

Modeling of Artificial Human Upper Limb

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ABSTRACT

Background & Objective: There is an increasing demand for computer aided instruments in medicine to assist doctors and technicians. This paper presents a simulation of skeletal model of human upper extremity, which monitors position, orientation, trajectory, force and torque generated by upper limb movement.

Materials and Methods: An artificial upper limb model is prepared with servo motors and aluminium T- section which moves in 2D vertical XY plane and whose control is through PC through user friendly software. In first phase: Values of time, power and torque were estimated for each joint after making the robot-model move in flexion and extension with different weights. In second phase: same values were estimated after strapping subjects arm and making the robot-model move in flexion and extension.

Results: Values of Power and Time taken by joints to lift weight at different speeds showed that torque and power are higher for higher flexion angle as well as higher load value. Experimental values for flexion of wrist ($p < 0.05$), elbow ($p < 0.01$), shoulder ($p < 0.05$) with subjects, showed that time taken by elbow was lesser than that taken by wrist and time taken by shoulder was still lesser than elbow for same amount of weight lifted. Results considering force sensor showed that motor torque rises when load is lifted against gravity.

Conclusion: This model could be used as a tool in neuromuscular disorders for enhancing the functionality of robot assisted upper limb therapy and data from model could help the therapist to know about actual resistance force at each joint and quality of exercise trajectory achieved by each subject.

KEY WORDS: Torque; Upper Extremity; Power; Robotics; Anthropomorphic Arm; Simulation

INTRODUCTION

The study of upper limb movement or work performed by upper limb and its motion analysis has attracted the attention of researchers and become an important tool in clinical research. Mechanical analysis of upper limb requires information about kinematics, forces and moments generated at three joints. While dynamics analysis of a rigid body presents no theoretical problem, the analysis of upper limb is a complex task because of its anatomical features. Computer aided instruments are used for assistance to optimize clinical treatment and prosthetic devices. Hence, human modelling simulation has to be realistic i.e. both geometries and movements have to be reproduced precisely.^[1]

At Rehabilitation Institute Michigan, Detroit, a robotic arm was employed which performed five movement patterns with eight points.^[2] In a pilot study, Cozen used the principle of robot assisted active single upper limb exercise.^[3] The Massachusetts Institute of Technology developed the 'MIT manus', a planar manipulator with 3 DOF, for a series of clinical trials and found that manipulator of impaired upper limb influenced recovery.^[4] The assisted Rehabilitation and measurement guide built by the Rehabilitation Institute Chicago, Illinois; had 3 controlled DOF; designed to provide assistive therapy to patients with chronic hemi paresis.^[5] Abdullah et al developed a therapeutic robot for upper limb rehabilitation^[6], whereas Tolbert and colleagues analysed the kinetics of normal and prosthetic wrists for development of artificial wrist joint model.^[7]

Effects of robotic therapy on motor impairment and recovery were shown by Fasoli and Krebs^[8], robotic and mechatronic systems were applied in special education and vocal training by some researchers^[9], whereas some used them for estimation of body segment parameters^[10].

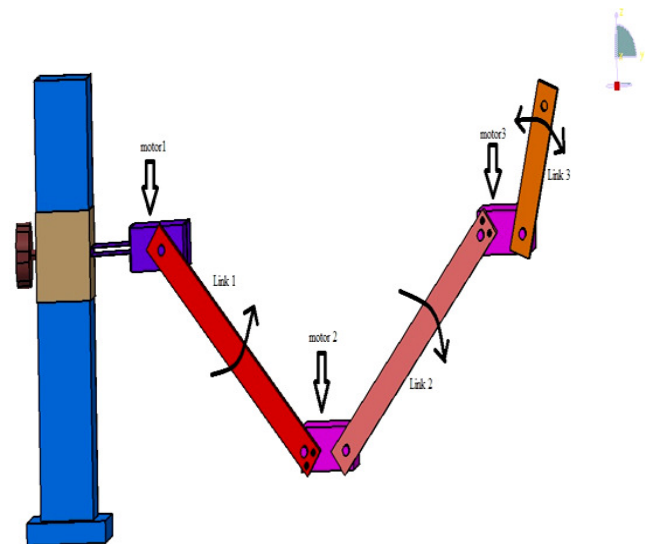
Here, we deal with description of geometrical constraints to mimic the movement of upper limb segments with 2 DOF.^[11] For each joint a set of

equations was deduced and used to simulate relative motion.^[12] An anthropomorphic arm was developed consisting of mechanical limbs powered by servo motors operating in 2-D plane and its analysis was done. Motions supported by the current version of system are shoulder, elbow flexion and wrist flexion-extension.

