CHAPTER 5

OPTIMISATION OF LIFTING POSTURE

5.1 INTRODUCTION

Ergonomic approach to the Manual Material Handling (MMH) tasks like lifting, pushing and pulling is of interest to the industrial ergonomists. MMH especially, lifting poses a risk to many and considered as prime cause of back-pain and various other joint impairments. Industrial ergonomists place heavy emphasis on optimisation of posture for safe lifting. In vitro and in vivo studies on real subjects are risky and studies on cadaveric FSU are time consuming. Biomechanics provides estimation of various mechanical stresses acting on the body while a person manually handles an object. Estimation of stresses acting on the body musculoskeletal system based on biomechanical model was found to be successful (Maurel et al 1996). Field industrial ergonomists who recognises the importance of the dynamics of MMH activities have limited access to dynamic analysis. Techniques in human motion synthesis can be used to generate motions using a computer. These techniques thus provide the means for ergonomists to perform dynamic biomechanical analysis without actually collecting time-displacement data (Oliver et al 1991). Biomechanical analysis treats the human body as a system of links and connecting joints. In this study an attempt has been made to develop a biomechanical model for sagittal lifting.
LIFTING METHODS

Several lifting strategies have been described: the back or stoop lift (knees straight and back bent), deep squat lift with back straight or flexed back (knees flexed more than 90 degrees), free style or partial squat with back straight (knees flexed no more than 90 degrees), trunk kinetic lift (from deep squat, the hips and pelvis move first), two stage leg lift or leg roll (from a deep squat, the weight is transferred to one or both thighs, then lifted), and the golfer’s lift for very light loads (one arm is used as support while the lifter is bending forward with a straight back while the lifter is bending forward with a straight back pivoting around the hip joint of the straight leg).

The most popular styles discussed in the literature are the squat lift (Fig. 5.1) with the back either in slight lordosis or the back more kyphotic, the freestyle posture, the bent or stooped lift (Fig. 5.2), the weight lifter’s lift, and the golfer’s lift for lifting loads.

5.2.1 Use of correct lifting techniques

A person can more or less freely choose a lifting technique. In such instances, prior training will ensure that the best possible posture is adopted during the lift. In practice improved lifting techniques are often not feasible because of the restrictions at the workplace. Also, ingrained habits and movements can only be changed after intensive training and repetition.

5.2.2 Lifting posture advocated by NIOSH

In practice, optimum lifting conditions seldom exist. A method developed by National Institute for Occupational Safety and Health (NIOSH),
Fig. 5.1 Stoop lift
Fig. 5.2 Squat lift
U.S.A., can be used to determine the maximum load in unfavourable lifting conditions. This takes into account the horizontal and vertical distance between the load and the body, the trunk rotation, the vertical displacement, duration and the coupling between the hands and the load. It assumes among other things that the lifting postures can be freely chosen and the load is lifted with both the hands.

5.2.3 Lifting posture advocated by OWAS

One example of a method of observing the postural load is the ovaka working posture analysis system (OWAS) developed by a Finnish steel company, in association with Finnish Institute of occupational Health for the use by work study engineers in their daily work. The method was successfully implemented by occupational physiotherapists (Cartas et al 1993).

The OWAS method aims at recording and identifying poor working postures. In this system, postures are grouped according to the general features of the task (standing, sitting, position of back, arms and legs). Based on the improvement required, these postures have been divided into four operative classes:

1. A normal posture which, except in special cases needs no attention.

2. A posture which receives attention at the next regular check up of the working method.

3. A posture, which must be attended to in the near future.

4. A posture, which requires immediate attention.
5.3 COMPUTER SIMULATION FOR MMH

Most analysis procedures to evaluate the musculoskeletal stress warrant accurate depiction of posture. In occupational settings, determining the risk of low back pain through posture and hand load sampling approach is found to be yielding desired results (Neumann, 2001). National Institute For Occupational Safety and health (NIOSH) recognised the problem of work related back injuries and published the Work Practice Guide (WPG) for manual lifting. Actual biomechanical analysis of lifting exertions often require measured values of applied trunk moments and forces as base line or validation data. Accurate measures of the trunk kinetic data are difficult to achieve from dynamic exertions without significant approximation of motion constraints. It calls for experimental set up proposed by Granata (1996).

