1O}\right)W_O \tag{2}$$

Referring anthropometric data [J. L. S. Fariborz Tayyari.(1997)] ;

a) O_1O_5length measured from the elbow to tip ofamiddle finger taken as47.9 cm.

b) O_3O_5length of hand measured from wrist to tip ofthemiddlefingeras 19.7 cm.

c) O_1O length measured from elbow to the point of bicep insertion taken as 5 cm.

The effective length of the lever O_1O_4 is given by the equation ;

$$O_1O_4=O_1O_3+O_3O_4 \tag{3}$$

$$O_1O_4=(O_1O_5 - O_3O_5)+O_3O_4 \tag{4}$$

Substituting the values in equation (4) , we get value of O_1O_4as 38.5 cm.

Substituting the values of O_1O, O_1O_4 in the equation (2),therelation between P and Wo.

$$P = 7.7\, W_O \text{ Kg} \tag{5}$$

Equation (5) establishes muscle force is 7.7 times the weight of the object it needs to hold the object neglecting weight of forearm and the hand. This weight is not uniformly distributed over the whole forearm and hand. This can be broken into small segments and torques of each segment can be found. Method II is an approach considering the weight of the arm. This is a highly simplified model.

3.1.2 Method II: Considering the weight of body segments:

It is assumed that the upper arm and lower arm are mutually perpendicular. The body segment weight of the arm is uniformly distributed as a single element rigid body, i.e. it experiences no bending at any section. Considering, an average weight (W) of the subject participated intheexperiment as 70.5 kg, W_{FA} weight of the forearm considering the center of gravity of the forearm at the point O_2 .The mass fortheupper arm is considered to be 2.8 %, forearm as 1.7 %,and thehand as 0.6 % of body mass,W_{FA} is 1.7% of Wi.e 1.2 Kg. The length ofthelower hand including hand$O_1O_4$is 38.5 cmandthecenter of gravity (CG) of the forearm is at 43.3% ofthelength ofthelower arm from elbow to wrist joint O_1O_3 is 28.2 cm [J. L. S. Fariborz Tayyari.(1997)]. Thus O_1O_2 is calculated as 12.21 cm, length at which effective moment of W_{FA}acts.Summing the torques about the joint we get equations (6) & (7):

$$O_1O.P=O_1O_2W_{LA} +O_1O_4W_O kg \tag{6}$$

$$P= 2.93 + 7.7\, W_O\, kg \tag{7}$$

From the equations (6) and (7) it can be noted muscle force obtained from the method II is greater than the one obtained from themethod I. Comparison of the estimated muscle force for the five objects are tabulated in table 1.

Table 1: Minimum holding force for the objects using two mathematical models

Mass of objects in Kg		Mathematical Model Force N		Methods I & II		
		Method I	Method II	Average % Variation	s^2 Variance	**σ** Standard deviation
Pen	0.015	0.11	3.04	0.04	2.14	
Ball	0.060	0.46	3.39	0.14	2.14	
Disposable Cup	0.212	1.63	4.56	0.36	2.14	***1.46***
Bottle	1.092	8.40	11.33	0.74	2.14	
Book	1.18	9.08	12.01	0.76	2.14	
Average	***0.51***	***3.93***	***6.86***	***0.40***		

3.1.3 Method III. Mathematical modeling to determine force considering various joint angles

Muscle forces are determined using static analysis of human arm, when the upperarm, lower arm, and wrist are at various angular positions. To calculate the holding force the arm must be in the state of equilibrium i.e Thus,$\sum F_x = 0$, $\sum F_y = 0$ *and* $\sum M = 0$.

Moments at each joint at three angular positions were determined for the objects ball, book, bottle, pen and a disposable cup for the joint angles θ_1,θ_2, θ_3 at the wrist, elbow, and shoulder respectively (as depicted in free body diagram in Fig. 2. Segmental hand length is 0.096 m, forearm 0.206 m and upper arm as 0.365 m, the mass of hand as 0.42 kg, forearmas1.2 kg and upper arm as 1.97 kg are taken from standard anthropometric data[Fariborz and Tayyari.(1997)].

