1. INTRODUCTION

Biped robots are studied because of their extreme application and future role in human life and there are many projects [1]-[3] regarding to this matter. Most of these projects focused on walking with subjects such as dynamic modeling, mechanism design, path generation, establishing stability criterion, etc. But running robot is almost a new topic and there are many unsolved problems. Study of running robots is important because of these reasons: 1- increasing robots maneuverability. For example, jumping over large obstacles or a crevasse on the ground. 2- increasing robots operation speed. Current humanoid robots operate very slowly. Development of running robots can improve operation speed. 3- increasing robots efficiency. Using an elastic mechanism in each leg, energy consumption for a specific displacement can decrease.

Running robots have been intensively studied at MIT leg lab by Raibert and his colleagues [4]. Most of their robots are driven by pneumatic and hydraulic actuators and they are equipped by prismatic knees.

Bruderlin and Calvert [5] used a simple dynamics model and control system to generate the leg motions for a simulation of human walking. They used a telescoping leg with two degrees of freedom as the leg model for the stance phase and a compound pendulum model for the swing phase.

Using a similar to Raibert control strategy, Hodgins simulated a running human model in the computer graphics media [6]. Her robot had 17 links and 30 DOF and the equations of motion were generated using a commercially available computer software [7].

Ahmadi and Buehler proposed experimental implementation of an energy efficient “Controlled Passive Dynamic Running” strategy (CPDR) on a planar one-legged running robot with hip and leg compliance. Their ARL Monopod II [8] is an electrically powered running robot of 18 kg weight and could run at 1.25 m/s with a power expenditure of only 48 W.

Other running and hopping robot is called HRP-2LR [9]. Using a dynamic model of HRP-2LR, hopping patterns were calculated so that it followed the desired profiles of the total linear and angular momentum. For this purpose Resolved Momentum Control was used. Finally, a running pattern of 0.06 s flight and 0.3 s support phase was tested. HRP-2LR could successfully run with average speed of 0.16 m/s.

The world’s first running humanoid robot was introduced by Sony Corporation on 2003 [10]. Their robot Qrio is a self-contained 38 DOF humanoid, 580 mm height, 7 kg weight. Qrio demonstrated running with 14 m/min (0.23 m/s) whose flight phase is approx. 20 ms.

Last running humanoid robot, called “NEW ASIMO”, was introduced by Honda Corporation on 2006. Honda claims that it is the most advanced humanoid in the world. Their robot can run with speed of 6 km/h on straight line and 3 km/h on circular path. The technical details of ORIO and ASIMO have not been well disclosed yet.

This paper has following sections. In section II, a description of human gait is provided. Then our robots mechanisms are introduced. Kinematical and dynamical equations of robots are presented in section III. Section IV is devoted to robots path generation. Finally, in section V,
the paper results such as calculated torques and forces, ground reaction force, energy consumption, and comparison between two robots are presented.

2. WALKING, RUNNING AND ROBOTS MECHANISM

The locomotion of bipeds can be divided into two main groups, walking and running. The two forms have very different characteristics. However, the main difference is the contact of the feet with the ground. During walking at least, one foot is on the ground at all times, and during the double support phase even two. Whereas while running only one foot touches the ground simultaneously.

Running is executed as a sequence of strides, which alternate between the two legs. Each leg’s stride can be roughly divided into three phases: support, drive, and recovery. Support and drive occur when the foot is in contact with the ground, during single support phase. Recovery occurs when the foot is off the ground. Since only one foot is on the ground at a time in running, one leg is always in recovery, while the other goes through support and drive. Then, briefly, as the runner leaps through the air, both legs are in recovery.

In this work, after a deep study on human gait, the following mechanisms were designed. These mechanism have 9 links with 9 DOF, including: torso (trunk and head) (1), hands (2), thighs (2), shanks (2), and feet (2).

It is assumed that the angle between upper arm and forearm during running has a constant value, $\beta$. For a given $\beta$, a program calculates center of mass (COM) and moment of inertia of each hand. Also, knee joints of Robot II are prismatic, which provide the potential to use springs in knees for energy recovery.

All physical parameters of the robots links are based on"Dempster's Body Segment Parameter Data for 2-D studies" [11], as like as human body segments are. Here, it is assumed that the robots have total mass of $M=65$ kg, total height of $H=1.8$ m, and $\beta=90^\circ$. Physical parameters of the robots links for these values are shown in Table 1. Also, torso (trunk and head) length is $l_t=0.8460$ m. The physical parameters description of robots is shown in Table 2.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_i$</td>
<td>Mass of link $i$</td>
<td>(Kg)</td>
</tr>
<tr>
<td>$l_i$</td>
<td>Length of link $i$</td>
<td>(m)</td>
</tr>
<tr>
<td>$a_i$</td>
<td>Distance between the center of mass of link $i$ and its lower end</td>
<td>(m)</td>
</tr>
<tr>
<td>$I_i$</td>
<td>Moment of inertia with respect to an axis passing through the center of mass of link $i$</td>
<td>(kgm$^2$)</td>
</tr>
<tr>
<td>$q_i$</td>
<td>Angle of link $i$ with respect to the vertical, or linear displacement at knees</td>
<td>(deg - m)</td>
</tr>
<tr>
<td>$(x_{bi}, y_{bi})$</td>
<td>Position of the point of support</td>
<td>(m)</td>
</tr>
<tr>
<td>$(x_{ci}, y_{ci})$</td>
<td>Position of the center of mass of link $i$, with respect to $(x_{bi}, y_{bi})$</td>
<td>(m)</td>
</tr>
</tbody>
</table>

