Design of Upper Limb Exoskeleton for Elbow Motion Assistance

Project work carried out at

Centre for Artificial Intelligence and Robotics, DRDO Bangalore

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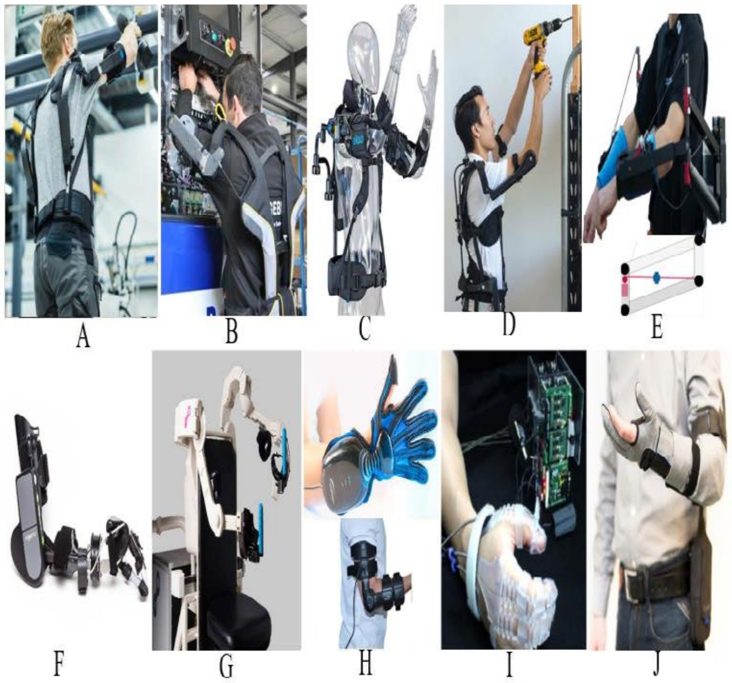
Presentation Roadmap

Active Elbow Orthosis (Ripel et al.)

1 Introduction

- Exoskeleton : External skeleton that supports and protects an animal's body, in contrast to the internal skeleton [Wikipedia].
- wearable Devices : Enable limb movement with greater strength and endurance.
- Commercially Available Upper Limb Exoskeletons

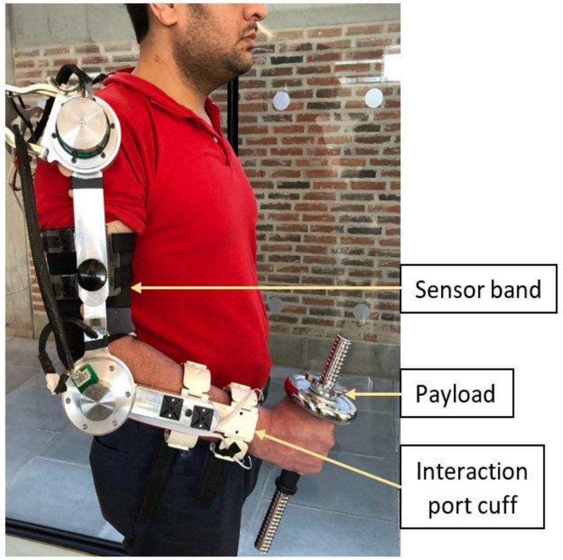
Sr.	Company	Product	Reference
A	Skelex	Exoskeleton	www.skelex.com
B	GOBIO	Ergosquelettes	www.gobio-robot.com
C	Ekso Bionics	EksoVest	www.eksobionics.com/eksoworks
D	SUIT X	MAX	www.suitx.com
E	RoboMate	Parallelogram	www.robo-mate.eu/
F	RB3D	Hercule Exo	www.rb3d.com/en/exoskeletons
G	Kinetek	ALEx Arm	www.wearable-robotics.com/kinetek
H	MediTouch	ArmTutor	meditouch.co.il/products/armtutor/
I	Exo Glove	Exo Glove	www.wevolver.com/wevolver.staff/exo.glove
J	BioServo	Iron hand	www.bioservo.com/professional/ironhand



Commercially Available Exoskeletons

Upper Limb Exoskeleton for Assistance

- Aim
  - Design of upper limb exoskeleton for assistance to elbow motion under varying external loads in the hands.
- Objectives
  - To do the kinematics and dynamics of human hand movements considering single degree of freedom joints in body.
  - To analyze the motion captured data of soldiers carrying different loads in hands with different walking speeds.
  - To select torque actuators for exoskeleton based on required joint torques after inverse dynamics of human motion data in Opensim software



Upper Limb Exo. [Bai et al., 2020]

3 Related Work

Classification of Upper Limb Exoskeletons

❖ Upper Limb Exoskeletons are Electromechanical Systems which are designed to interact with the user for the purpose of

- ❖ Power Amplification,
- ❖ Assistance, or
- ❖ Substitution of Motor Function

Degree of Freedom	• Single Joint Exoskeletons • Multi Joint Exoskeletons
Type of Actuation	• Active (Electric, Hydraulic and Pneumatic) • Passive (Springs, Gravity)
Joints	• Elbow • Hand
Application	• Rehabilitation • Manufacturing / Military

3 Related Work

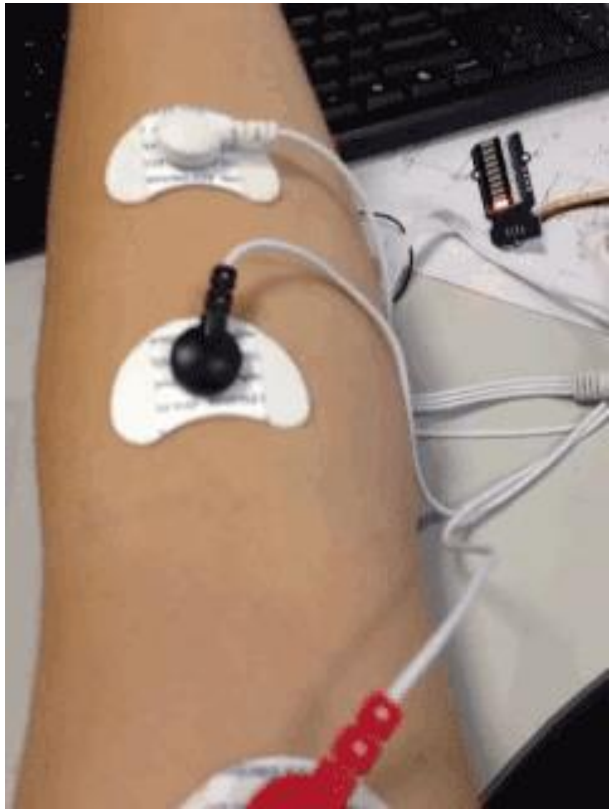
Sr	Exoskeleton	DoF	Actuation Type	Sensors	Control Strategy	Applications	Current Status
1	Elbow Exoskeleton	2	Elastic Actuators, Cables	Gamma torque sensor	Impedance, Torque	Robotic Therapy Applications	Prototype
2	Exosuit	7	Dc Motors, Cable	MyoWare sensors	EMG Based Impedance	Assistance	Prototype
3	Proto-mate	2	Parallel Springs	Surface EMG Sensor	Passive Wearable	Assist Automotive Workers	Developed
4	Mulos	5	Electric Motors, Cable	Encoders	PID Control	Assist to Limb Weakness	Prototype
5	Portable Assist Arm	1	DC Motors	EMG	Brain Computer Interface	Assistance	Lab Prototype
6	Ikerlan's Othosis	5	DC Motors	Torque Sensor	PID Control	Augment Physical Performance	Prototype
7	Ramos Exoskeleton	3	Pneumatic	Surface EMG	Genetic Algorithm	Assist in Lifting of Weights	Developed
8	Active Elbow Ortho	1	DC Servo Motors	Strain Gauge Sensor	Impedance	Power Assistance	Lab Prototype