MATERIALS AND METHODS

Experimental Setup: With three servo motors M1, M2, M3 and three upper limb models of length L1, L2, L3 fabricated from aluminum, fitment components were secured by screws. A clamp to house each motor was fabricated and mounted on a stand with a board support base. The model with revolute joints and links moves in a 2-D vertical X-Y plane. A computer system with the required software and hardware developed is used to support the arm movements and record the readings onto a data logger. The limb motion animation in real time is achieved through biomechanical equations for calculations of torque and power.

Figure-1: Experimental Setup Depicting the Artificial Upper Limb Mounted on Support in Flexed Position



Experimental Procedure: In the first phase study was conducted in three steps. In first step-wrist motor (M3) was clamped and necessary connections made, at the wrist end weights ranging from 20 g and above were suspended. For each weight suspended motor was energized

and wrist was moved with zero reference (straight horizontal position) to maximum based on flexion and extension limiting values.

The model was based on following assumptions:

- Joints of upper limb are frictionless pin joints
- Upper limb segments are rigid with mass concentrated at the centres of the mass
- Air friction is insignificant

Computer software used for this purpose is X-interface for robotic hand simulation – rotation sensor for angle measurement, force sensor, servo motor controller.^[13]

For each reading Torque and Power^[14] is estimated and graphs are plotted.

Torque (N-m) = [Load (g) x (10/100)] x [Arm length (cm) / 100]

Power (W) = [Torque(N-m)] x [Angle(degrees) x (pi/180) x [Time(s)/0.01]

Similarly in second step readings with elbow motor (M2) were taken and in third step readings with shoulder motor (M3) were taken. The servo motor has proportional control and uses error sensing feedback to correct the performance mechanism.

In the second phase, readings for thirty different subjects were taken, arm and forearm of the subjects were strapped with artificial robo-model then readings for all three joints were taken one after the other by moving one joint and fixing the other two.

Finally a set of experiment was also conducted with the developed model using a force sensor mounted on the end of the wrist.^[15] Weight values 10, 20, 30,800 g were taken and readings were recorded for forces acting at all the three joints by connecting a sensor interfaced card to the system which would immediately perceive signals from the force sensor and all the data collected was stored in the data logger at regular intervals. Readings were transferred to the excel sheet and necessary calculations were done for the values of torque and power. The intervals can be defined by the user as per the requirements of the physiotherapy exercises.

Figure-2: Human Upper Limb Fabricated Model in Flexed Position



Figure-3: Human Upper Limb Model with Subject



Figures 2 and 3 show the human upper limb fabricated model in flexed position without subject and the same model in straight position with subject respectively.

RESULTS

Table 1 depicts the values of time taken to lift 200 g of weight by the wrist joint at different speeds and Graph I depicts Torque/Power versus for 800 g of load for wrist joint.

From the table 1 and Figure 4 it is observed that for a particular load value, as the flexion increases the torque and power also increases and time taken to complete the flexion also increases. Power value while lowering is more than that while raising the load, this is due to the addition of gravitation force and the requirement of a resisting reverse torque against the direction of downward motion to make the wrist link move uniformly and not dropping suddenly with an impact.

Table-1: Experimental Values for Power and Time Taken by the Wrist Joint to Lift 200 g wt at Different Speeds

Angle Rotated	Speed 1 (s)	Torque N-m	Power W	Speed 2 (s)	Torque N-m	Power W	Speed 3(s)	Torque W	Power N-m
0 to 10	0.4	0.00830757	0.00362486	0.3	0.008307573	0.00483315	0.2	0.00830757	0.0072
10 to 0	0.3	0.00830757	0.00483315	0.3	0.008307573	0.00483315	0.1	0.00830757	0.0145
0 to 20	0.5	0.01636273	0.01142334	0.4	0.016362725	0.014279171	0.2	0.01636273	0.0286
20 to 0	0.4	0.01636273	0.01427917	0.3	0.016362725	0.019038895	0.1	0.01636273	0.0571
0 to 30	0.7	0.0239207	0.01789264	0.6	0.023920704	0.020874752	0.2	0.0239207	0.0626
30 to 0	0.5	0.0239207	0.0250497	0.4	0.023920704	0.031312128	0.1	0.0239207	0.1252
0 to 40	0.9	0.03075186	0.02385428	0.8	0.030751864	0.026836064	0.4	0.03075186	0.0537
40 to 0	0.8	0.03075186	0.02683606	0.7	0.030751864	0.030669788	0.2	0.03075186	0.1073
0 to 50	1.2	0.03664864	0.02665165	1	0.036648645	0.031981976	0.5	0.03664864	0.064
50 to 0	1.2	0.03664864	0.02665165	0.8	0.036648645	0.03997747	0.3	0.03664864	0.1066
0 to 60	1.4	0.04143187	0.03099097	1.1	0.041431875	0.039443052	0.6	0.04143187	0.0723
60 to 0	1.2	0.04143187	0.03615613	1	0.041431875	0.043387358	0.5	0.04143187	0.0868
0 to 70	1.5	0.04495622	0.03661625	1.3	0.044956218	0.042249524	0.8	0.04495622	0.0687
70 to 0	1.3	0.04495622	0.04224952	1.1	0.044956218	0.049931256	0.7	0.04495622	0.0785