3. ROBOTS KINEMATICS AND DYNAMICS

Whereas running is cyclic motion, firstly one stride (half cycle) is considered and then it can be repeated for the next strides.

The positive direction of link angles, link torques and joint torques is clockwise direction.

3.1 Single Support Phase

Fig 2 shows the robots in single support phase, in which robot base has a fixed position, i.e. $(x_b, y_b)=0$ or cte. So, the links COM position of Robot I and Robot II will be Eqs (1) and Eqs (2), respectively. Note that in all equations, it is assumed that support leg is the leg consisting of links 1, 2 and 3.

![Fig 1: Robots mechanism and their parameters](image1)

![Fig 2: The Robots variables and joint numbers](image2)
\begin{align*}
\dot{x}_i &= -a_i \sin q_i \\
\dot{y}_i &= a_i \cos q_i \\
x_{i,2} &= -l_i \sin q_i - a_i \sin q_2 \\
y_{i,2} &= l_i \cos q_i + a_i \cos q_2 \\
x_{i,3} &= -l_i \sin q_i - (l_i + a_i - q_3) \sin q_3 \\
y_{i,3} &= l_i + a_i - q_3 \cos q_3 \\
x_{i,4} &= -l_i \sin q_i - (l_i + l_3 - q_4) \sin q_4 \\
y_{i,4} &= l_i + l_3 - q_4 \cos q_4
\end{align*}

(1)

\begin{align*}
\dot{x}_i &= -a_i \sin q_i \\
\dot{y}_i &= a_i \cos q_i \\
x_{i,2} &= -l_i \sin q_i - a_i \sin q_2 \\
y_{i,2} &= l_i \cos q_i + a_i \cos q_2 \\
x_{i,3} &= -l_i \sin q_i - (l_i + a_i - q_3) \sin q_3 \\
y_{i,3} &= l_i + a_i - q_3 \cos q_3 \\
x_{i,4} &= -l_i \sin q_i - (l_i + l_3 - q_4) \sin q_4 \\
y_{i,4} &= l_i + l_3 - q_4 \cos q_4
\end{align*}

(2)

By differentiating the above equations with respect to time, link COM velocities and then kinetic energy of the robots can be obtained. Gravitational potential energy easily will be:

\begin{equation}
V = \sum_{i=1}^{9} v_i = \sum_{i=1}^{9} m_i g y_{ci}
\end{equation}

(3)

Where \( V \) is potential energy of the robot and \( g \) is the gravitational constant. It is assumed that the friction of the ground is large enough to ensure no slipping of the supporting end. By applying the Lagrange's equation of motion for a conservative system, the dynamic model of each biped robot in single support phase is given as:

\begin{equation}
M_j(q) \ddot{q} + V_j(q, \dot{q}) + G_j(q) = T_j
\end{equation}

(4)

Where \( M_j \) is a 9×9 symmetric, positive-definite inertia matrix, \( V_j \) is a 9×1 column vector containing the effects of the Coriolis and centripetal torques, \( G_j \) is a 9×1 column gravity vector, \( T_j \) is a 9×1 column link torques and forces vector (not joint torques and forces vector) and \( q \) is a 9×1 column robot variables vector. For example, one term of these matrices \( (M_j) \) is written below. For Robot I:

\begin{equation}
M_{j,12} = (m_2 + m_3 + m_4 + m_5 + m_6 + m_7 + m_8) \frac{a_i}{l_2} + m_5 \sin(q_i - q_2)
\end{equation}

(5)

And for Robot II:

\begin{equation}
M_{j,12} = (m_2 + m_3 + m_4 + m_5 + m_6 + m_7 + m_8 + m_9) \frac{a_i}{l_2} + m_5 \sin(q_i - q_2)
\end{equation}

(6)

It is clear that equations of motion of a prismatic knee robot, like Robot II, are more complicated than a rotary knee robot, like Robot I.