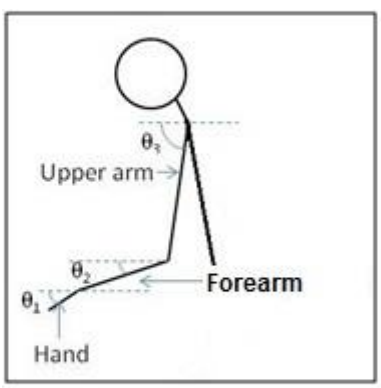

Figure2: Free Body Diagram of the human hand at angular positions

- For the hand Segment

$\mathbf{W_o}$ is the force due to the weight of the object (external load). $\mathbf{W_H}$ is a force due to the weight of the hand, m_H is the mass of hand taken as 0.6% of total body weight.Average body weight is assumed as 70.5 Kg. M_w as the resultant moment at the wrist, $F_{xw}$is the resultant force in the x-direction, F_{yw} is the resultant force in the y-direction, at the wrist to maintain static equilibrium. Fig. 3 depicts free body diagram of hand segment. θ_1 is the angle of the hand relative to the horizontal, SL_1 is segmental length as measured from the wrist to the center of mass of hand taken as 0.096 m and θ_1 fixed at 0^o.

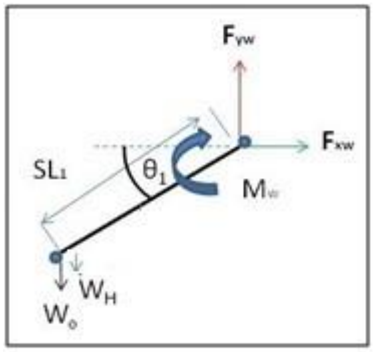

Figure 3: Free body diagram of the hand segment

For static equilibrium;

$$\sum F_x = F_{xw} = 0 \quad (8)$$

$$\sum F_y = F_{yw} - W_o - W_H = 0 \quad (9)$$

$$\sum M_w = M_w - (W_o + W_H).\ SL_1 .\ Cos\ \theta_1 = 0 \quad (10)$$

hence, the moment about wrist due to the weight of hand and object is derived as :

$$M_w = (W_o + W_H)\ SL_1 .\ Cos\ \theta_1 \quad (11)$$

Value of M_w obtained from equation (11) is used in the next section.

- For the forearm segment :

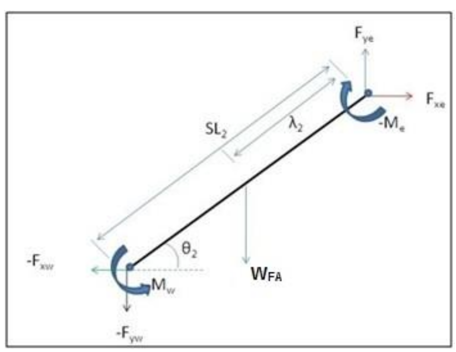

Figure 4: Free body diagram of forearm segment

The forearm segment as depicted in Fig. 4 includes forces at the wrist, that is equal in magnitude and opposite in direction from those obtained for the hand segment.The angle between the forearm relative to horizontal is $\boldsymbol{\theta_2}$, $\mathbf{SL_2}$ measures the length from the wrist to elbow taken as 0.48 m,$\boldsymbol{\lambda_2}$ is the location of center mass from the elbow assumed to be 43% of SL_2 i.e 0.206 m. $\mathbf{M_e}$ resultant moment of the elbow, $\mathbf{F_{xe}}$ resultant force in the **x** and

$\mathbf{F_{ye}}$resultant force in the y-direction at the elbow.$\mathbf{W_{FA}}$ the force due to the weight of the forearm and $\mathbf{M_{FA}}$ mass of forearm which is assumed as 1.6 Kg and weight 16 N[Fariborz and Tayyari.(1997)]. M_w obtained from the previous section.

For static equilibrium at elbow ;

$\sum F_x = - F_{xw} + F_{xe} = 0$ (12)

$\sum F_y = - F_{yw} - W_{FA} + F_{ye} = 0$ (13)

$\sum M_e = M_e - M_w - W_{FA}. \lambda_2.SL_2.Cos\ \theta_2 - F_{yw}.SL_2.Cos\ \theta_2 - F_{xw}.SL_2\ Sin\ \theta_2 = 0$ (14)

as , $F_{xe}=0$ and

$F_{ye} = F_{yw} + W_{FA}$ (15)

$M_e = M_w + W_{FA}. \lambda_2.SL_2.Cos\ \theta_2 + F_{yw} . SL_2.Cos\ \theta_2 + F_{yw}. SL_2\ Sin\ \theta_2$ (16)

Muscle force is given by$F = \frac{M_e}{\lambda_3 Cos\,\theta_2}$ (17)

Substituting the values of λ_2, M_e and θ_2 for the joint angles 0°, 15°, 30°, 45° in the equation (17), the forces, F_{Ball},F_{Book},F_{Bottle},F_{Pen},$F_{Dis.cup}$ due to moment M_e at the elbow were determined and are tabulated in table 2.