Table-2: Experimental Values of Torque and Power Obtained for Wrist Motor Rotation for Lifting 400 g Load Placed at the End of Wrist

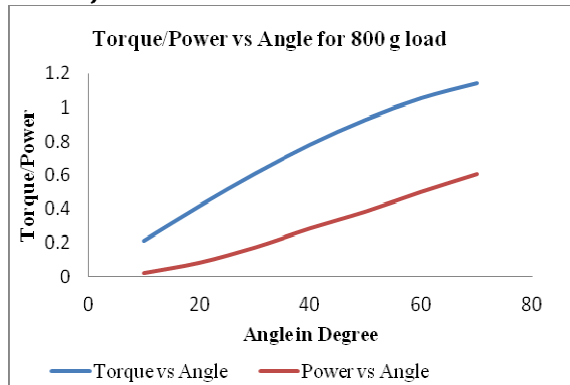
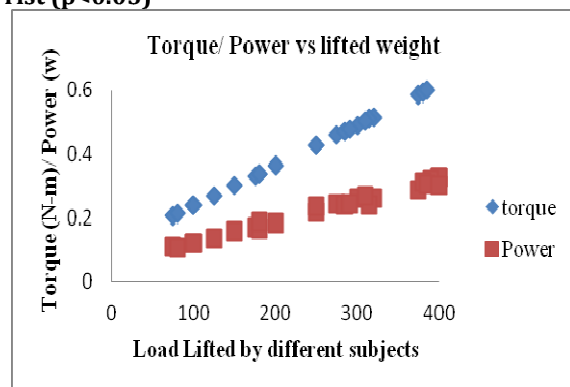
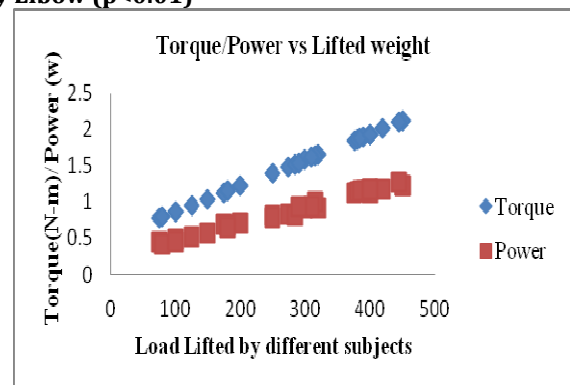
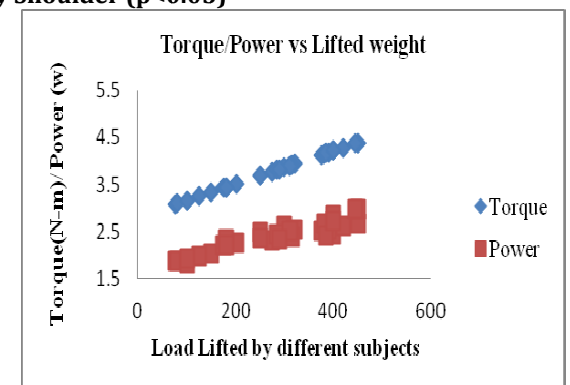
Angle	S 1	Torque	Power	S 2	Torque	Power	S 3	Torque	Power	S 4	Torque	Power	S 5	Torque	Power
0 to 10	1.8	0.54	0.05236	1.7	0.54	0.05544	1.6	0.54	0.058905	1.5	0.54	0.062832	1.4	0.54	0.06732
10 to 0	1.6	0.54	0.058905	1.5	0.54	0.062832	1.4	0.54	0.06732	1.3	0.54	0.072498	1.2	0.54	0.07854
0 to 20	1.9	1.05	0.192905	1.8	1.05	0.203622	1.7	1.05	0.215599	1.5	1.05	0.244346	1.5	1.05	0.244346
20 to 0	1.8	1.05	0.203622	1.7	1.05	0.215599	1.6	1.05	0.229074	1.4	1.05	0.261799	1.4	1.05	0.261799
0 to 30	2	1.54	0.403171	1.9	1.54	0.424391	1.8	1.54	0.447968	1.7	1.54	0.474319	1.6	1.54	0.503964
30 to 0	1.9	1.54	0.424391	1.8	1.54	0.447968	1.7	1.54	0.474319	1.6	1.54	0.503964	1.5	1.54	0.537561
0 to 40	2.1	1.98	0.658238	2	1.98	0.69115	1.9	1.98	0.727527	1.8	1.98	0.767945	1.7	1.98	0.813118
40 to 0	2	1.98	0.69115	1.9	1.98	0.727527	1.8	1.98	0.767945	1.7	1.98	0.813118	1.6	1.98	0.863938
0 to 50	2.2	2.36	0.936131	2.1	2.36	0.980709	2	2.36	1.029744	1.9	2.36	1.083941	1.8	2.36	1.14416
50 to 0	2.1	2.36	0.980709	2	2.36	1.029744	1.9	2.36	1.083941	1.8	2.36	1.14416	1.7	2.36	1.211464
0 to 60	2.3	2.67	1.21566	2.2	2.67	1.270917	2.1	2.67	1.331437	2	2.67	1.398009	1.9	2.67	1.471588
60 to 0	2.2	2.67	1.270917	2.1	2.67	1.331437	2	2.67	1.398009	1.9	2.67	1.471588	1.8	2.67	1.553343
0 to 70	2.4	2.9	1.476258	2.3	2.9	1.540443	2.2	2.9	1.610463	2.1	2.9	1.687152	2	2.9	1.771509
70 to 0	2.3	2.9	1.540443	2.2	2.9	1.610463	2	2.9	1.771509	1.9	2.9	1.864747	1.9	2.9	1.864747