3.2 Advantages and Disadvantages of Actuation Types

Actuation Type	Advantages	Disadvantages
Electric	High precision for position control High repeatability and smooth functioning Silent operation and easy to program	Expensive price May overheat Large Size and weight
Hydraulic	Large torque Larger power to weight ratio Constant force	Fluid leakage Lots of parts required to operate (pumps, valves)
Pneumatic	Easy to operate and install Low price Light weight and safe operation	Lower efficiency More price due to air compressor Difficult to build complex projects

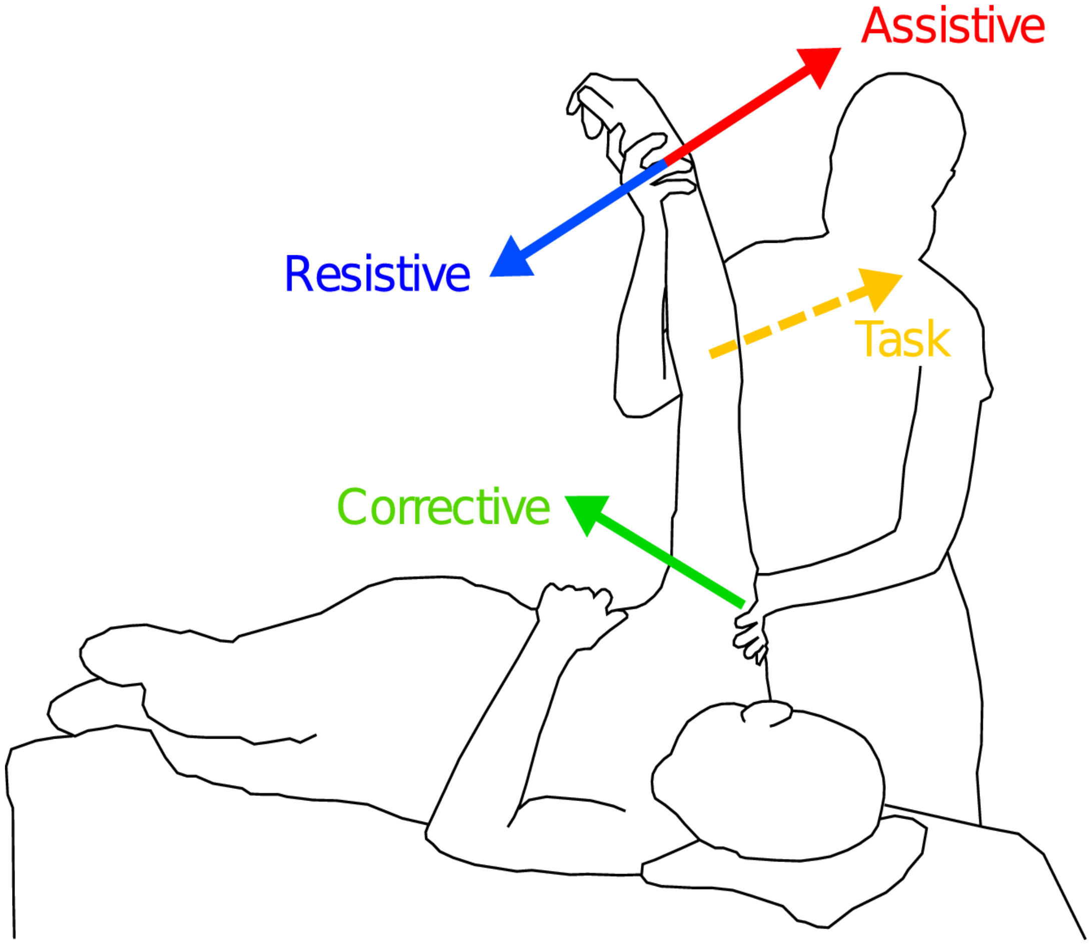
Sensors

- EMG Sensors
  - The Electromyography Sensor (EMG) allows the user to measure the electrical activity of muscles
- IMU Sensors
  - Measures and reports a body's specific force, angular rate, and sometimes the orientation of the body.
  - Consist of Accelerometers, gyroscopes and magnetometers.



EMG Sensor Placed on Hand

3.4 Control strategies used in the recent Exoskeleton Robots



Assistive mode

1. Passive control

   Passive trajectory tracking, Passive mirroring, Passive stretching

2. Triggered passive control
3. Partially assistive control

   Impedance/Admittance control, Attractive force-field, Model-based assistance, Offline adaptive control

Corrective mode

1. Tunneling
2. Coordination control

Resistive mode

no controls developed yet

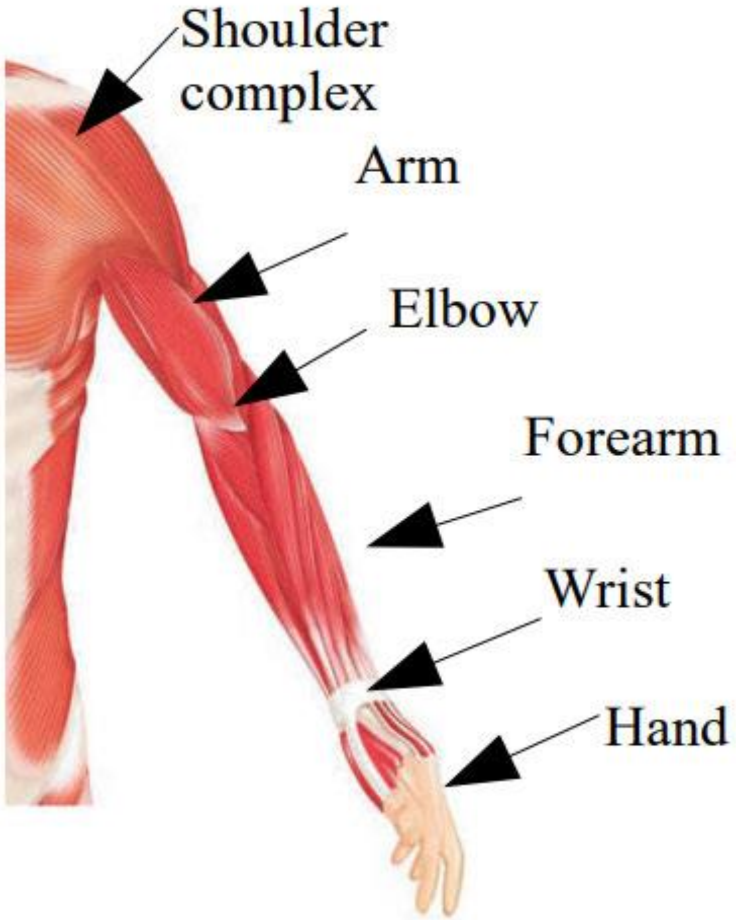
Control strategies used in [Tommaso et al., 2016]