Computer simulation of human characters requires more or less the development of an idealised underlying mechanical model. Generally the form of a wire frame hierarchy of one-DOF rotational joints are taken. This approach is sufficient for most of the human joints (Maurel 1996). Predicted motion pattern by computer motion simulation resembles the observed motion pattern (Lin et al 1999).

5.4 DEVELOPMENT OF THE PROPOSED MODEL

The objective of the research is to develop a five-segment biomechanical model for determining optimum lifting posture. The model is proposed to be analysed through computer simulation for the objective of minimisation of combined torques at the joints. An optimisation programme (OP) has been developed for analysis.
Given a subject's anthropometric data, the OP will analyse and will predict the optimum motion pattern and posture. To begin with the development, a five-segment biomechanical model proposed by Lin (1999) is chosen. The reason for this choice lays in the confidence that beginning with the known is more likely to ensure the objective.

5.4.1 Biomechanical model of human body

Biomechanical analysis treats the human body as a system of links and connecting joints. The biomechanical model used in the simulation is a five-segment whole-body symmetrical lifting model. Fig. 5.3 shows the link-segment diagram of the model and the coordinate convention. The human body consists of the lower leg, upper leg, trunk, upper arm, and lower arm. The five joints under consideration are the elbow, shoulder, hip, knee and ankle. While lifting, the center of gravity of the body parts and load must be kept within the base of the support described by the position of the feet. A safe posture for lifting loads can be arrived at from a consideration of the principles of body mechanics. The body must be erect so that the weights of the body parts are transmitted through the lumbar spine. The product of the two is referred to as the load moment. In general, a lifting action, which starts at a distance and moves towards a person's body, is likely to be easier to control than one, which starts close to the body and moves away (Phesant 1991). Posture determines the distance of load from the body while lifting. In order to analyse, measurement of angles between body parts or their angles in relation to the environment are required. In order to investigate the risks of a particular lifting task, it is necessary to collect displacement-time data at the workstation or a laboratory mock up. This can be difficult, time consuming and costly, whereas
Fig. 5.3 The link-segment model of the lifting person

-π < \theta/E/S/K/H/A < π
with the help of a suitable biomechanical model, satisfactory postural analysis can be made using computer simulation.

Biomechanical model shown in Fig. 5.3 is applied for the study. In this model, the body is modelled as a system of links, which are articulated at the ankles, knees, hip, shoulders and elbows. The various inputs to the model are height (H), standing elbow height (EH), length of the radius bone (R), length of tibia bone (T), foot length (F), mass of the subject (M), load to be lifted in Kg (FL) and the distance to the load from ankle (X).

Some of the notations and definition of terms used in this study are listed below.

Sagittal Plane : An imaginary plane that bisects the human body into left and right halves.

Upper bound angle : Maximum included angle of a particular joint.

Lower bound angle : Minimum included angle of a particular joint.

Proximal : Position nearer to a reference point.

Distal : Opposite of Proximal.

5.4.2 Computation of torques

The upper arm and the forearm are considered as two links with shoulder and elbow as the connecting joints. (Fig. 5.4). Fig. 5.5 shows the forces and torques acting on the two links. Fig. 5.6 shows the generalized two links arrangement (Groover et al 1986) with load and resultant torques.
Fig. 5.4 Shoulder and elbow joint

Fig. 5.5 Forces and torques acting on the two links (Shoulder and elbow)

Fig. 5.6 Generalised links (Groover et al, 1983)
From Fig. 5.6 the following equations are derived.

\[ R_1 = [L_1 \cos \theta_1, L_1 \sin \theta_1] \] ----- 5.1

\[ R_2 = [L_2 \cos(\theta_1+\theta_2), L_2 \sin(\theta_1+\theta_2)] \] ----- 5.2

Where \( R_1 \) and \( R_2 \) are the link vectors.