Table-3: Experimental Values of Torque and Power Obtained for Elbow Motor Rotation for 600 g Load Placed at the End of Wrist

Angle	S 1	Torque	Power	S 2	Torque	Power	S 3	Torque	Power	S 4	Torque	Power	S 5	Torque	Power
0 to 10	1.8	0.69	0.066904	1.8	0.69	0.066904	1.7	0.69	0.07084	1.6	0.69	0.075267	1.5	0.69	0.080285
10 to 0	1.7	0.69	0.07084	1.7	0.69	0.07084	1.6	0.69	0.075267	1.5	0.69	0.080285	1.4	0.69	0.08602
0 to 20	2	1.36	0.237365	1.9	1.36	0.249858	1.8	1.36	0.263739	1.7	1.36	0.279253	1.6	1.36	0.296706
20 to 0	1.9	1.36	0.249858	1.8	1.36	0.263739	1.7	1.36	0.279253	1.6	1.36	0.296706	1.5	1.36	0.316486
0 to 30	2.1	1.99	0.496172	2	1.99	0.520981	1.9	1.99	0.548401	1.8	1.99	0.578868	1.7	1.99	0.612919
30 to 0	2	1.99	0.520981	1.9	1.99	0.548401	1.8	1.99	0.578868	1.7	1.99	0.612919	1.6	1.99	0.651226
0 to 40	2.2	2.56	0.812371	2.1	2.56	0.851056	2	2.56	0.893609	1.9	2.56	0.940641	1.8	2.56	0.992898
40 to 0	2.1	2.56	0.851056	2	2.56	0.893609	1.9	2.56	0.940641	1.8	2.56	0.992898	1.7	2.56	1.051304
0 to 50	2.4	3.05	1.109011	2.3	3.05	1.157229	2.2	3.05	1.209831	2	3.05	1.330814	1.9	3.05	1.400856
50 to 0	2.2	3.05	1.209831	2.2	3.05	1.209831	2.1	3.05	1.267441	1.9	3.05	1.400856	1.8	3.05	1.478682
0 to 60	2.5	3.45	1.445133	2.4	3.45	1.505346	2.3	3.45	1.570796	2.2	3.45	1.642196	2	3.45	1.806416
60 to 0	2.3	3.45	1.570796	2.2	3.45	1.642196	2.2	3.45	1.642196	2.1	3.45	1.720396	1.9	3.45	1.90149
0 to 70	2.6	3.74	1.757412	2.5	3.74	1.827709	2.4	3.74	1.903863	2.3	3.74	1.98664	2.2	3.74	2.076942
70 to 0	2.5	3.74	1.827709	2.4	3.74	1.903863	2.3	3.74	1.98664	2.2	3.74	2.076942	2	3.74	2.284636