Table 2: Muscular force at the elbow at different angles

θ_2	Muscle force for forearm in Newton				
	F_{Pen}	F_{Ball}	$F_{Dis\ Cup}$	F_{Bottle}	F_{Book}
0°	104.56	105.80	109.94	134.12	136.53
15°	108.92	110.20	114.52	139.71	142.22
30°	161.24	163.10	169.37	205.92	209.57
45°	202.32	204.66	212.55	258.55	263.14

- For the upper - arm segment

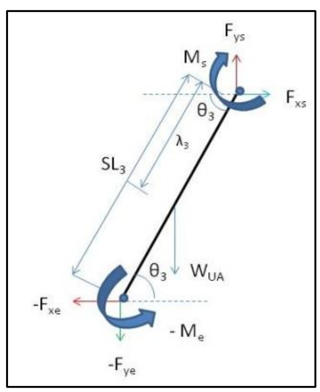

Figure 5: Free body diagram of upper arm segment

From the forearm segment, resultant forces and moment at the elbow are calculated. These are with equal magnitudes and opposite direction for the upper arm segment,θ_3 is the joint angle of the upper arm relative to horizontal, SL_3 measured the length from the elbow to the shoulder taken as 0.365 m. λ_3 location of the center of mass from the shoulder which assumed to be 43.6% of SL_3. M_s resultant moment, F_{xs} resultant force in x-direction,F_{ys} resultant force in y-direction at the shoulder as depicted in the Fig.5. The weight of Upper arm 'm_{UA}' is 2.8% of total body mass i.e 1.974 kg, the force due to the weight of upper arm $\mathbf{W_{UA}}$.For static equilibrium at shoulder joint ;

$$\sum F_x = -F_{xe} + F_{xs} = 0 \tag{18}$$

$$\sum F_y = -F_{ye} - W_{UA} + F_{ys} = 0 \tag{19}$$

As $F_{xe} = 0,\ F_{xs} = 0$

$$\sum M_e = M_s - M_e - W_{UA}.\ \lambda_3.SL_3.Cos\ \theta_3 - F_{ye}\ .\ SL_3.Cos\ \theta_3 - F_{xe}.\ SL_3\ Sin\ \theta_3 = 0. \tag{20}$$

$$M_s = M_e + W_{UA}.\ \lambda_3.SL_3.Cos\ \theta_3 + F_{ye}\ .\ SL_3.Cos\ \theta_3 + F_{xe}.\ SL_3\ Sin\ \theta_3 \tag{21}$$

The motion of the upper arm is taken in clockwise direction starting from 360^o to 315^o.

Substituting the values of θ_3, λ_3,M_s in the equation(22) forces F_{uBall}, $F_{uBook,}$ $F_{uBottle,}$ F_{uPen}, $F_{uDiscup}$ are obtained (tabulated in table 3).

These forces are acting in the perpendicular direction to the upper arm due to the moment at shoulder M_s. Muscle force required is given by ;

$$F = \frac{M_e}{\lambda_3 \text{Cos}\ \theta_3} \tag{22}$$

Table 3: Force due to moment at upper arm at shoulder joint angles

θ_3	Muscle force for upper arm in Newton				
	F_{uPen}	F_{uball}	$F_{uDiscup}$	$F_{uBottle}$	F_{uBook}
360	264.74	267.35	276.12	327.25	332.35
345	268.72	271.38	280.32	332.43	337.63
330	284.78	287.63	297.20	353.04	358.61
315	320.81	324.08	335.07	399.16	405.56

The model is verified experimentally using EMG data.

