Chapter 7
CONTROL SYSTEM

For selection of a suitable actuator, torque determination is carried out through modeling process. Mathematical equations are derived to study the dynamic performance of the system. Thereafter virtual testing has been carried out using MATLAB. Control operation of two link manipulator is performed using Lagrangian model in MATLAB simulink software. The voice controlled commands are opted for controlling operations for the two link manipulator system through a mobile application. The details of the controlling methodologies are presented in this chapter.

7.1. MATHEMATICAL MODELING

Modeling is the process of deriving the mathematical equations for a system to know dynamic performance in all operating conditions. In this work, a prosthetic leg is formed as a physical system which resembles like a two-link manipulator as shown in Figure 7.1. Two-link manipulator is a non-linear system. To model this system, physical laws such as Lagrangian and Newton mechanics are applied. Lagrangian equations are derived from the ‘energy balance’ equations, Newton mechanics equations are derived from ‘force balance’ equations. In this work Lagrangian equation approach is followed to carry out the modeling for two-link manipulator.

Figure: 7.1. Anatomy of Two Link Manipulator
The kinetic energy for the Link 1 with the linear velocity \( \dot{v}_1 = \frac{1}{2} L \dot{\theta}_1 \), angular velocity \( \dot{\theta}_1 \), moment of inertia \( I_1 = \frac{1}{12} m_1 L_1^2 \), and mass \( m_1 \) is

\[
\mathcal{K}_1 = \frac{1}{2} m_1 \dot{v}_1^2 + \frac{1}{2} I_1 \dot{\theta}_1^2 = \frac{1}{8} m_1 L_1^2 \dot{\theta}_1^2 + \frac{1}{24} m_1 L_1^2 \dot{\theta}_1^2 = \frac{1}{6} m_1 L_1^2 \dot{\theta}_1^2 \tag{7.1}
\]

and its potential energy is

\[
P_1 = \frac{1}{6} m_1 g L_1 \sin \theta_1 \tag{7.2}
\]

where \( g \) is the acceleration due to gravity which is negative in Y-axis direction.

The kinetic energy of link 2 with \( \omega_2 = \dot{\theta}_1 + \dot{\theta}_2 \) and \( I_2 = \frac{1}{12} m_2 L_2^2 \) is

\[
\mathcal{K}_2 = \frac{1}{2} m_2 \dot{v}_2^2 + \frac{1}{2} I_2 \omega_2^2 = \frac{1}{2} m_2 \left[ L_2^2 \dot{\theta}_1^2 + \frac{1}{4} L_2^2 (\dot{\theta}_1 + \dot{\theta}_2)^2 + L_1 L_2 C_2 (\dot{\theta}_1^2 + \dot{\theta}_2) \right] + \frac{1}{24} m_2 L_2^2 (\dot{\theta}_1 + \dot{\theta}_2)^2
\]

\[
= \frac{1}{2} m_2 \dot{L}_2^2 \dot{\theta}_1^2 + \frac{1}{6} m_2 \dot{L}_2^2 \dot{\theta}_1^2 + 2 \dot{\theta}_1 \dot{\theta}_2 + \frac{1}{2} m_2 \dot{L}_1 \dot{L}_2 C_2 (\dot{\theta}_1^2 + \dot{\theta}_2) \tag{7.3}
\]

The potential energy of link 2 is

\[
P_2 = m_2 g L_2 S_1 + \frac{1}{2} m_2 g L_2 S_{12} \tag{7.4}
\]

The Lagrangian \( \mathcal{L} = \mathcal{K} - P = \mathcal{K}_1 + \mathcal{K}_2 - P_1 - P_2 \) is obtained from equations 7.1 to 7.4

Rearranging and simplifying, one can write

\[
\mathcal{L} = \frac{1}{2} \left( \frac{1}{3} m_1 + m_2 \right) \dot{L}_1 \dot{\theta}_1^2 + \frac{1}{6} m_2 \dot{L}_2^2 \dot{\theta}_1^2 + \dot{\theta}_1^2 + 2 \dot{\theta}_1 \dot{\theta}_2 + \frac{1}{2} m_2 \dot{L}_1 \dot{L}_2 C_2 (\dot{\theta}_1^2 + \dot{\theta}_2) - \left( \frac{1}{2} m_1 + m_2 \right) g L_1 S_1 - \frac{1}{2} m_2 g L_2 S_{12} \tag{7.5}
\]