3.5 Biomechanics

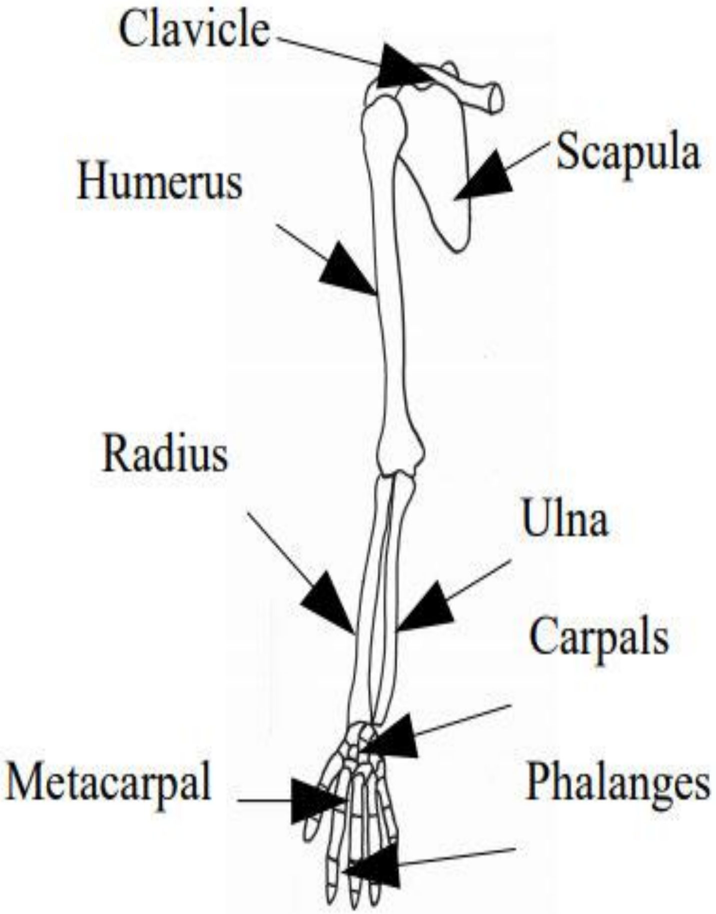
Biomechanics of Upper Limb

- Upper Limb consists of
  - Hand
  - Wrist
  - Forearm
  - Elbow
  - Arm
  - Shoulder Complex

- Bones
  - clavicle,
  - scapula
  - Humerus
  - Ulna
  - Radius



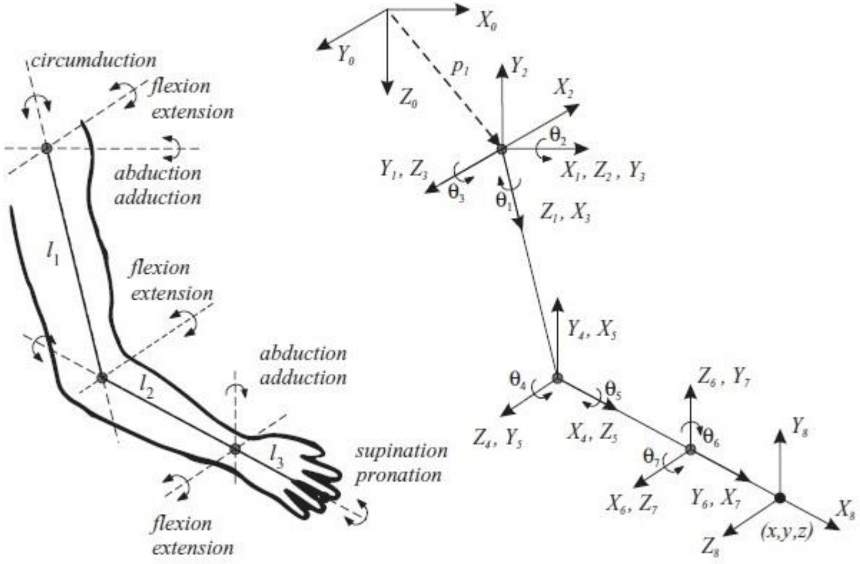
Upper Limb



Bones

DH Notations of Human Hand

- The Denavit Hartenberg (DH) notations of the human hand.
- DH Parameters of Human Hand.
- The greater the number of DOF, the better the assistance, But, complex structure and increase weight.
- So in this project work, we are considering :
  - Shoulder joint with 1 DOF (Flexion Extension).
  - Elbow Joint with 1 DOF (Flexion Extension)



Joint	β_i	Number	α_i	a_i	d_i	θ_i
Base	0	$1_{(0\to1)}$	0	a_0	d_0	0
Shoulder	(−90) medial rotation/lateral rotation (+90)	$2_{(1\to2)}$	-90°	0	0	β_1+90°
Shoulder	(−180) abduction/adduction (+50)	$3_{(2\to3)}$	$+90^\circ$	0	0	β_2+90°
Shoulder	(−180) flexion/extension(+80)	$4_{(3\to4)}$	0	l_1	0	β_3+90°
Elbow	(−10) extension/flexion (+145)	$5_{(4\to5)}$	$+90^\circ$	0	0	β_4+90°
Elbow	(−90) pronation/supination (+90)	$6_{(5\to6)}$	$+90^\circ$	0	l_2	β_5+90°
Wrist	(−90) flexion/extension (+70)	$7_{(6\to7)}$	$+90^\circ$	0	0	β_6+90°
Wrist	(−15) abduction/adduction (+40)	$8_{(7\to8)}$	0	l_3	0	β_7

Wearable Robots: Biomechatronic Exoskeletons, Book by J. Pons, 2009.

4.1 Arm with Exoskeleton Links

Exoskeleton with right upper arm

- Upper limb musculoskeletal model of hand for the biomechanical investigation of elbow flexion movement [Lin-lin Zhang et al.]
- Exoskeleton Links created in Solidworks
  - Length of upper arm : 274 mm
  - Length of forearm : 382 mm
- Exoskeleton attached to the right arm of Human in Opensim software
- Material for Exoskeleton Links can be
  - Aluminum,
  - titanium alloy,
  - carbon fiber

Human Arm with Exoskeleton Links created in Opensim Software

4.3 Dynamics of Exoskeleton

Free Body Diagram with Torque Equation

- The amount of power assist, Assist Ratio (A_r),

  $A_r = T_e / (T_e + T_h)$

  Where,

  T_h = Human joint torque and

  T_e = Exoskeleton joint torque.