3.2 Experimental method

3.2.1 Grip/holding force from EMG

Electromyography (EMG) is the method of recording the electrical activity of a muscle, including information about the physiological processes that occur during muscle contraction. It is the visualization of the electrical signals of muscles, the electrical manifestation of the neuromuscular activation associated with a contracting muscle [Fariborz and Tayyari. (1997); Shimizu et al.(1996);Staudenmann,Kingma, Daffertshofer, et al.(2006)]. A mass of muscle consists of many muscle fibers, at rest, each muscle fiber has a charge separation across its covering membrane (outer surface positive with respect to the inside of the fiber) giving rise to a polarized state. The action potentials from a group of muscle fibers organized into functional units are called motor units (MUs) [Jamal.(2012); De Luca et al.(2014)]. Increasing firing rates of motor units increase muscular force [Nawab, Chang, De Luca.(2010)]. When detecting and recording the signal, there are two main issues of concern that influence the fidelity of the signal. The first is the signal to noise ratio, which is the ratio of the energy in the signal to the energy in the noise signal. In general, noise is defined as those electrical signals that are not part of the wanted signal. The other is the distortion of the signal, meaning that the relative contribution of any frequency component in the EMG signal should not be altered [Jamal.(2012); De Luca.(2002);De Luca, Donald Gilmore, Kuznetsov, et al . (2010);Young.(1975)].Using EMG signals it is possible to approximate the values of forces acting on the muscles to achieve desired gripping postures. Predictionof muscle force based on EMG is an important issue in biomechanics and kinesiology. The purpose of this study is to find out actual values of gripping force a healthy human requires while holding objects in daily use.Experimentation using a non-invasive s-EMG sensor on different subjects for holding a book, ball, pen, bottle and a disposable cup filled with water is performed and discussed in coming section.

3.2.2 Muscle Force in concentric contraction of Muscle

Hill (1938) introduced an empirical relationship between the tension and velocity of the muscle movement, for a skeletal muscle bundle fixed at a certain length stimulated and then released to a shorter length. The force-velocity curve for a contracting muscle has the shape of a rectangular hyperbola and Hill derived the relation from this curve as given by equation (23).

$$(v + b)(F + a) = b(F_0 + a) \tag{23}$$

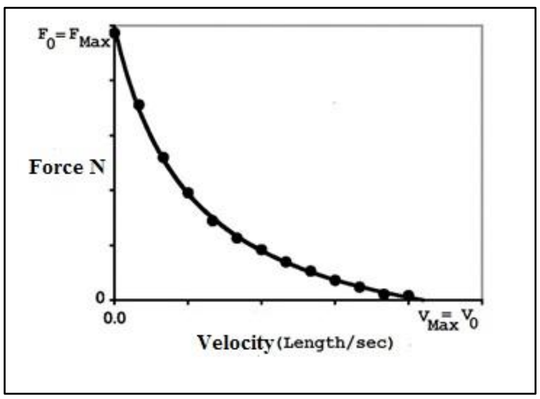

Figure 6: Force-Velocity response for shortening of skeletal muscle[C. D. Kuthe.(2015)]

Where F represents muscle force, *v* the velocity of the muscle contraction, *a* and *b* are constants. The constant F_0 is the maximum force developed in the muscle under anisometric condition at resting length of the muscle. Equation (3.24) represents the maximum isometric force, by using smoothened EMG signal [A. L. Hof and J. Van den Berg.(1981); A. L. Hof.(2015)].

$$F_{max} = F_0 = \begin{cases} Max\ (F_t) \\ F_t = g\ E(t) \end{cases} \tag{24}$$

Where F_t is the muscle force at instant t during static contraction, E (t) is the smoothened EMG at that instant of contraction and *g* is the gain factor of S-EMG.A dimensionless form of Hill's equation is derived using constraints of isometric contraction and maximum velocity of shortening. Therefore, at isometric condition $F=F_0$ for v=0 (refer figure 6).

The smoothened EMG signals were used to compute the force during contraction due to the maximal removal of noise from such signals. RMS (root mean square) EMG signals were calculated from smoothened EMG signals for the every 1-s period of contraction of 60-s. The muscle force was computed from smoothened EMG for all contractions for each subject using equation (25).

$$F_t = g * E(t) \tag{25}$$

The gain factor g for the EMG acquisition machine is specified as 9.09 by the manufacturer of data acquisition system.

3.2.3 Experiment setup and Method

Surface EMG recording setup was used for capturing the data. The setup comprised of :

1) Adata acquisition system from ADI Instruments,Power Lab 2/26 with Transistor-transistor logic (TTL) trigger input, analog inputs and 2 analog outputs (differential mode only). With maximum 100 kS/s sample rate and >95 dB Common Mode Rejection Ratio (CMRR), Interfaced with LabChart data acquisition and analysis software. Shown in Fig. 7a.

2) Trigno wireless base unit capable of streaming data digitally via analog channels for integration with sensors for the capturing EMG signalsthroughdata acquisition system.Shown in Fig 7b.

3) Wireless Trigno EMG sensors only compatible withthewireless base unit.Shown in Fig. 7c.

4) Lab Chart Data acquisition software from AD Instrumentstoacquire biological signals from multiple sources simultaneously.