The Lagrange-Euler formulation for link 1, gives the torque \( \tau_1 \) for joint 1 as

\[
\tau_1 = \frac{d}{dt} \left( \frac{\partial \mathcal{L}}{\partial \dot{\theta}_1} \right) - \frac{\partial \mathcal{L}}{\partial \theta_1} \tag{7.6}
\]
\[
\tau_1 = \left[ \frac{1}{3} m_1 + m_2 \right] L_1^2 + \frac{1}{3} m_2 L_2^2 + m_2 L_1 L_2 C_2 \right] \dot{\theta}_1 + m_2 \left[ \frac{1}{3} L_2^2 + \frac{1}{2} L_1 L_2 C_2 \right] \dot{\theta}_2 - m_2 L_1 L_2 S_2 \dot{\theta}_1 \dot{\theta}_2 - \frac{1}{2} m_2 L_1 L_2 S_2 \ddot{\theta}_2 + \left( \frac{1}{2} m_1 + m_2 \right) gL_1 C_1 + \frac{1}{2} m_2 gL_2 C_{12} \quad (7.7(a))
\]

Similarly, for joint 2, gives the torque \( \tau_2 \) as
\[
\tau_2 = m_2 \left[ \frac{1}{3} L_2^2 + \frac{1}{2} L_1 L_2 C_2 \right] \ddot{\theta}_1 + \frac{1}{3} m_2 L_2^2 \ddot{\theta}_2 + \frac{1}{2} m_2 L_1 L_2 S_2 \ddot{\theta}_1^2 + \frac{1}{2} m_2 gL_2 C_{12} \quad (7.7(b))
\]

Equations (7.7(a)) and (7.7(b)) are the EOM (dynamic model) of the 2-link planar manipulator. Both the joints are revolute. The generalized torques \( \tau_1 \) and \( \tau_2 \) represent the actual joint torques.

Equations (7.7(a)) and (7.7(b)) are written in compact form as
\[
\tau_1 = M_{11} \ddot{\theta}_1 + M_{12} \ddot{\theta}_2 + H_1 + G_1 \quad (7.8)
\]
\[
\tau_2 = M_{21} \ddot{\theta}_1 + M_{22} \ddot{\theta}_2 + H_2 + G_2 \quad (7.9)
\]

where the effective inertia (\( M_{11} \) and \( M_{22} \)), effective coupling inertia (\( M_{12} \) and \( M_{21} \)), and the centrifugal and coriolis acceleration forces (\( H_1 \),\( H_2 \),\( G_1 \) and \( G_2 \)) are
\[
M_{11} = \left[ \frac{1}{3} m_1 + m_2 \right] L_1^2 + \frac{1}{3} m_2 L_2^2 + m_2 L_1 L_2 C_2 \right]
\]
\[
M_{12} = M_{21} = m_2 \left[ \frac{1}{3} L_2^2 + \frac{1}{2} L_1 L_2 C_2 \right]
\]
\[
M_{22} = \frac{1}{3} m_2 L_2^2
\]
\[
H_1 = -m_2 L_1 L_2 S_2 \dot{\theta}_1 \ddot{\theta}_2 - \frac{1}{2} m_2 L_1 L_2 S_2 \dot{\theta}_1^2
\]
\[
H_2 = \frac{1}{2} m_2 L_1 L_2 S_2 \dot{\theta}_1^2
\]
\[
G_1 = \left[ \left( \frac{1}{3} m_1 + m_2 \right) L_1 C_1 + \frac{1}{2} m_2 L_2 C_{12} \right] g
\]
\[
G_2 = \frac{1}{2} m_2 L_2 C_{12} g
\]
From the anthropometry analysis, the parameters required to test the system are \( m_1, m_2, L_1, L_2 \) and number of legs conducting experiments on a group of people in the age of 20-25 having an average height of 5 to 6 feet. Table 7.1 gives the parametric values.

<table>
<thead>
<tr>
<th>Age Group (Years)</th>
<th>( m_1 )</th>
<th>( m_2 )</th>
<th>( L_1 )</th>
<th>( L_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 – 25</td>
<td>3.62 Kg</td>
<td>3.46 Kg</td>
<td>0.577 m</td>
<td>0.312 m</td>
</tr>
</tbody>
</table>

Using the parametric values in Table 7.1, the effective inertia, the effective coupling inertia, centrifugal and coriolis acceleration forces are evaluated using MATLAB/Simulink tool.

\[
M_{11} = 10 + 6C_2, \quad M_{12} = M_{21} = 2 + 2C_2 \quad \& \quad M_{22} = 2
\]

\[
H_1 = -6S_2DT_1DT_2 - 3S_2DT_2^2DT_1 \quad \& \quad H_2 = 3S_2DT_1DT_1
\]

\[
G_1 = 2gC_{12} + 9gC_1 \quad \& \quad G_2 = 3gC_{12}
\]

The torque equations are modeled using MATLAB / Simulink software to test the performance of the system with the above parameters. The network or sequence of operations can be inferred from Figure 7.2 and Figure 7.3.