  In torque equation,

  θ = Exoskeleton joint angle,

  I_e = Moment of inertia for the exoskeleton

  I_L = Moment of inertia for external load

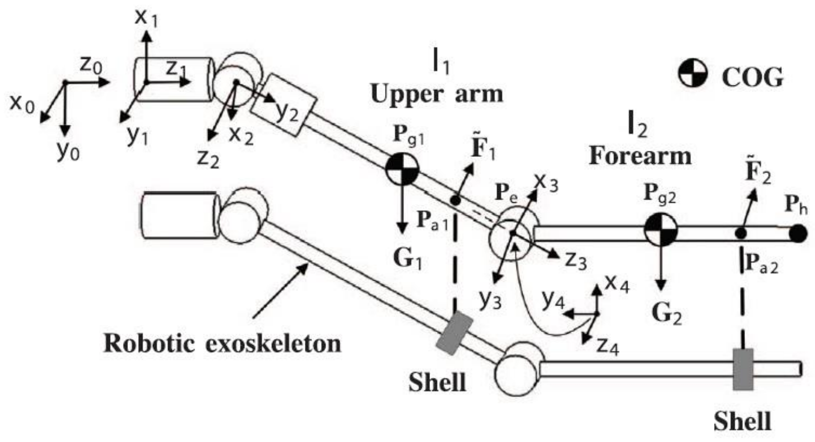
  $C_e(\theta, \dot{\theta})$ = coefficients for friction and coriolis effects

  M_e = Mass of exoskeleton Links

  M_L = Mass of external load

  A_e = Distance of COG from the joint axis for the Exoskeleton link

  A_L = Distance of COG from the joint axis for the external load



Human Arm with Exoskeleton : FBD with DH Notations

Total joint torque, $T_j = T_e + T_h$

$$T_j = [I_e + I_L]\ddot{\theta} + [C_e(\theta, \dot{\theta})]\dot{\theta} + [M_e A_e + M_L A_L]\sin(\theta)$$

Experimental Task

To study biomechanics of human movement,

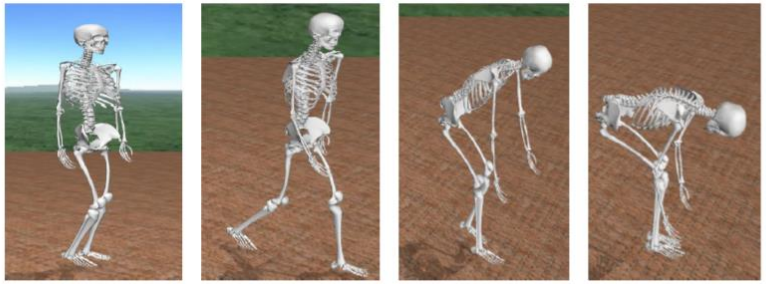
Experimental data captured using Xsense motion capture technology with the help of placing inertial measurement units (IMUs) on the different parts of the body.

The task :

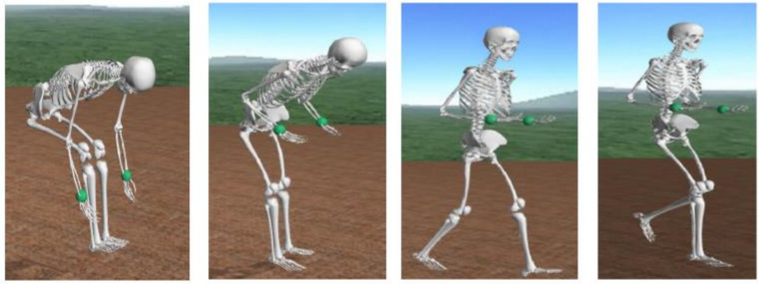
- ❖ Walk for certain distance up to the box for picking,
- ❖ Bend down and pick up the box,
- ❖ Walk with the box and place the box at a specific location.

❖ Experimental tests were conducted for 3 different boxes

- ❖ 17 Kg box,
- ❖ 22.6 Kg box and
- ❖ 29 Kg box



a. Walk for certain distance up to the box and bending for lifting the box



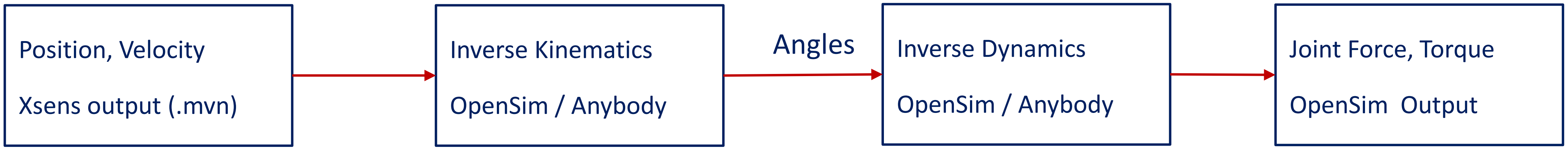
b. Lifting of box and start walking with box in hands

c. Walk with box and place the box at specific position

5.1 Inverse Dynamics of Motion Data

- Inverse dynamics
  - Computing forces
  - Computing moments of force (torques)
  - Based on the kinematics (motion) of a body and the body's inertial properties.
- Software like Anybody Technology and Opensim : Biomechanical analysis.
- The external forces in hands :
  - Equally distributing the external loads in the hands.

    Example, for 17 Kg of load, force in left hand = 8.5*9.81 = 83.385 N.



5.2 Analysis of Experimental Motion Data

Angular Position Range

- Joint range of motion
  - gives the information about the extreme ends of the human joints for a given task.
  - Maximum and minimum values.

Elbow angle of 0 degrees

Elbow angle of 110 degrees

Test		Test 1	Test 2	Test 3	Test 4
Mass	Joint	Angular Position in Degrees			
17 Kg	Shoulder	-3.09 to 78.74	-7.391 to 78.67	-7.91 to 80.13	-8.59 to 80.78
	Elbow	1.38 to 96.25	1.43 to 102.1	-0.23 to 110.58	-0.68 to 111.7
	Lumbar	-47.61 to 4.58	-47.96 to 2.86	-44.69 to 7.85	-41.82 to 10.3
22.6 Kg	Shoulder	-13.21 to 76.5	-11.23 to 78.49	-19.86 to 77.92	-15.47 to 79.8
	Elbow	1.11 to 114.2	0.11 to 123.64	-2.60 to 127.71	-0.05 to 119.8
	Lumbar	-46.41 to 6.53	-47.55 to 5.15	-42.24 to 2.93	-44.25 to 4.99
29 Kg	Shoulder	-25.78 to 76.2	-27.50 to 85.94		
	Elbow	-0.65 to 123.7	0.74 to 119.46		
	Lumbar	-42.27 to 6.02	-43.83 to 3.23		

5.2 Analysis of Experimental Motion Data

Maximum Angular Velocity

- Range of motion, velocity and acceleration are useful in selection of actuators for the exoskeleton body.
- Joint angular velocity
  - Useful in selection of gear ratio for gearing mechanism of the actuator
  - Maximum Values.
  - Fluctuations
  - Maximum while bending for lifting weight.
  - Else, variation -40 to 40 degress per second

Test		Test 1	Test 2	Test 3	Test 4
Mass	Joint	Angular Velocity in Degrees /Second			
17 Kg	Shoulder	157.79	175.90	217.72	197.67
	Elbow	219.44	193.32	222.88	277.31
	Lumbar	92.67	100.61	103.71	86.52
22.6 Kg	Shoulder	178.82	219.90	258.06	227.22
	Elbow	250.44	266.43	319.71	226.32
	Lumbar	100.15	96.82	96.83	92.07
29 Kg	Shoulder	203.97	198.24		
	Elbow	219.44	220.02		
	Lumbar	96.83	95.11		

5.2 Analysis of Experimental Motion Data

Maximum Angular Acceleration

- Range of motion, velocity and acceleration are useful in selection of actuators for the exoskeleton body.
- Joint angular acceleration
  - Maximum Values while bending and lifting of weight.
  - Else, for elbow, fluctuations -300 to 300 degrees per second^2.