5) A Computer/ laptop with Windows operating system with Lab chart installed.

Fig7a, 7b, 7c depicts the instruments used in the experimentation.

Figure:7a Power Lab 2/26 (ADI Instruments)

Figure:7b Trigno wireless unit(Delsys)

Figure:7c Trigno EMG sensors(Delsys)

3.2.4 Experimentation procedure

Surface EMG Recordings

Bipolar surface electrodes with contact material of 99.9% silver were placed on the belly of the biceps brachii, at 1/3 length of the line between one end of muscle (the fossa cubit) and other end (medial acromion).

The contact area of electrode bar was 5 mm x 1 mm and the adhesive sticker was used to stick the electrode on muscle. The surface electrodes were positioned exactly by following the recommendations of the Surface Electromyography for the Non-Invasive Assessment of Muscles [Delsys]. The separate reference electrode was not required as it was already enclosed in the housing of the surface electrode as shown in Fig.7c.

The low resistance between the electrodes was obtained by cleaning and lightly abrading the skin. EMG signals were pre-amplified withagain of 9.09 (common mode rejection ratio of 95 dB, baseline noise of 0.5 mV RMS), filtered with a band-pass frequency between 5 Hz and 500 Hz, digitized at a frequency of 1kHz and recorded by Power Lab data acquisition unit (AD Instruments, Australia)[Kuthe.(2015); Delsys; Kuthe, Uddanwadiker, A. Ramteke.(2014)].

3.2.5 Experimentation to compute muscle force from S-EMG

Twenty-onesubjectsvolunteered in the experimentation. After signing the experiment protocol consentthey were asked to sit in the comfortable sitting posture and two non-invasive surface EMG sensors were fixed on biceps and flexor digitorium superficial [Vigneswari, Savithri, Mahendran.(2015)]. The upper arms parallel tothetorso, forearm at a right angle with upper arm without any support to the elbow. The wrist (hand) and forearm maintained zero joint angles. The subjects were asked to hold following five objects in adaptive grasp position ;

1) A tennis ball weighing 0.060 kg.
2) Bottle filled with 1.092 kg water positioned vertically at the center of gravity of bottle.
3) Abook havingtheweight of 1.18 kg in ahorizontal position supported on four fingers onthelowerside and locked by the thumb on the upper side of the book.
4) Apenof 0.015 kg gripped in writing posture.
5) Athin-walled collared plastic disposable cup having a weight of 0.212 kg filled with water. Cup supported at the collar while gripping and all five fingers about the curved surface.

Each object was held for eight seconds and raw EMG signals were recorded for five repetitions. A gap of nearly five minutes was maintained between consecutive repetitions of readings for a particular object and fifteen minutes for a changeover of the objects. This was to ensure elimination of possible fatigue, which may arise during contraction of the muscles throughout experimentation.

3.2.6 Signal Processing of S-EMG

The detected signals were converted into numerical sequences using analog-to-digital conversion. The amplitude of these signals varies continuously throughout their range. The analog-to-digital conversion process generates a sequence of numbers representing the amplitude of the analog signal at a specific point in time. The resulting number sequence is called a digital signal, and the analog signal is said to be sampled [De Luca.(2003)][Rose.(2014)]. S-EMG signals detected with sensors placed on the skin consist of the electrical activity originating from the contracting muscle, EMG signals from active neighboring muscles (crosstalk muscles), baseline noise in the recording system and the skin-electrode interface. Crosstalk signals distort signal and mislead the interpretation of the activation timing and force magnitude of the target muscle. Proper placement techniques for surface EMG Sensors is thus important for good results [Delsys], [De Luca, Kuznetsov, Gilmore, et al.(2011)].It is also concluded that the amplitude of the EMG signal at any instant in time is stochastic or random. Visual inspection of the gross EMG signal showed its amplitude is almost proportional to the force exerted by the underlying muscleandsignaltonoise ratio of three was found to be the minimum required to obtain a reliable motor unit yield [Cao.(2010);Zaheer, Roy, De Luca.(2012)]. EMG data wererecorded in the form oftherawwaveform and further processed for the rectification of the waveform to convert into numerical data for statistical analysis. Muscle force values varied from subject to subject. In addition, a prominent characteristic of windowed RMS is its variability, which makes it inherently difficult to compare signal amplitude across different individuals, different muscles or even across different sessions within the same individual. To compensate the variability of these factors, the windowed RMS signals have to be normalized. The measured force is normalized and expressed as a percentage of MVC. The raw data was filtered at bandpass in the range of 5 to 500 Hz., frequencies below 5 Hz and above 500 Hz are attenuated because low-end cutoff removes the electrical noise associated with wire sway and biological artifacts and high-end cutoff eliminates tissue noise at the electrode site.Thewaveform is further filtered to absolute values using a tool called Arithmetic. It is further smoothed to Triangular (Bartlett) window, to remove unwanted noise created by high-frequency components. Smoothing works in real time during the sampling and on pre-recorded data. Finally, the waveform was filtered at a low pass to allow low frequencies pass and stop high frequencies. Using Lab chart the numeric values for each waveform for every reading in volts is compiled and direct root mean square value is obtained. Fig.8, showsanEMGwaveform of raw, filtered to bandpass, absolute value and finally smoothened for evaluating RMS value.