The coordinates \( X \) and \( Y \) for the point \( W \) are given by

\[ X = [L_1 \cos \theta_1 + L_2 \cos(\theta_1+\theta_2)] \]

\[ Y = [L_1 \sin \theta_1 + L_2 \sin(\theta_1+\theta_2)] \]

The torques \( T_1 \) and \( T_2 \) are given by

\[ T_1 = T_2 + R_1 \times F \]

\[ T_2 = R_2 \times F \]

Where, \( F \) is the force acting at the hand.

\[ T_1 = [R_2 + R_1] \times F \]

\[ F = [F_x, F_y] \]

\[ T_1 = [L_1 \cos \theta_1 + L_2 \cos(\theta_1+\theta_2)], [L_1 \sin \theta_1 + L_2 \sin(\theta_1+\theta_2)] \times [F_x, F_y] \]

Since vector cross products \((a,b) \times (c,d)\) is \( ad-bc \):

\[ T_1 = \{[L_1 \cos \theta_1 + L_2 \cos(\theta_1+\theta_2)] * F_y\} - \{[L_1 \sin \theta_1 + L_2 \sin(\theta_1+\theta_2)] * F_x\} \] ----- 5.3

\[ T_2 = \{[L_2 \cos(\theta_1+\theta_2)] * F_y\} - \{[L_2 \sin(\theta_1+\theta_2)] * F_x\} \] ----- 5.4

Therefore, for a given force vector \( F \), the torques at each joint can be computed. The above equations did not consider the compensation for gravity and self-weight of the links. Same way it can be applied and the torque due to
centre of gravity can be computed. These torque values should be added to the joint torque values.

Assuming the centre of mass at 0.5L, torque due to Self-weight is given by

\[ T_{g2} = \frac{g \left[m_2 L^2 \cos(\theta_1 + \theta_2)\right]}{2} \] \hspace{1cm} ---- 5.5

\[ T_{g1} = \left\{ \frac{g \left[m_1 + 2m_2 \right] L \cos \theta_1}{2} \right\} + \left\{ \frac{g[m_2 L^2 \cos(\theta_1 + \theta_2)]}{2} \right\} \] \hspace{1cm} ---- 5.6

\[ T_{g1} \text{ and } T_{g2} \text{ are to be added to } T_1 \text{ and } T_2 \text{ respectively to get the total torque. Similar approach is used to arrive at the torque for all the joints through computer programming.} \]

5.4.3 The optimisation model

The optimisation of posture based on minimisation of total torque is explored. The objective function is shown in equation 5.7.

\[ \text{Minimize } T = | \{ T_a + T_k + T_h + T_s + T_e \} | \] \hspace{1cm} ---- 5.7

Where \( T_a = \) Torque at ankle \( T_k = \) Torque at knee \( T_h = \) Torque at hip \( T_s = \) Torque at shoulder \( T_e = \) Torque at elbow \( T = \) Total torque

While minimising the torque to complete the task, it is bound by various constraints like joint mobility and collision avoidance.
Joint mobility constraint

\[ X_{J,jL} \leq X_j(t) \leq X_{J,u}, \quad j = 1 \text{ to } 5, \quad 0 \leq t \leq T \quad \text{(5.8)} \]

Where, \( X_j(t) \) = included angle of the joint at time \( t \)

- \( X_{J,jL} \) = minimum included angle (lower bound angle) of the joint
- \( X_{J,u} \) = maximum included (upper bound angle) angle of the joint.

Where, \( X_j(t) \) is joint included angle which is defined as the relative angle between the two adjacent links connected by that joint. The included angles for various joints are given by

- \( X_1(t) = \) Included angle at elbow \( = \pi - S + E \)
- \( X_2(t) = \) Included angle at shoulder \( = \pi - S + H \)
- \( X_3(t) = \) Included angle at hip \( = \pi - K + H \)
- \( X_4(t) = \) Included angle at knee \( = \pi - K + A \)
- \( X_5(t) = \) Included angle at ankle \( = A \)

Where,

- \( A = \) Angle between lower leg and horizontal
- \( K = \) Angle between thigh and horizontal
- \( H = \) Angle between trunk and horizontal
- \( S = \) Angle between upper arm and horizontal
- \( E = \) Angle between lower arm and horizontal