Table-4: Experimental Values of Torque and Power Obtained for Shoulder Motor Rotation for Lifting 100 g Load Placed at the End of Wrist

Angle	S 1	Torque	Power	S 2	Torque	Power	S 3	Torque	Power	S 4	Torque	Power	S 5	Torque	Power
0 to 10	2	0.86	0.075049	1.9	0.86	0.078999	1.8	0.86	0.083388	1.8	0.86	0.083388	1.9	0.86	0.078999
0 to 20	1.8	1.69	0.327734	2	1.69	0.294961	1.7	1.69	0.347013	1.7	1.69	0.347013	1.9	1.69	0.310485
0 to 30	2.1	2.47	0.615852	2	2.47	0.646644	2	2.47	0.646644	1.9	2.47	0.680678	1.7	2.47	0.760758
0 to 40	2	3.18	1.110029	2	3.18	1.110029	2.3	3.18	0.965243	1.9	3.18	1.168452	1.7	3.18	1.305917
0 to 50	2.5	3.79	1.32296	2.3	3.79	1.438	2.2	3.79	1.503363	2.1	3.79	1.574952	2.2	3.79	1.503363
0 to 60	2.5	4.29	1.796991	2.2	4.29	2.042035	2.2	4.29	2.042035	2.1	4.29	2.139275	2.1	4.29	2.139275
0 to 70	2.4	4.65	2.367103	2.3	4.65	2.47002	2.3	4.65	2.47002	2	4.65	2.840523	2	4.65	2.840523

Figure-4: Torque/Power vs. Angle for 800 g of Load for Wrist Joint**Figure-5: Relation between Torque/Power for Different Values Load Lifted by Different Subjects by Wrist ($p < 0.05$)****Figure-6: Relation between Torque/Power for Different Values of Load Lifted by Different Subjects by Elbow ($p < 0.01$)****Figure-7: Relation between Torque/Power for Different Values of Load Lifted by Different Subjects by Shoulder ($p < 0.05$)**

A set of results was obtained after hands of different subjects were placed on the three links and strapped to the links. Graphs obtained for the same values are shown below. For experimental values of wrist joint flexion with subjects, p is < 0.05 , for values elbow joint flexion with subjects, p is < 0.01 and for values of shoulder joint flexion with subjects, p is < 0.05 .

These results show that during the lowering process while returning from the raised position there is an increase in torque and power values slightly higher than that during raising, this is due to the fact that load is in the direction of the gravitational force downward. The motor has to gather more power to develop more torque so that load and arm doesn't fall off suddenly overcoming the retaining torque produced by the retaining magnetic field of the motor.

DISCUSSION

This robotic technique offers the possibility of assisting simple active upper limb exercises for patients with neurological diseases such as stroke, multiple sclerosis, etc. Here, practical modelling of the human upper limb is achieved with fabricated revolute links and joints, representing the human hand and its characteristic with as much realism as possible. From the experiments conducted on the developed model considering all the steps it was observed that the trend of the relations is similar in all the cases with the values almost same with minimum allowable error. With the help of such a model the limiting values of torque and power required and the correct position for lifting and lowering loads can be predicted. A time base solution can be obtained to predict the energy level requirement in a human being.

This investigation allows one to perform the spatial movement of upper limb in a very realistic way. The results guarantee not only an accurate visualization of movements for computer graphics applications, but they can also give information about the precise positioning of each body segment. All these parameters are very useful to design efficient prosthetic devices,

to plan optimized rehabilitative procedures and to improve surgical computer aided techniques. The presented approach can be extended for the simulation of other physiological joints, those of knee or foot. Factors influencing joint movements such as age, sex, body built, physical exercise, fatigue, handedness, etc. were also taken into consideration.^[16] Hence, the clinician can implement an exercise of greater movement or can change the exercise or reduce its duration. The clinician can also identify the muscle group used by the subject to perform the task with help of the model. This capability would indicate whether a weak muscle has improved or the subject was depending on stronger muscle to perform a particular task.

The system that is prepared here and tested with normal subjects is very basic, it did not offer the full range of movement patterns, nor full options for the therapist in order to select speeds, repetitions and variations; work can still be carried out which can offer more choices to the therapist. Even though this robotic system has many advantages in routine aspects of therapy, an initial testing on patients and further development is still required for this robotic system before being extended to physical trials.

CONCLUSION

This model could be used as a tool in neuromuscular disorders for enhancing the functionality of robot assisted upper limb therapy and data from model could help the therapist to know about actual resistance force at each joint and quality of exercise trajectory achieved by each subject.

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