Figure: 7.2. MATLAB / Simulink based two link manipulator
Figure 7.2 shows the MATLAB / Simulink model for the two-link manipulator having Hip Angle ($\theta_1$) & Knee Angle ($\theta_2$) as inputs and torque produced at each link as an output.

7.1.1. Acquisition of Hip and Knee Angles

Experiments on healthy persons in the age group of 20 to 30 with an average height of 5ft to 6 ft have been performed to acquire the knee and hip angles.

Figure 7.4. Angle Measurements at Hip and Knee joints with embedding Arduino
For the measured hip and knee joint angles (θ₁ and θ₂) shown in Figure 7.5(a) & 7.5(b) and are used for torque analysis for the subjects considered. The results are shown in Figure 7.6.

Figure: 7.5(a). Hip Angle measured data for different persons using MPU6050

Figure: 7.5(b). Hip & Knee Angle measured data for different persons using MPU6050
Figure: 7.6. Velocity, Acceleration and Torques Generated by Two Link Manipulator
7.1.2. Actuator Selection

From the generated torques in Figure 7.6, for different persons in the age group of 20 to 25 show a maximum torque of “150 N-m” and a minimum torque of “100N-m” at Hip and a maximum torque of “50 N-m” and a minimum torque of “20 N-m” at Knee.

For an effected people, prosthetic leg can manage a maximum walking speed of 2 Kmph. The maximum and minimum torques will be 15-20% that of a healthy person.

For an allowable maximum speed of 1000 rpm, gear train ratio of 50% (20 rpm) and for maximum torque as a starting torque, \( P = \frac{2\pi N \tau}{60} \)

At Hip

Max Torque T = 100 N-m (40% allowance for effected people)
Speed of the motor = N = 100 Rpm (Reduced to the Hip with a Gear Ratio of 50:1)
Power Rating of the Motor = 1.1 KW
Power Rating in HP = 1100/736 = 1.5 Hp

At Knee

Max Torque T = 30 N-m (40% allowance for effected people)
Speed of the motor = N = 100 Rpm (Reduced to the Hip with a Gear Ratio of 50:1)
Power Rating of the Motor = 0.35 KW
Power Rating in HP = 350/736 = 0.4 Hp

To control the Prosthetic leg under abnormal conditions, a sophisticated control strategy is required[40]. For the two-link manipulator, many control strategies (viz., P, PD, PI, PID and artificial intelligent controllers) have been applied [41].

As the two-link manipulator is a MIMO system, two dedicated controllers are essential, whose selection is based on minimum size and cost effective with acceptable accuracy as illustrated in Figure 7.7. PI controllers are named for its accuracy in trajectory tracking applications.

![Figure 7.7. PI Controller](image)

Figure: 7.7. PI Controller
7.2. TORQUE EVALUATION IN GAIT CYCLE

Intense research has been carried out to find out the voluntary muscle strength in every moving physical component of the human being.[42] Strength has been expressed in multiple ways including finding the maximum weight to be lifted and finding torques related to corresponding angle. These values help in determining whether the person has a sound physical component or not. While such values provide valid quantitative estimates of strength, it cannot be fully expressed by any single value. Maximum voluntary joint torque changes substantially with change in the joint angle. The effort has been to generate a mathematical model of a leg and determine the torque of the hip joint and the knee joint. The model has been validated for the torque produced by a sound human leg as shown in Figure 7.8[43].

Figure: 7.8. The line diagram representation of the human leg

Lagrange-Euler formulation enables to obtain a dynamic model of any n-DOF chain link manipulator. It establishes a relation between joint positions, velocities, accelerations and the generalized torque applied at the joints. It makes use of the transformation matrices.