(Chaffin and Anderson 1991) (Fig 5.3)
Collision avoidance constraint

The constraint with respect to collision is formulated as follows:

Referring to Fig. 5.7, the constraint can be formulated as follows:

\[
\text{If } (T \times \cos(A)) \leq X \text{ then there is no chance for collision.}
\]

Where,

\[
T = \text{Length of tibia} \\
A = \text{angle between lower leg and horizontal} \\
X = \text{distance between load and ankle joint.}
\]

The following assumptions are made:

1. The biomechanical model of the human body consists of lower leg, upper leg, trunk, upper arm and lower arm and the joints associated with them are elbow, shoulder, hip, knee and ankle.
2. The body's configurations at any moment in time can be completely specified by the angles at joints with respect to the horizontal.

Given the weight of the load, inertial property of the segments and lengths of segments, joint forces and moments can be calculated using the equations given in section 5.4.2.

The following are the limitations of the model.

1. The model developed is a two dimensional one
2. The model can be used for sagittal lifting only.

5.4.4 Analysis of the model through simulation

For computing the various torques, the data on length of links, center of gravity of links, mass of links, the load lifted and the angles at joints are required. The anthropometric data on five different individuals (Table 5.1) is considered (Krishniah 1986)

In order to analyse the model, segment Mass/Total mass and Center of Mass/Segment length are required. This is given by Dempster's body segment parameter data (Winter, 1990). The required body segment parameters are given in Table 5.2. Standard anthropometric proportions to be considered for optimisation are listed in the Table 5.3. The ranges of the allowable angular movements of articulated joints considered for the study are shown in Table 5.4. (Bernard et al 1999).

The optimisation programme based on “Visual Basic”, generates different set of possible joint angles, in steps and total torque is calculated for
each set for a given lifting height and load for a person, and that posture for which the total torque is the least is given as visual basic output frame as optimal lifting posture by the OP.

A sample calculation is shown below.

For example, consider the person JW having anthropometric data as shown in Table 5.1, and let the load lifted be 20 Kg, height of lift be 60 cm and distance between load and ankle joint be 35 cm.

Calculations for the above are as shown below:

For the subject: JW

**Anthropometric data (Table 5.1)**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (M)</td>
<td>60 Kg</td>
</tr>
<tr>
<td>Foot Length (F)</td>
<td>29 cm</td>
</tr>
<tr>
<td>Height (H)</td>
<td>183 cm</td>
</tr>
<tr>
<td>Wrist Grip (WG)</td>
<td>8 cm</td>
</tr>
<tr>
<td>Standing</td>
<td></td>
</tr>
<tr>
<td>Elbow Height (EH)</td>
<td>8 cm</td>
</tr>
<tr>
<td>Radius (R)</td>
<td>30 cm</td>
</tr>
<tr>
<td>Tibia (T)</td>
<td>43 cm</td>
</tr>
</tbody>
</table>
Table 5.1 Anthropometric data of five subjects

<table>
<thead>
<tr>
<th>Symbol</th>
<th>M</th>
<th>H</th>
<th>EH</th>
<th>R</th>
<th>T</th>
<th>F</th>
<th>WG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub</td>
<td>Body Weight (kg)</td>
<td>Body Height (cm)</td>
<td>Standing Elbow Ht.(cm)</td>
<td>Radius bone (cm)</td>
<td>Tibia bone (cm)</td>
<td>Foot (cm)</td>
<td>Wrist to grip (cm)</td>
</tr>
<tr>
<td>TK</td>
<td>57</td>
<td>170.5</td>
<td>104.5</td>
<td>26</td>
<td>38</td>
<td>26.5</td>
<td>10</td>
</tr>
<tr>
<td>JW</td>
<td>60</td>
<td>183</td>
<td>113.5</td>
<td>30</td>
<td>43</td>
<td>29.0</td>
<td>8</td>
</tr>
<tr>
<td>SR</td>
<td>42</td>
<td>159</td>
<td>101.5</td>
<td>25</td>
<td>37</td>
<td>25.5</td>
<td>8.5</td>
</tr>
<tr>
<td>SM</td>
<td>68</td>
<td>166</td>
<td>193.0</td>
<td>27</td>
<td>40</td>
<td>25</td>
<td>8.5</td>
</tr>
<tr>
<td>SB</td>
<td>61</td>
<td>176</td>
<td>111.0</td>
<td>26.5</td>
<td>42.5</td>
<td>28.5</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Table 5.2 Body segment parameters