### 3.2 Flight Phase

In this phase, the robots base is not fixed anymore and varies with time. So in Eqs (1) and (2), \( x_6 \) should be added to \( x_i \) and \( y_6 \) should be added to \( y_i \) as follows:

\begin{align*}
\dot{x}_i &= x_i - a_i \sin q_i \\
\dot{y}_i &= y_i + a_i \cos q_i
\end{align*}

(7)

\begin{align*}
\dot{x}_i &= x_i - l_i \sin q_i - a_i \sin q_2 \\
\dot{y}_i &= y_i + l_i \cos q_i + a_i \cos q_2
\end{align*}

(8)

With the same approach, robots equations of motion in flight phase can be obtained, as follows:

\begin{equation}
M_j(q) \ddot{q} + V_j(q, \dot{q}) + G_j(q) = T_j
\end{equation}

(9)

### 3.3 Joint Torques and Ground Reaction Force

In Eqs (4) and (8), \( T_j \) is the link torques vector. But we are interested to define joint (or actuators) torques and forces, \( T_j \). Eqs (10) show the relation between \( T_j \) and \( T_j \) for Robot I, and Eqs (11) show the relation between \( T_j \) and \( T_j \) for Robot II. It can be seen that \( T_j \) is an 8×1 column vector because the angle \( q_j \) at the contact point with the ground (hypothetical joint 0) is controlled only indirectly using the gravitational effects (it is not controllable because of the unilaterality of contact force). This is one of the difficulties to work with biped robots.

\begin{equation}
T_j = \begin{bmatrix}
T_{j,1} \\
T_{j,2} \\
T_{j,3} \\
T_{j,4} \\
T_{j,5} \\
T_{j,6} \\
T_{j,7} \\
T_{j,8} \\
T_{j,9}
\end{bmatrix}
\end{equation}

(10)

\begin{equation}
T_j = \begin{bmatrix}
T_{j,1} \\
T_{j,2} \\
T_{j,3} \\
T_{j,4} \\
T_{j,5} \\
T_{j,6} \\
T_{j,7} \\
T_{j,8} \\
T_{j,9}
\end{bmatrix}
\end{equation}

(11)

Ground reaction force, \( F \), has two main components,
normal \((F_n)\) and tangential \((F_t)\) as shown in Fig (3). \(F_n\) is easily calculated by Eq (12), but calculation of \(F_t\) is so difficult. Note that \(F_n\) has the most portion of \(F\), specially at the beginning of single support phase.

\[
F_n = \frac{T_{\mu} - T_{\nu}}{l_i} \tag{12}
\]

\(F_n\) is easily calculated by Eq (12), but calculation of \(F_t\) is so difficult. Note that \(F_n\) has the most portion of \(F\), specially at the beginning of single support phase.

**4. PATH GENERATION**

Third-order spline method has been used for running path generation. Breakpoints were achieved by photography captured from human running on toes at average speed of 2 m/s. Firstly, for a given input data, the trajectories of hip, ankle 1 (joint 1) and ankle 6 (joint 6) were calculated (see Fig 4).

![Hip and Ankles Trajectory](image)

Fig 4: Hip and ankles trajectory (one cycle)

Then, for a given input data, the angle trajectories of link 1 and 6 were calculated (see Fig 5).

![Feet Trajectory](image)

Fig 5: Feet trajectory (one cycle)

Hip, ankles and feet trajectories are the same for both robots. Using hip and ankles trajectories and inverse kinematics of each robot, trajectory of other links i.e. link 2, 3, 4 and 5 can be obtained (see Fig 6 and 7).

5. SIMULATION RESULTS

The graphical results from the simulation using MATLAB for the biped robots, running two strides (one cycle) are plotted in Fig (8) to Fig (13). Both robots run with speed of 2 m/s. Duration of single support phase is 0.267 s, and duration of flight phase is 0.2 s. So, one stride duration is 0.427 s. Fig (8) and Fig (11) show calculated torques and forces for Robot I and Robot II. As can be seen, when one leg is in recovery (i.e. off the ground), its joint torques or forces are nearly zero, but other leg joint torques or forces have a large amount. Also, almost all joint torques of each leg, have a local maximum at first and end of single support phase, because of ground impact shock and needed power for starting of flight phase.

### 5.1 The Normal Ground Reaction Force (NGRF)

The NGRF of Robot I and Robot II is depicted in Fig (9) and Fig (12), respectively. It should be noted that, \(F_n\) profile of Robot I is very close to experimental measurement of ground reaction force.

By comparing Fig (9) and Fig (12) it is clear that the NGRF of robot I is nearly 4 times greater than the NGRF of Robot II. It shows that prismatic knees (or telescopic legs) can effectively decrease the amount of ground reaction force.

### 5.2 The Robots Energy Consumption

Fig (10) and (13) show the energy consumption of Robot I and Robot II during one stride (half cycle), respectively. As can be seen, both robots have a similar energy consumption profile. Robot I consumes 1.108 kJ and Robot II consumes 0.527 kJ for one stride, so Robot I energy consumption is more than 2 times greater than Robot II energy consumption. It shows that prismatic knees (or telescopic legs) can effectively decrease the amount of energy consumption during running motion.
Fig 8: Robot I joint torques

Fig 9: Robot I normal ground reaction force

Fig 10: Robot I energy consumption during one stride

Fig 11: Robot II joint torques and forces

Fig 12: Robot II normal ground reaction force

Fig 13: Robot II energy consumption during one stride
6. REFERENCES