Test		Test 1	Test 2	Test 3	Test 4
Mass	Joint	Angular Acceleration in Degrees /Second^2			
17 Kg	Shoulder	1840.91	1428.4	2589.2	1497.7
	Elbow	2704.53	2579.5	1663.9	1787.1
	Lumbar	499.62	497.84	740.83	531.13
22.6 Kg	Shoulder	1303.77	-2360	2997.66	2677.43
	Elbow	2598.36	2516.4	4839.77	1994.46
	Lumbar	647.1	559.78	856.57	791.46
29 Kg	Shoulder	1367.42	3606.77		
	Elbow	2715.87	2361.73		
	Lumbar	794.12	643.43		

5.2 Analysis of Experimental Motion Data

Maximum Joint Reaction Moments

- Joint reaction moment
  - Useful in selecting the actuator torque to be required and
  - sets the minimum limit for joint torque needed.

Test		Test 1	Test 2	Test 3	Test 4
Mass	Joint	Moment in Nm			
17 Kg	Shoulder	26.34	27.90	28.68	27.46
	Elbow	27.86	27.59	27.69	27.78
	Lumbar	80.20	84.27	82.89	76.47
22.6 Kg	Shoulder	36.04	35.71	34.36	34.09
	Elbow	34.76	35.41	34.05	35.42
	Lumbar	80.77	95.49	136.76	132.23
29 Kg	Shoulder	32.36	37.94		
	Elbow	32.83	32.2		
	Lumbar	149.28	185.81		

Specifications of Actuator

The information regarding joint speeds and torque is used.

Assume : input speed or input torque to find the motor's minimum requirements.

The gearing ratio of gearing mechanism of the actuator,

$$Gear\ Ratio = GR = \tau_0 / \tau_i = N_i / N_0 \text{ -------- } (1)$$

The electric power equation for electric rotary actuators is as follows,

$$Power = P = 2\pi\tau_i N_i / 60 = 2\pi\tau_0 N_0 / 60 \text{ -------}(2)$$

Table 5.2 Parameters of Gear Ratio and Power Equation

Sr. No.	Parameter	Description	Unit
1	GR	Gear Ratio	-
2	τ_i	Motor Input Torque	Nm
3	τ_0	Motor Output Torque	Nm
4	N_i	Motor Input Speed	rpm
5	N_0	Motor Output Speed	rpm
6	P	Power	W

5.4 Selection of Actuator

Gear Ratio

- Maximum elbow joint torque and speed are
- $Torque = \tau_0 = 35.42\ Nm$ And
- $Speed = N_0 = 319.71/60 = 5.318\ rpm$
- Therefore, $Gear\ Ratio =$

$$GR = \tau_i N_i = \tau_0 N_0 = (35.42)(5.318) = 188.375$$

Table 4.5 Maximum Joint Parameters

Joint	Angular Velocity	Angular Acceleration	Moment
	Degree / Second	Degree / Second^2	Nm
Shoulder	258.06	3606.77	37.94
Elbow	319.71	4839.77	35.42
Lumbar	103.71	856.57	185.81

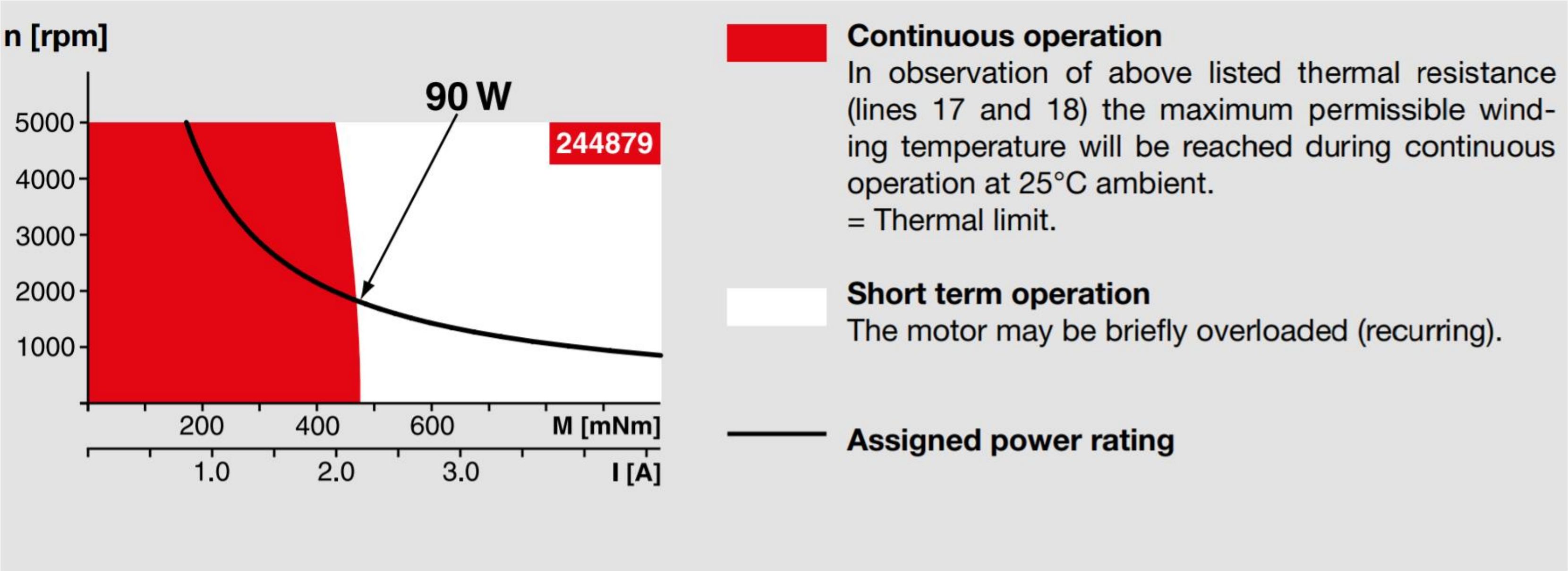
Table 5.3 Requirement of Motor speed and Torques for Elbow Joint

Sr. No.	Motor Input Speed	Motor Input Torque	Gear Ratio
Unit	rpm	Nm	-
1	500	0.37675	94.0146
2	1000	0.188375	188.0292
3	2000	0.0941875	376.0584
4	3000	0.0627916	564.0882
5	4000	0.04709375	752.1168

5.5 Selection of Actuator

Motor Selection for Elbow Joint

- The power requirement, $Power = P = 2\pi(35.42)(5.318)\ 60 = 19.725$ W.
- With factor of safety of 1.5, Power $P' = 1.5(P) = 29.6\ W \approx 30$ W.
- Selected Motor 1 : Maxon EC90 Flat, 90 W with Hall effect sensor , 24V Battery



Operating Range of Maxon EC90 Flat, 90 W Motor

In ADAMS and Opensim

- Do Simulation of Elbow Joint Motion in ADAMS Software.

- Analyze Muscle Forces for elbow flexion in OpenSim Software.

ADAMS :

- The Multibody Dynamics Simulation Solution
- To study the dynamics of moving parts, and how loads and forces are distributed throughout mechanical systems.