According to Lagrange-Euler equation the dynamic model of a 2-DOF system and 2-link equation can be written in the form

\[
\begin{bmatrix}
\tau_1 \\
\tau_2
\end{bmatrix} = \begin{bmatrix}
m_1 l_1^2 \left( \frac{5}{3} + C_2 \right) & m_1 l_1^2 \left( \frac{1}{3} + \frac{1}{2} C_2 \right) \\
m_2 l_2^2 \left( \frac{1}{3} + \frac{1}{2} C_2 \right) & \frac{1}{3} m_2 l_2^2
\end{bmatrix} \begin{bmatrix}
\theta_1'' \\
\theta_2''
\end{bmatrix} + m \begin{bmatrix}
-m_1 l_1^2 S_2 \theta_1' \theta_2' - \frac{1}{2} m_1 l_1^2 S_2 \theta_2'^2 \\
\frac{1}{2} m_2 l_2^2 S_2 \theta_1'^2
\end{bmatrix}
\]

\[+ \begin{bmatrix}
\frac{1}{2} m_1 g l_1 C_{12} + \frac{3}{2} m_1 g l_1 C_1 \\
\frac{1}{2} m_2 g l_2 C_{12}
\end{bmatrix} - - - (7.10)\]
Where,

\[ m_1 = \text{mass of the link 1}, \quad m_2 = \text{mass of the link 2}, \]
\[ l_1 = \text{length of the link 1}, \quad l_2 = \text{length of the link 2} \]
\[ \theta_1 = \text{angular displacement of the first link with respect to sagittal plane} \]
\[ \theta_2 = \text{angular displacement of the second link with respect to the first link} \]
\[ \theta_{12} = \theta_2 + \theta_1, \quad s_1 = \sin \theta_1, \quad s_2 = \sin \theta_2, \quad s_{12} = \sin \theta_{12}, \quad c_1 = \cos \theta_1, \quad c_2 = \cos \theta_2 \text{ and } c_{12} = \cos \theta_{12} \]

The matrix equation 7.10 has been incorporated into a MATLAB Simulink model. The model has been designed in such a way that the input will be the time instance from the start of the gait cycle. This will provide a range of torques produced by the hip joint and the knee joint with respect to the angles which are subtended at different postures of the gait cycle.

The length of the upper link (thigh) is: \( l_1 = 0.33349 \text{H} \).

The length of the lower link (shank) is: \( l_2 = 0.324 \text{H} \).

Here ‘H’ is the height of the person in meters.

Mass of link \( m_1 \) and link2 \( m_2 \) determined for a six ft height healthy person are: \( m_1 = 10.5 \text{ kg} \) and \( m_2 = 6.18 \text{kg} \)

The joint angles have been recorded and noted for an entire gait cycle which ends within 1 second. Table 7.2 provides the angular readings in radians with GAIT time.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.61</td>
<td>-0.09</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>0.52</td>
<td>-0.17</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>0.3</td>
<td>-0.25</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>0.26</td>
<td>-0.17</td>
</tr>
<tr>
<td>5</td>
<td>0.4</td>
<td>-0.23</td>
<td>-0.001</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>-0.24</td>
<td>-0.17</td>
</tr>
<tr>
<td>7</td>
<td>0.6</td>
<td>-0.22</td>
<td>-0.21</td>
</tr>
<tr>
<td>8</td>
<td>0.7</td>
<td>0.17</td>
<td>-0.50</td>
</tr>
<tr>
<td>9</td>
<td>0.8</td>
<td>0.51</td>
<td>-0.93</td>
</tr>
<tr>
<td>10</td>
<td>0.9</td>
<td>0.54</td>
<td>-0.79</td>
</tr>
<tr>
<td>11</td>
<td>1.0</td>
<td>0.59</td>
<td>-0.27</td>
</tr>
</tbody>
</table>

The relation of time and angle in radians has been developed using the MAT lab command “cftool” through Curve fitting concept for both knee and hip angles.
The relationship between the hip angle (radians) and the time has been given as:

$$\theta(t) = 22.58t^4 + 44.56t^3 - 24.14t^2 + 2.166t + 0.5682$$  \hspace{1cm} (7.11)

The relationship between the knee angle (radians) and time has been given as:

$$\theta(t) = 27.64t^4 - 50.66t^3 + 27.34t^2 - 4.563t + 0.04563$$  \hspace{1cm} (7.12)

Figures 7.9 to 7.12 shows the curves generated from equation 7.11 and 7.12 along with measured data.
The two relations (7.11) and (7.12) have been incorporated in the MATLAB Simulink model to find $\theta''$, $\theta'$ and $\theta$ components in the Lagrange-Euler equation.