<table>
<thead>
<tr>
<th>Segment Name</th>
<th>Symbol</th>
<th>Segment Mass</th>
<th>Centre of mass</th>
<th>Segment length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total Mass</td>
<td>Segment length</td>
<td>R proximal</td>
</tr>
<tr>
<td>Hand</td>
<td>WcHa</td>
<td>0.0060</td>
<td>0.506</td>
<td></td>
</tr>
<tr>
<td>Forearm</td>
<td>EcLA</td>
<td>0.016</td>
<td>0.430</td>
<td></td>
</tr>
<tr>
<td>Upper arm</td>
<td>ScUA</td>
<td>0.0280</td>
<td>0.436</td>
<td></td>
</tr>
<tr>
<td>Trunk, Head</td>
<td>HicT</td>
<td>0.578</td>
<td>0.340</td>
<td></td>
</tr>
<tr>
<td>Thigh</td>
<td>KcUl</td>
<td>0.100</td>
<td>0.433</td>
<td></td>
</tr>
<tr>
<td>Leg</td>
<td>AcLL</td>
<td>0.0465</td>
<td>0.433</td>
<td></td>
</tr>
<tr>
<td>Foot</td>
<td>AcF</td>
<td>0.0145</td>
<td>0.500</td>
<td></td>
</tr>
</tbody>
</table>
Table 5.3 Anthropometric proportions

<table>
<thead>
<tr>
<th>Links</th>
<th>Description</th>
<th>Anthropometric proportions in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Ankle height (Malleous Height)</td>
<td>$0.304^*F$</td>
</tr>
<tr>
<td>L2</td>
<td>Ankle to Knee</td>
<td>$1.0076^*T$</td>
</tr>
<tr>
<td>L3</td>
<td>Knee to Hip</td>
<td>$132.825 + (0.8172^*T)$</td>
</tr>
<tr>
<td>L4</td>
<td>Hip to Shoulder</td>
<td>$EH + L5 - (L1+L2+L3)$</td>
</tr>
<tr>
<td>L5</td>
<td>Shoulder to Elbow</td>
<td>$58.075+(0.9646^*R)$</td>
</tr>
<tr>
<td>L6</td>
<td>Elbow to Wrist</td>
<td>$1.0709^*R$</td>
</tr>
<tr>
<td>L7</td>
<td>Wrist to Grip</td>
<td>$WG$</td>
</tr>
<tr>
<td>L8</td>
<td>Shoulder to top of Head</td>
<td>$H - (EH+LS)$</td>
</tr>
<tr>
<td>L9</td>
<td>Hip to top of the Head</td>
<td>$L4+L8$</td>
</tr>
</tbody>
</table>

Table 5.4 Ranges of joint included angles, in degrees

<table>
<thead>
<tr>
<th>Joint</th>
<th>Lower Bound Angle (LBA)</th>
<th>Upper Bound Angle (UBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elbow</td>
<td>38</td>
<td>180</td>
</tr>
<tr>
<td>Shoulder</td>
<td>-61</td>
<td>188</td>
</tr>
<tr>
<td>Hip</td>
<td>67</td>
<td>180</td>
</tr>
<tr>
<td>Knee</td>
<td>67</td>
<td>180</td>
</tr>
<tr>
<td>Ankle</td>
<td>55</td>
<td>90</td>
</tr>
</tbody>
</table>
Lift data

Let

Load FL = 20 Kg
Lift Height h = 60 cm
X = 35 cm

Calculation of link lengths (Table 5.3)