OpenSim

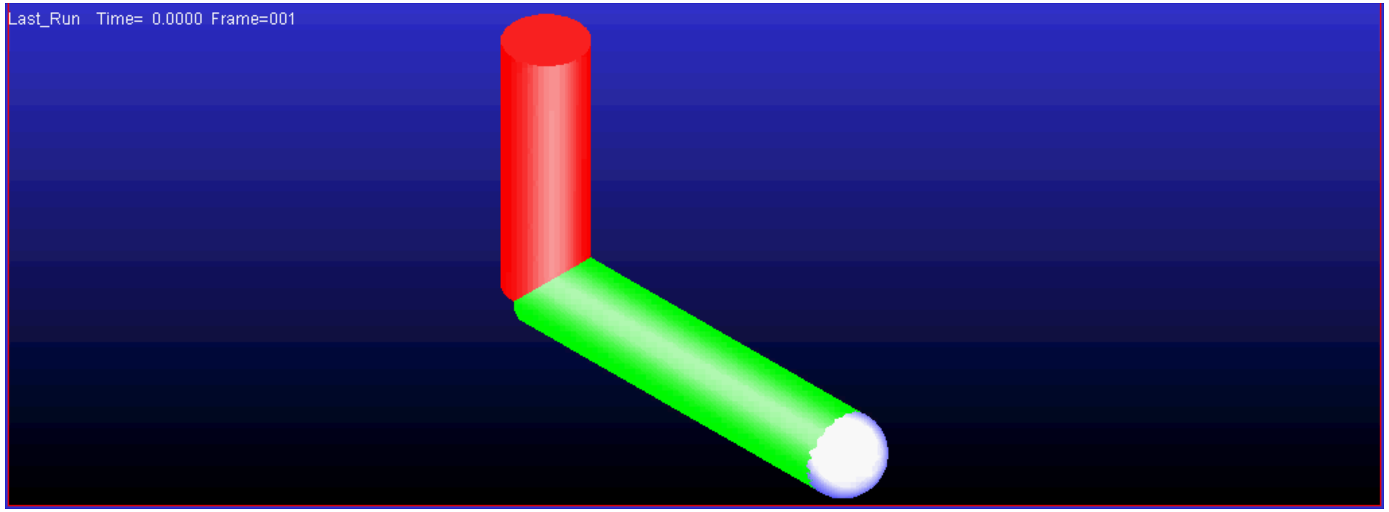
- Freely available
- Develop models of musculoskeletal structures and
- Create dynamic simulations of movements.

6 Results of Simulations

Elbow Torque Estimation

- ❖ Parameters of Human hand for simulation in ADAMS.
- ❖ From research work on upper limb musculoskeletal model of hand for the biomechanical investigation of elbow flexion movement by Lin-lin Zhang et al. in 2011.

Segment	Humerus	Radius_Ulna
Mass (kg)	1.81	1.58
Length (cm)	27.4	38.253
Diameter (cm)	8.330	9.460
Ixx (kg.cm^2)	121.089	194.876
Iyy (kg.cm^2)	121.089	194.876
Izz (kg.cm^2)	15.699	4.418

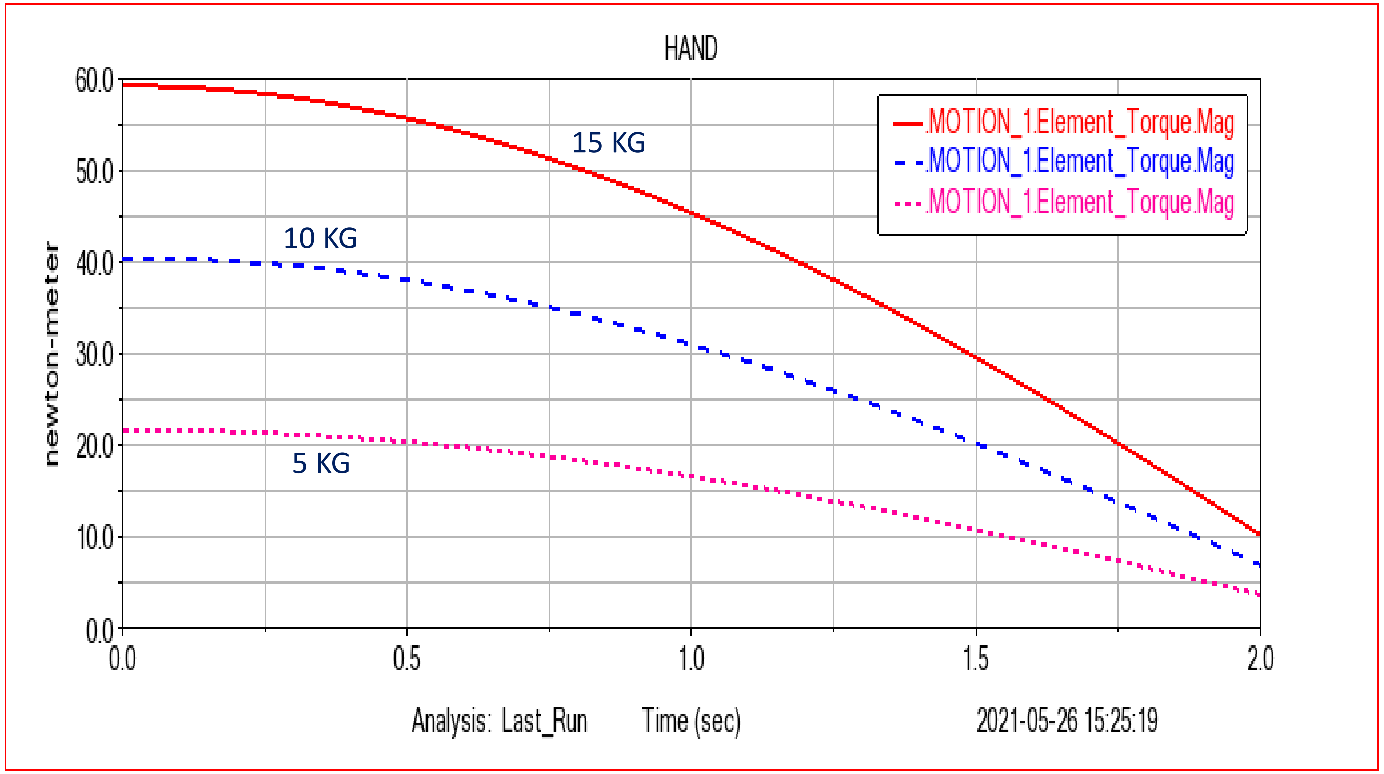


6.1 Elbow Torque Estimation

Simulation Results in ADAMS

- Elbow Joint Torque
- Initially, more torque as starting from rest.
- Simulation in ADAMS with varying External Weight in Hand
  - 5 KG
  - 10 KG
  - 15 KG

Elbow Joint Moment (Nm)



Time (seconds)