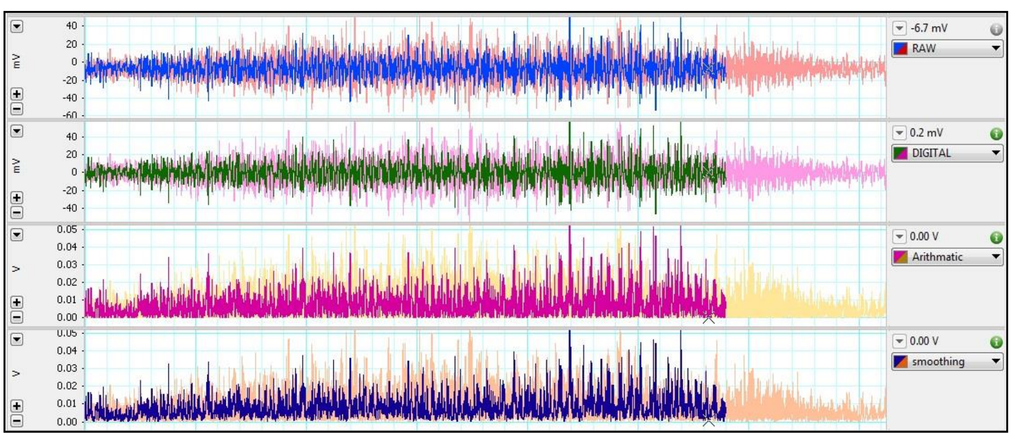

Figure 8:EMG waveform recorded on lab chart

4 Results

4.1 Results from mathematical models

4.1.1 The mathematical model I & II

These two models were derived applying the concept of mechanic principal for static analysis considering human arm as class three lever. In human biomechanics, the muscle forces to hold the object is combined efforts of biceps brachii, triceps brachii, wrist flexors and extensors. Biceps and triceps are the antagonistic pairs of muscles. The lifting of the force is due to the contraction of biceps wherein triceps relaxes after removal of the load.

In the model I the weight of the forearm and the hand was neglected considering forearm as class three lever pivoted at the elbow at one end and weight on the hand at the other end, assuming force is applied a the point of insertion of the biceps brachiis, between the two ends close to the elbow. In the model II, the weight of the forearm and hand are taken into account which results in the increase of force as mentioned in the equation (3.7).

These two models are derived with an assumption that the forearm makes a right angle with the upper arm without any involvement of the upper arm. They demonstrate maximum force required to hold or to grip the object without considering the joint angles. These two models present generalized form to estimate muscle force. A comprehensive solution is derived from Model III. Fig. 9 depicts a comparison between model I & II. The average variation of 40.5% is attributed to the weight of the body segments considered in model II.