Ankle Height L1 = 0.304 x F
= 0.304 x 290
= 88.16 mm
= 0.0882 m

Ankle to knee length L2 = 1.0076 x T
= 1.0076 x 430
= 433.29 cm
= 0.433 m

Knee to hip length L3 = 132.825 + (0.8172 x T)
= 132.825 + (0.8172 x 430)
= 484.22 mm

Hip to shoulder length L4 = EH + L5 - (L1+L2+L3)
= 1135+347.46 - (88.16+433.29+484.22)
= 476.76 mm
= 0.477 m
Shoulder to elbow length \( L_5 = 58.075 + (0.9646 \times R) \)
\[ = 58.075 + (0.9646 \times 300) \]
\[ = 347.455 \text{ mm} \]
\[ = 0.347 \text{ m} \]

Elbow to wrist length \( L_6 = 1.0709 \times R \)
\[ = 1.0709 \times 300 \]
\[ = 321.27 \text{ mm} \]
\[ = 0.321 \text{ m} \]

Wrist to grip \( L_7 = W_G \)
\[ = 80 \text{ mm} \]
\[ = 0.08 \text{ m} \]

Shoulder to top of the head length

\[ L_8 = H - (EH + L_5) \]
\[ = 1830 - (1135 + 347.46) \]
\[ = 347.54 \text{ mm} \]
\[ = 0.3475 \text{ m} \]

Hip to top of the head \( L_9 = L_4 + L_8 \)
\[ = 476.76 + 347.54 \]
\[ = 824.3 \text{ mm} \]
\[ = 0.824 \text{ m} \]

Mass of link

\begin{align*}
\text{Body mass} & = 60 \text{ Kg} \\
\text{Hand mass} & = 0.006 \times 60 = 0.36 \text{ Kg}
\end{align*}
Fore arm mass = 0.016 x 60 = 0.96 Kg
Upper arm mass = 0.028 x 60 = 1.68 Kg
Trunk and head mass = 0.578 x 60 = 34.68 Kg
Thigh (Upper leg) mass = 0.1 x 60 = 6 Kg
Lower Leg mass = 0.0465 x 60 = 2.79 Kg
Foot mass = 0.0145 x 60 = 0.87 Kg

C.G. of Mass Link (R_proximal) (Table 5.2)

<table>
<thead>
<tr>
<th>Segment</th>
<th>Equation</th>
<th>Length (mm)</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WcHa</td>
<td>0.506 x 748.73</td>
<td>378.86 mm</td>
<td>0.379 m</td>
</tr>
<tr>
<td>EcLA</td>
<td>0.43 x 321.27</td>
<td>138.15 mm</td>
<td>0.138 m</td>
</tr>
<tr>
<td>ScUA</td>
<td>0.436 x 347.46</td>
<td>151.49 mm</td>
<td>0.151 m</td>
</tr>
<tr>
<td>HicT</td>
<td>0.34 x 824.3</td>
<td>280.26 mm</td>
<td>0.28 m</td>
</tr>
<tr>
<td>AcLL</td>
<td>0.433 x 433.29</td>
<td>187.6 mm</td>
<td>0.188 m</td>
</tr>
<tr>
<td>KeUl</td>
<td>0.433 x 476.76</td>
<td>206.44 mm</td>
<td>0.2064 m</td>
</tr>
<tr>
<td>AcF</td>
<td>0.5 x 88.16</td>
<td>44.08 mm</td>
<td>0.441 m</td>
</tr>
</tbody>
</table>

Analysis of the model

The body's configuration at any moment in time can be completely specified by the angles of each segment with respect to horizontal, once we know the height of lift (h) and distance between the load and Ankle (X).
For a height of lift, \( h = 40 \text{ cm} \) and the distance between load and ankle \( X = 35 \text{ cm} \), let one set of possible joint angles be (can be obtained by simulating one possible posture for given lifting height and distance between load and ankle joint).