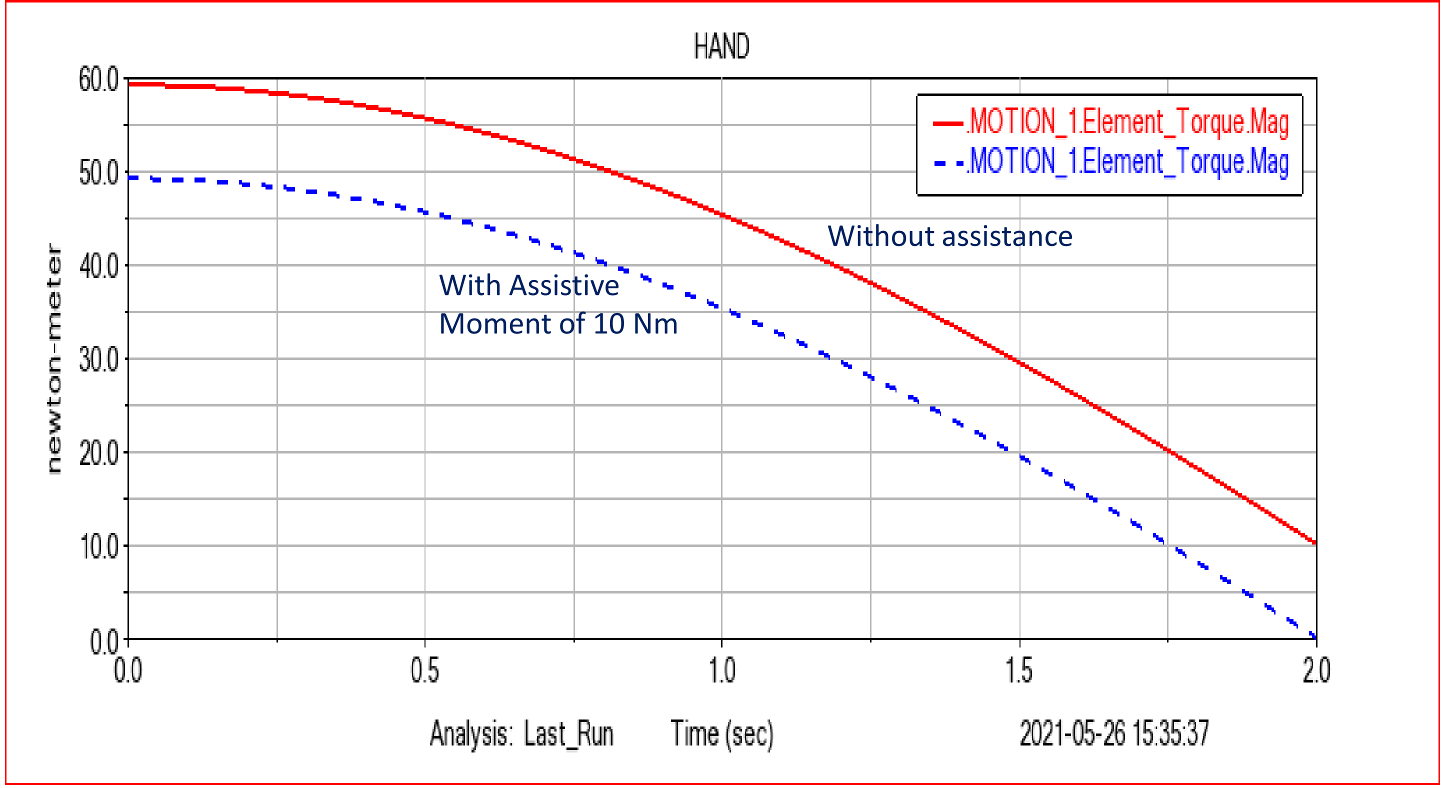
Elbow Flexion Moment Vs Time

6.2 Elbow Torque Estimation

Simulation Results in ADAMS

- Elbow Joint Torque of magnitude 10 Nm is applied to assist the flexion motion.
- Simulation in ADAMS with External Weight in Hand
  - 15 KG
  - Decrease in elbow flexion moment generated in hand

Elbow Joint Moment (Nm)



Time (seconds)

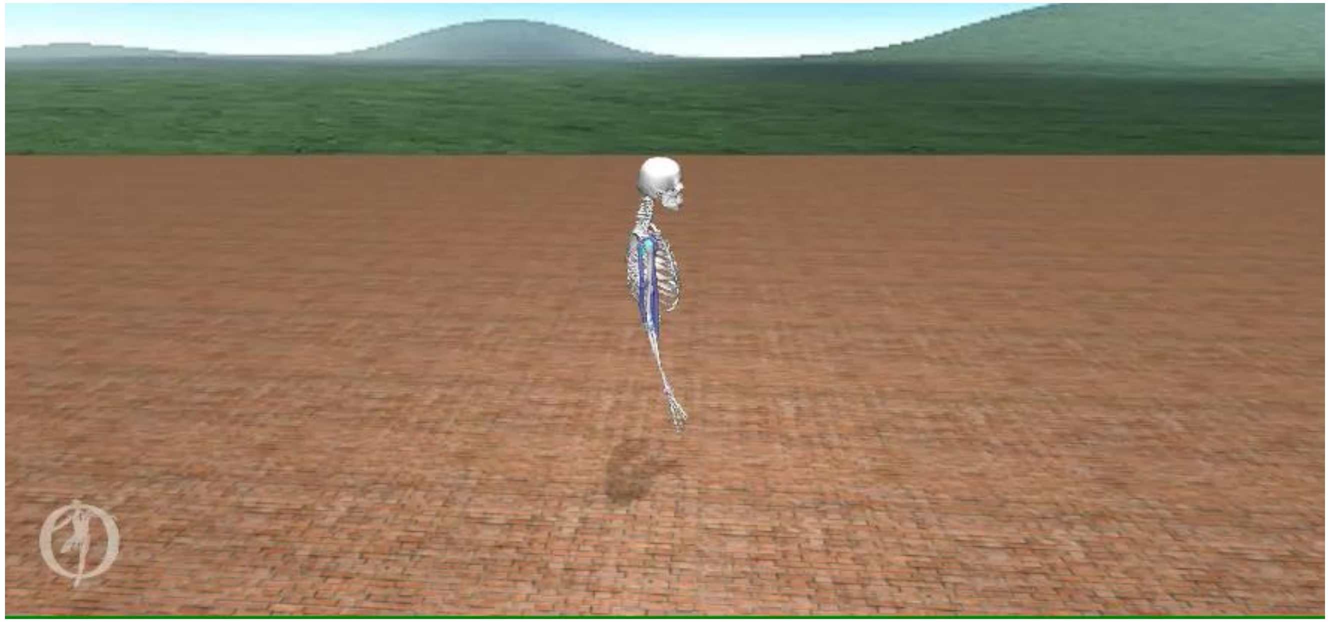
Elbow Flexion Moment with Assistance Vs Time

6.3 Analysis in OpenSim MATLAB API

MATLAB – Opensim Simulation

- Simulation
  - Inverse Kinematics and dynamics of Arm.
  - Elbow Flexion 0 to 130 degrees.