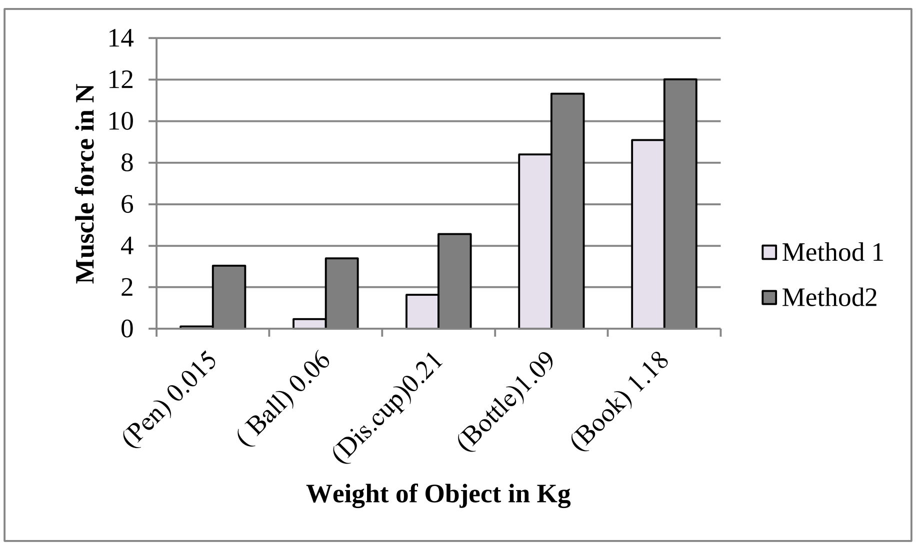

Figure 9: Comparison between Mathematical Model I and II

A comprehensive solution is derived from Model III

4.1.2 The mathematical model III

This model as discussed inthesection is derived considering the mass of the body segments, joint angles at the elbow and the shoulder. The moment of forces is modeled to estimate the muscle force at the elbow. For all the objects, with the increase in elbow joint angle, muscle force increases (Fig 10). These forces are assumed to be perpendicular to the forearm acting at the center of mass.

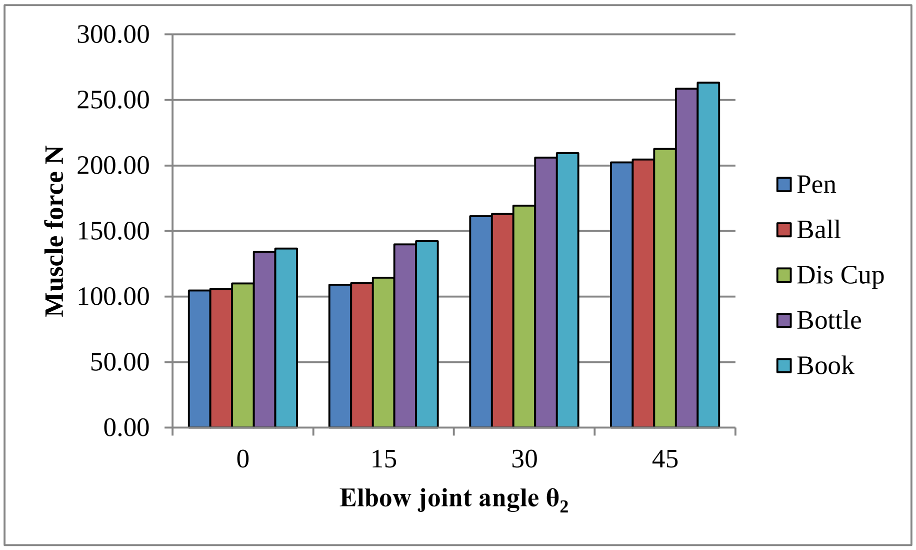

Figure 10: Graph muscle force v/s elbow joint angle θ2

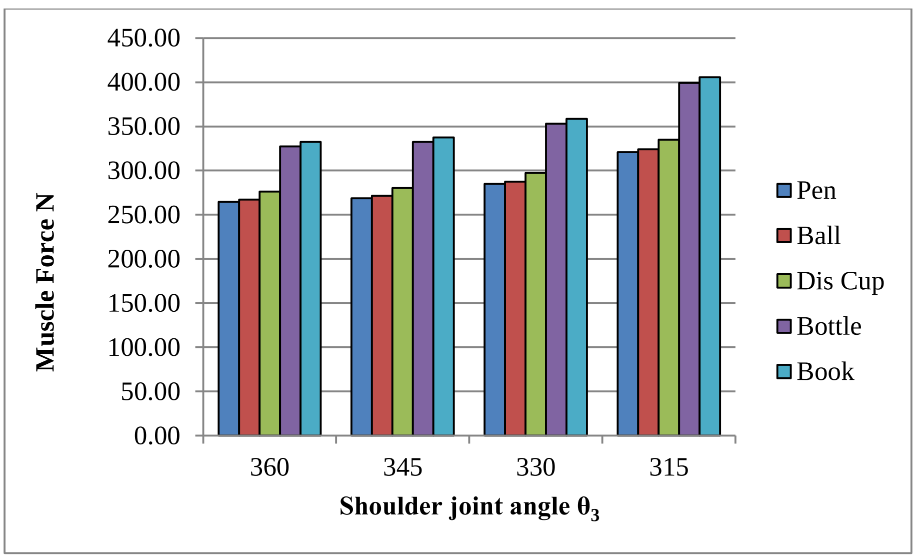

Figure 11: Graph Muscle force in upper arm v/s joint angle θ_3

The Graph in the Fig. 11 shows force required to hold the object when the upper arm is subjected to various shoulder joint angles. It demonstrates less variation in the forces. Effect of elbow joint angle is more significant as compared to shoulder angle.Hence actual values are obtained using EMG Machine.