The Lagrange-Euler equation has been used in a Simulink model providing the input for the time from the start of the gait cycle. The joint has been established as a function of time to determine the angular displacement, angular velocity and acceleration for the torque evaluation. Figures 7.13 to 7.24 show the matrix of the Lagrange-Euler in the Simulink model.
Figure: 7.13. Matlab Simulink Modelling for the Hip and Knee Joint Torques

Figure: 7.14. Representation of the Acceleration Components of First Matrix
Figure: 7.15. Representation of Acceleration Components of first matrix (first row, first element)

Figure: 7.16. Representation of Acceleration Components of first matrix (first row, second element)
Figure: 7.17. Representation of Acceleration Components of first matrix (second row, first element)

Figure: 7.18. Representation of Acceleration Components of first matrix (second row, second element)
Figure: 7.19. Representation of the velocity components of second matrix (Matrix 2)

Figure: 7.20. Representation of the velocity components of second matrix (first row element)
Figure 7.21. Representation of the velocity components of second matrix (second row element)

Figure 7.22. Representation of the components of third matrix (Matrix 3)
Figure: 7.23. Representation of Angular Displacement components of third matrix (first element)

Figure: 7.24. Representation of Angular Displacement components of third matrix (second element)
The range of torques generated during different postures of the leg for the entire gait cycle has been determined for both knee joint and hip joint. Figure 7.25 and 7.26 show the variation of torque with time at hip and knee joint.

![Figure 7.25. Torque generated at the hip joint](image1)

Table 7.3 gives the torque values at selected points of the Gait cycle. It is noted that the range of torque at the hip joint is 300 to 350 N-m, whereas it is 40-50N-m at knee joint.

![Figure 7.26. Torque generated at the knee joint](image2)
Table: 7.3. Torques for selected points of the Gait Cycle.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Time of GAIT (in Sec)</th>
<th>Angle of Hip (in Radians)</th>
<th>Angle of Knee (in Radians)</th>
<th>Torque at Hip Joint (in N-m)</th>
<th>Torque at Knee Joint (in N-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.61</td>
<td>-0.09</td>
<td>83.87</td>
<td>1.758</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>0.52</td>
<td>-0.17</td>
<td>7.373</td>
<td>36.91</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>0.3</td>
<td>-0.25</td>
<td>57.11</td>
<td>1.757</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>0.26</td>
<td>-0.17</td>
<td>143.8</td>
<td>6.681</td>
</tr>
<tr>
<td>5</td>
<td>0.4</td>
<td>-0.23</td>
<td>-0.001</td>
<td>156.9</td>
<td>77.84</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>-0.24</td>
<td>-0.17</td>
<td>251.5</td>
<td>33.22</td>
</tr>
<tr>
<td>7</td>
<td>0.6</td>
<td>-0.22</td>
<td>-0.21</td>
<td>212.7</td>
<td>20.44</td>
</tr>
<tr>
<td>8</td>
<td>0.7</td>
<td>0.17</td>
<td>-0.50</td>
<td>122.2</td>
<td>2.937</td>
</tr>
<tr>
<td>9</td>
<td>0.8</td>
<td>0.51</td>
<td>-0.93</td>
<td>33.32</td>
<td>.3325</td>
</tr>
<tr>
<td>10</td>
<td>0.9</td>
<td>0.54</td>
<td>-0.79</td>
<td>34.3</td>
<td>8.215</td>
</tr>
<tr>
<td>11</td>
<td>1.0</td>
<td>0.59</td>
<td>-0.27</td>
<td>172.2</td>
<td>44.64</td>
</tr>
</tbody>
</table>

The torque produced at the joints is determined for the time input with respect to the gait cycle. Changing the mass and length input for the thigh and the shank portion, it is possible to determine the amount of torque required for the motion of the leg of any human. The torques generated gives an idea about the soundness of the leg.

7.3. **OPERATION MECHANISMS**

Prosthetics could be active or passive. This study emphasizes on active prosthetic through speed control, which could be a wireless as it involves blue tooth for signal processing.

Commands delivered are converted from speech to word format using speech recognizer. The actuation parameters are calculated from gait analysis. Voice control contributes to trouble free handling of the prosthetic leg by reducing the effort made by the individual. In addition to this, it also manages emergency situations in a risk free and efficient manner.

Figure 7.27 show the flow chart illustrating the determination of angular displacements, mass and length of the joints, torque and angular velocity to estimate the RPM of the motor.

Torque and RPM are required for selection of a motor. Different cases are employed based on the angular displacements with the sagittal plane. The obtained Power gives the voltage value required for the movement of the links under various circumstances.
Angular displacements $\theta_1, \theta_2$ values are obtained with the help of the sensors.