- Elbow Angle \( E = 54^0 \)
- Shoulder Angle \( S = 106^0 \)
- Hip Angle \( H = 75^0 \)
- Knee Angle \( K = 108^0 \)
- Ankle \( A = 87^0 \)

Checking the data for joint mobility constraint

\[
X_1(t) = \text{Included angle at Elbow} = \pi - S + E = 180^0 - 106^0 + 54^0 = 128^0
\]

\[
X_2(t) = \text{Included angle at shoulder} = \pi - S + H = 180^0 - 106^0 + 75^0 = 149^0
\]

\[
X_3(t) = \text{Included angle at hip} = \pi - K + H = 180^0 - 108^0 + 75^0 = 147^0
\]
\[ X_4(t) = \text{Included angle at knee} \]
\[ = \pi - K + A \]
\[ = 180^\circ - 108^\circ + 87^\circ \]
\[ = 159^\circ \]

\[ X_5(t) = \text{Included angle at ankle} \]
\[ = A \]
\[ = 87^\circ \]

Since the included angles at all the joints are greater than respective lower bound angles and less than upper bound angles (Table 5.4), the above sets of joint angles satisfy the joint mobility constraint.

Also checking the data for the collision avoidance constraint

\[ T \cos A = 430 \cos 87^\circ = 2.25 \text{ cm} \]

Since \( T \cos A = 2.25 \text{ cm} \) is less than \( X \), the distance between the load and the ankle joint, the data satisfy the collision avoidance constraint.

**Calculation of Torques at the joints**

1. **Shoulder and Elbow joints**

   \[
   \text{Force} = FL + WcHa \\
   = (20 + 0.36) \times 9.81 = 199.73 \text{ N} \\
   \theta_1 = 54^\circ \\
   \theta_2 = 106^\circ + 54^\circ = 160^\circ 
   \]
Horizontal component
\[ F_x = 199.73 \cos 36^\circ = 161.58 \text{ N} \]
Vertical component
\[ F_y = 199.73 \sin 36^\circ = 117.64 \text{ N} \]

Link vectors
\[ R_1 = [L_1 \cos \theta_1, L_1 \sin \theta_1] \]
\[ R_2 = [L_2 \cos (\theta_1+\theta_2), L_2 \sin (\theta_1+\theta_2)] \]
\[ R_1 = [0.348 \cos 160^\circ, 0.348 \sin 160^\circ] \]
\[ = [-0.33, 0.12] \]
\[ R_2 = [0.321 \cos 214^\circ, 0.321 \sin 214^\circ] \]
\[ = [-0.27, -0.18] \]

Position of point W with coordinates X, Y
\[ X = [L_1 \cos \theta_1 + L_2 \cos (\theta_1+\theta_2)] \]
\[ Y = [L_1 \sin \theta_1 + L_2 \sin (\theta_1+\theta_2)] \]
\[ X = 0.33 - 0.27 = -0.6 \text{ m} \]
\[ Y = 0.12 - 0.18 = -0.06 \text{ m} \]

\[ T_1 = \{[L_1 \cos \theta_1 + L_2 \cos(\theta_1+\theta_2)] \times F_y\} - \{[L_1 \sin \theta_1 + L_2 \sin(\theta_1+\theta_2)] \times F_x\} \]
\[ = -0.06 \times 117.64 - (-0.6) \times 161.58 \]
\[ = -7.0584 + 96.948 \]
\[ = 89.88 \text{ Nm} \]

\[ T_2 = \{[L_2 \cos(\theta_1+\theta_2)] \times F_y\} - \{[L_2 \sin(\theta_1+\theta_2)] \times F_x\} \]
\[ = (-0.27) \times 117.64 - (-0.18) \times 161.58 \]
\[ = -31/7628 + 29.0844 = -2.68 \text{ Nm} \]
2. Hip and knee joints

\( \theta_1 = 15^\circ \) and \( \theta_2 = 33^\circ \)

\[ R_1 = [L1 \cos \theta_1, L1 \sin \theta_1] \]

\[ R_2 = [L2 \cos (\theta_1 + \theta_2), L2 \sin (\theta_1 + \theta_2)] \]

\[ R_1 = (0.47 \cos 15^\circ, 0.47 \sin 15^\circ) \]

\[ = (0.45, 0.12) \]

\[ R_2 = (0.484 \cos (15^\circ+33^\circ), 0.484 \sin (15^\circ+33^\circ)) \]

\[ = (0.32, 0.36) \]