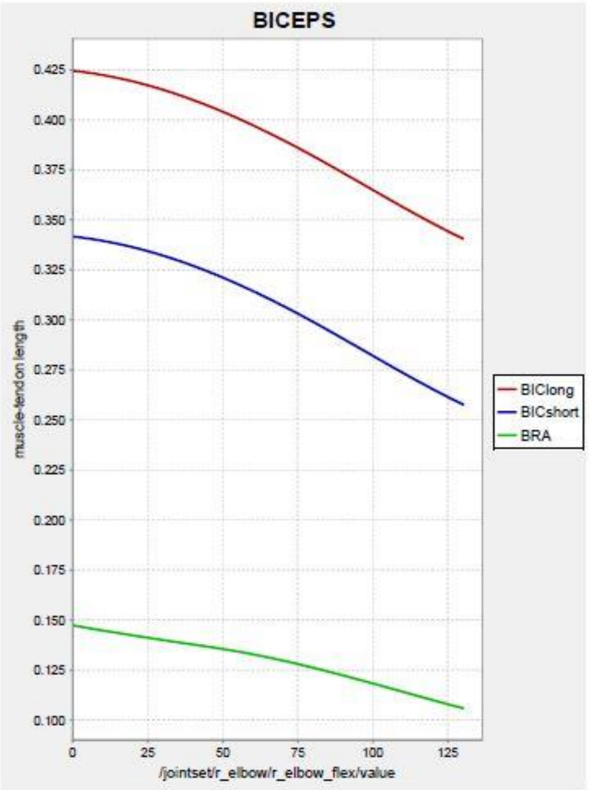
Recorded Simulation :
OpenSim.mp4



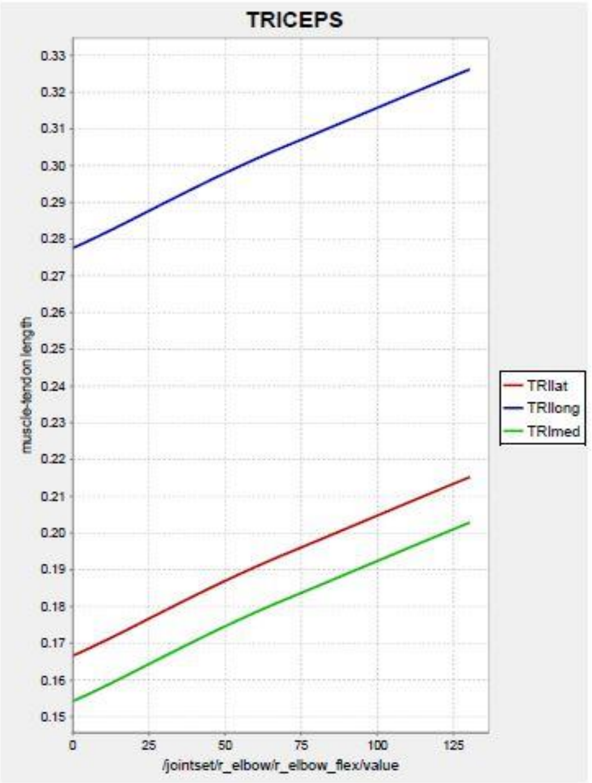
Muscle Tendon Length

- Simulation
  - Inverse Kinematics and dynamics of Arm.
  - Elbow Flexion 0 to 130 degrees.
  - Muscle Fibre Length Vs Elbow Flexion.
  - Triceps Muscles :
    - flexing the arm, extension
  - Biceps Muscles :
    - flexing the arm from relaxed position to full biceps curl, contraction.

Muscle Tendon Length (Metres)



Elbow Flexion Angle (Degrees)



Elbow Flexion Angle (Degrees)

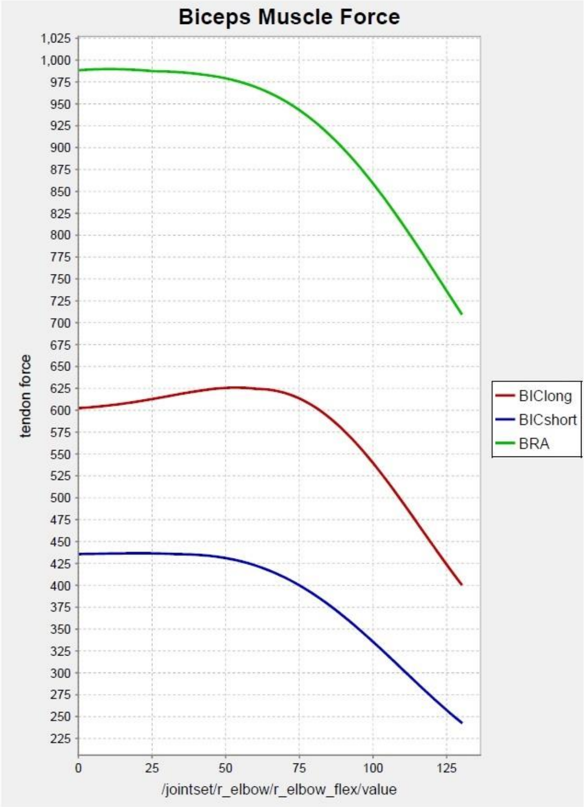
Muscle Fibre Length Vs Elbow Flexion

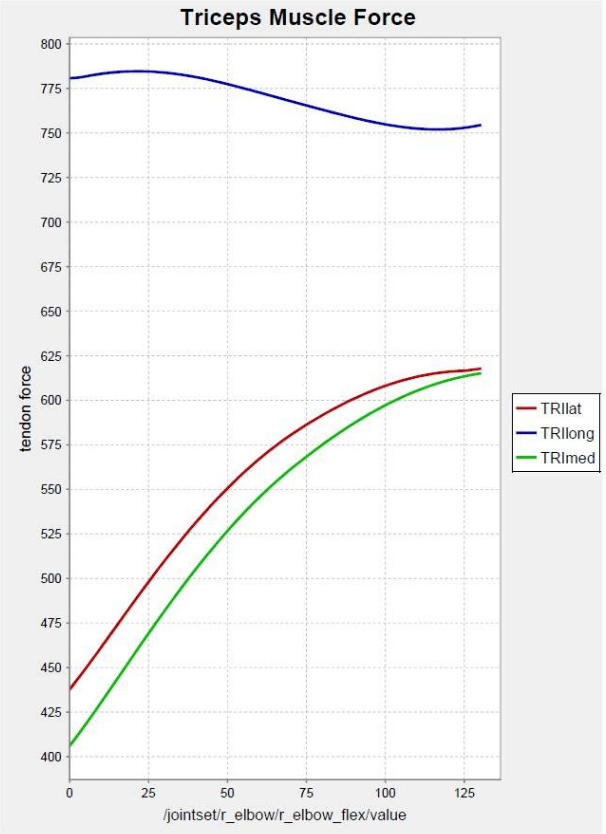
6.5 Analysis in OpenSim

Muscle Tendon Force

- ❖ Simulation
  - ❖ Inverse Kinematics and dynamics of Arm.
  - ❖ Elbow Flexion 0 to 130 degrees.
  - ❖ Muscle Tendon Force Vs Elbow Flexion.

Muscle Tendon Force (N)





Elbow Flexion Angle (Degrees) Elbow Flexion Angle (Degrees)

Muscle Tendon Force Vs Elbow Flexion

7 Conclusion and Future Scope

Conclusions

- ❖ Analysis of experimental motion data
  - ❖ Human carrying different weights and walking with different speeds.
- ❖ Inverse dynamics
  - ❖ Joint reaction moments which are required for actuator selection.
- ❖ Maximum angular velocity and acceleration
  - ❖ Selecting the gearing ratios for gearing mechanisms of actuators for exoskeleton.
- ❖ From the current study's perspective, Motor
  - ❖ Maxon EC90 Flat, 90 W motor and
- ❖ The selected gear ratio
  - ❖ 200, Commercially available for elbow joint actuator in exoskeleton.

7 Conclusion and Future Scope

Future Scope

- Now a days, considerable attention is given
    - To the development of soft exoskeletons
        - advanced textiles making them more user approachable and suitable to be used.

- The soft exoskeletons,
    - Light in weight
    - Ability to wear and interact with clothes, making it less visible
    - Different sizes
    - Do not have constraints on joints due to the non-rigid structure

Learnings Research Paper Status

Earning of Knowledge

- Adams : Mechanical dynamics
- Opensim : Biomechanics
- Matlab : Analysis of Data
- Solidworks : creating models
- Xsens : Real time motion capturing

- Research Paper Status
  - In progress
  - Under the constraints of CAIR, Bangalore

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Thank You

Any Suggestions, Questions…..