Lengths and mass of the corresponding links are assessed in SolidWorks virtual interface.

Torques $t_1, t_2$ are calculated with the torque determination equation.

Angular Velocity $\omega$ is computed using natural frequency of the system, with which required RPM for the motor is determined.

Power $P$ is evaluated using the obtained torque and RPM values through which corresponding voltage is calculated for the process.

MatLAB virtual domain is created to decrease the complexity of solving the numericals.

Figure: 7.27. Flow Chart for selection of Motor

Torque and RPM are required for selection of a motor. Different cases are employed based on the angular displacements with the sagittal plane. The obtained Power gives the voltage value required for the movement of the links under various circumstances.
The Bluetooth hardware shown in Figure 7.28 is HC-05. It is a serial port protocol (SPP) type with an inbuilt antenna to cover a range of 30 feet, with +4 dBm radio transmission, working at 2.4GHz. It comprises of 8MB flash memory and 26 MHz crystal clock.

The main back bone for data transmission in a HC05 is EN (enable), VCC (voltage), GND (ground), TXD (transmitter), RXD (receiver), STATE pins.

EN (enable) Pin: EN (enable) pin should be made high such that the device starts working to the corresponding commands.

VCC (Voltage): The input voltage to the Bluetooth device is given a supply voltage of 5V DC through this pin, by which the Bluetooth device gets on.

GND (Ground): The Ground (GND) is the pin which will be connected to the negative ends of the connections, i.e., 0V to the device.

TXD: TXD (Transmitter) transmits the serial data from HC05 blue tooth device to Aurdino serial Receive.

RXD: RXD (Receiver) pins receive the serial data from the Aurdino serial transmit.

State Pin: State Pin gives the info whether the device is connected or not.

In the present work the arduino used is UNO type, which comprises of ATmega328 microcontroller, 14 digital I/O pins, LED indicators for data transmission, receiving and also arduino power intimation as depicted in Figure 7.29.
MOTOR:

DC motor compatible for actuating with 1000 rpm and 30N-m torque is used for end effect to cause movement. When the Dc Motor is given the supply, the armature of the motor starts rotating. The current carrying conductor which is placed in the armature also experiences the magnetic lines of force or magnetic flux that is generated through the magnetic field which is generated around the armature coil of the motor. This in turns rotates the shaft which is connected as the output of the device.

The flow chart in Figure 7.30 show the sequence of execution of the setup.

Figure: 7.30. Flow Chart for Motor Control
The Electromyography (EMG) signals can control the prosthetic system through input responses from the muscle system to actuate the prosthetic system[21][44]. They are used for calculation of signal pattern library from different parts of human body, [45] [46] [47][48]. EMG method of controlling a prosthetic leg is costly and hence it is not opted as control strategy in the controlling process of prosthetic leg. Figures 7.31 and 7.32 show the EMG setup on human body.

Figure: 7.31. Electrodes placed on the muscles and with a comparison to the prototype

Figure: 7.32. EMGs analysis during cycling, jogging and standing
An app is specifically designed and developed to establish the connection between the end effect setup and user voice signal interpretation. The smart device with the app is paired with the Bluetooth available in the end effect setup. The commands for actuation are given to the app with mic in speech format. Speech collected is sent to google speech recognizer to convert into word format and sent to receiving Bluetooth. This app also facilitates to confirm the user connection established between the smart device and Bluetooth, through a toast message. Sequential progress of the app interface in the smart device can be observed from the screen as shown in Figure 7.33 to Figure 7.36.

Figure: 7.33. App Open Screen
Figure: 7.34. Bluetooth Selection Screen

Figure: 7.34. Bluetooth Connection Screen
Figure: 7.36. Voice Message Screen
Front end to back end process has been illustrated in the flow chart shown in Figure 7.37.

The input data and pre-fed logics are checked for analogy. The satisfied set of conditions are coordinated for sending the signal to the actuator and finally in accordance with the commands given by the user for the end effect actuation. The physical setup and equipment can be inferred from Figure 7.38.
7.4. SUMMARY

In this chapter, various methodologies viz., Lagrangian method and energy equation are used to determine the torques. Simulation studies have been made using MATLAB/ Simulink. Operating mechanisms viz., Bluetooth, Controlling App, EMG method have been selected and implemented in the prosthetic leg. Finally, the designed and fabricated prototype of the prosthetic leg is successfully tested for use.