\( T_{g2} = \{g [m_2 L_2 \cos (\theta_1 + \theta_2)]\}/2 \)

\[ = (9.81 \times 6 \times 0.32)/2 \]

\[ = 9.41 \text{ Nm} \]
\[ T_{gl} = \left\{ \frac{g (m_1 + 2m_2) L_1 \cos \theta_1}{2} \right\} + \left\{ \frac{g (m_2 L_2 \cos (\theta_1 + \theta_2))}{2} \right\} \]
\[ = \left\{ \frac{9.81 (34.68 + 2 \times 6) \times 0.45}{2} \right\} + 9.41 \]
\[ = 103.03 + 9.41 \]
\[ = 112.44 \text{ Nm.} \]

\[ T_h = T_{gl} = 112.44 \text{ Nm} \]
\[ T_k = T_{\theta_2} = 9.41 \text{ Nm} \]

3. **Ankle joint**

\[ T_a = g \times \text{Lower leg mass} \times R_{proximal \ for \ lower \ leg} \times \cos A \]
\[ = 9.81 \times 2.79 \times 0.188 \times \cos 870 \]

\[ T_a = 0.27 \text{ Nm} \]

**Total torque**
\[ T = T_a + T_k + T_h + T_\theta + T_e \]
\[ = 0.27 + 9.41 + 112.44 + 3.95 + 92.88 \]
\[ = 218.95 \text{ Nm} \]

Total torque for the above set of joints angles has been calculated to be 218.95 Nm.

Similarly, the optimisation programme based on visual basic, generates different set of possible joint angles, in steps and total torque is calculated for each set for a given lifting height and load for a person, and that posture for which the total torque is the least is given as visual basic output frame as optimal lifting posture by the OP.
5.5 RESULTS AND DISCUSSION

In this study, the biomechanical model was formulated to predict two dimensional joint motion for the lifting activities performed in sagittal plane. Given the actual initial and final postural configurations and the anthropometrical characteristics of subjects, the OP predicts the dynamic motions between the beginning and ending postures.

The model is used to predict the motions of 200 lifts, involving 5 persons, 4 different loads (5, 10, 15 and 20 Kg) and 10 different heights of lift (10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 cm). The data are checked for optimisation using various constraints like joint Mobility constraint and Collision avoidance constraint. After checking for both constraints, calculation, optimisation routine and the graphical simulation are performed using a programme based on “Visual Basic”. Some of the sample output frames are given in Fig 5.8 to 5.11.

Comparisons with actual motion data show promising results. The model proposed in this study has been developed for specific task conditions. Similar model can also be developed for different task conditions.

Model under this study can also be used to predict the lifting capability of individuals. This will be of great help to the Industrial managers for manual lifting tasks. Currently, no standard is available in Indian industries to serve as guidelines in this area.
Fig. 5.8 VB form showing optimal positions (20 Kg load and 60 cm height of lift)
Fig. 5.9 VB form showing optimal positions
(15 Kg load and 70 cm height of lift)
Fig. 5.10 VB form showing optimal positions
(5 Kg load and 60 cm height of lift)
Fig. 5.11 VB form showing optimal positions
(10 Kg load and 100 cm height of lift)
5.6 CONCLUSION

Techniques in human motion synthesis can be used to generate motions using a computer. In this study, a biomechanical model was developed for proper analysis and optimisation for minimum effort for lifting.

The objective is to arrive at an Optimisation Programme using biomechanical model for sagittal plane lifting. Computer simulated movements were compared with the actual motion data captured using video recording for its feasibility. Video recorded data sets of five subjects and their anthropometric data have been used for the validation of the model.

The following conclusion are made from this work

1. The optimisation of the minimal effort in the joint while lifting proves to be successful. It is also possible to simulate different scenarios of load lifting.

2. The results of the study confirms with the actual data, thereby proving the validity of the objective functions and the constraints. The formulation of the optimisation program is the crucial step in finding out the optimum solutions.