4.2 Results from experimentation

The root means square EMG values were obtained in volts. Using the relation in equation (4.3), grip force values for various objects were obtained in Newton. The mean values for the force were further calculated for the age groups 21 -30, 31-40, 41-50 and 51-55. The average values of the forces for various age groups for the five objects obtained experimentally arepresented in table 4.Fig. 11 represents a graph plotted between grip force and the objects for the various age groups.The overall average gripping force of 85 N is estimated to hold the objects used in the experiment.

Table 4: Grip force in Newton acquired from S-EMG for five objects

Age	Pen	Ball	Dis.Cup	Bottle	Book
21-30	64	83	74	86	145
31-40	88	115	72	85	129
41-50	81	106	72	82	102
51-55	35	62	65	82	69

5 Discussionand conclusion

The mathematical models are derived considering human arm as rigid mechanical members subjected to moments due to the weight and positioned at certain angles. The forces obtained are maximum values to hold the weight at a particular position. However, in reality the human hand has a complex shape and set of agonistic and antagonistic muscles which control the muscular forces to hold the object.The purpose of the experimentation was to estimate the muscle forces for holding/gripping of objects using Force- EMG relation stated in the equation (3.25). The experimental results obtained are optimal, much accurate than the generalized mathematical models.The experimental data demonstrated subjects of age group 31to 50 years applied more force as compared to the subjects from 21 to 55 years age group to hold a tennis ball.In the case of grasping a book, maximum muscle force is obtained from the subjects of the age group 21 to 30 years and minimal force above fifty years,experimental results the indicates reduction of grip strength with increase in the age. To hold a bottle filled with water,experimental results reveal a proportional variation,while holding a pen for the writing the experimental result shows the larger grip force by 31-50 years age group and least as expected by the senior most age group. To hold a thin-walledplastic disposable cup filled with water, less and controlled grip force was desired.The values of muscle force obtained from the experimentation are optimum values which depend upon the nature of the gripping habits subjects are used to. Fig.12 depicts a graph between the muscle force and the weight of the objects.

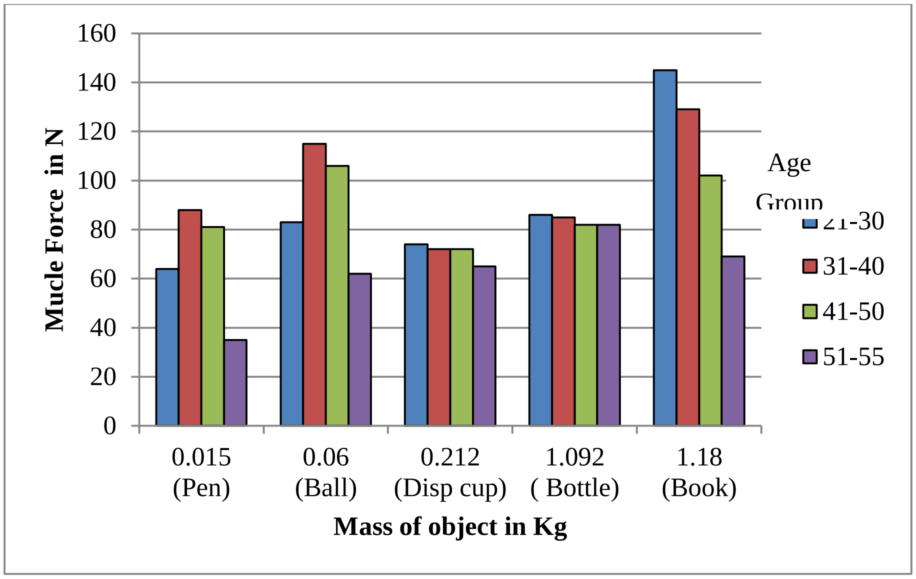

Figure 12: Grip force and weight of objects in various age groups

The outcome of this research paper is useful for various applications necessary for sports, ergonomics and occupational therapy related fields. We intend to use the results of grip force obtained from the experimentation for the calibration of actuators used in our research -development of automated artificial prosthetic hand.

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