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DYNAMICS SIMULATION OF TWO BIPED RUNNING ROBOTS

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ABSTRACT

Design and simulation of two running biped robots is addressed in this paper, called Robot I and Robot II. The robots consist of 9 links. All joints of Robot I are rotary joints and only the knee joints of Robot II are prismatic. All physical characteristics of robots body are as like as human bodies are. It is assumed that: 1- all joints are friction-free 2- all joints are driven by an independent driver 3- motion of all links occurs in sagittal plane (2D motion). Firstly, kinematical equations of links are presented. Then derived equations of motion of robots, using Lagrange method, in two main phases of running, i.e., single support and flight phases are discussed. For interpolation trajectory of the robots path, with the given break points of hip and two ankles, third-order spline method has been used. Finally, most important results of this work that come from comparison between two robots from following viewpoints are presented: equations of motion complexity, energy consumption for the same motion, ground impact force, etc.

Keywords: Biped Robot, Running, Dynamics, Trajectory, Energy.

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).

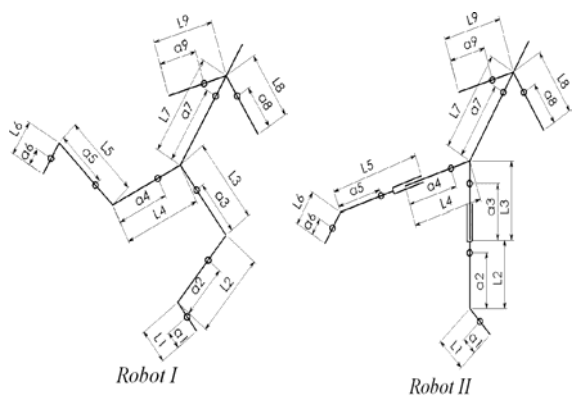

Fig 1: Robots mechanism and their parameters

It is assumed that the angle between upper arm and forearm during running has a constant value, β. For a given β, 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.

Table 1: The Robots physical parameters

Link no.	$l_i(m)$	$a_i(m)$	$m_i(kg)$	$I_i(kgm^2)$
1 & 6	0.2232	0.1116	0.9425	0.0106
2 & 5	0.4428	0.2502	3.0225	0.0540
3 & 4	0.4410	0.2502	6.5000	0.1320
7	0.5184	0.5580	37.5700	2.5483
8 & 9	0.3960	$l_i - a_i = 0.2711$	3.2500	0.1729

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 β=90°. 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 2: Description of the physical parameters

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

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.

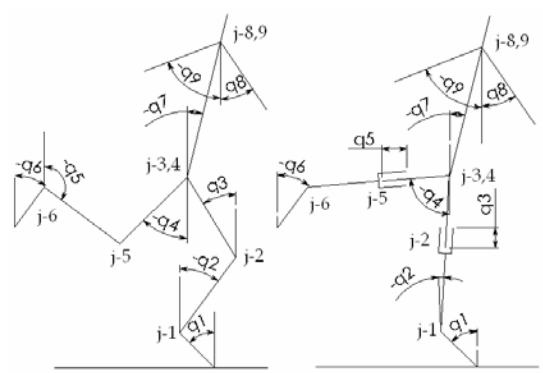

Fig 2: The Robots variables and joint numbers

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*.

$$
\begin{aligned}
x_{c1} &= -a_1.\sin q_1 \\
y_{c1} &= a_1.\cos q_1 \\
x_{c2} &= -l_1.\sin q_1 - a_2.\sin q_2 \\
y_{c2} &= l_1.\cos q_1 + a_2.\cos q_2 \\
x_{c3} &= -l_1.\sin q_1 - l_2.\sin q_2 - a_3.\sin q_3 \\
y_{c3} &= l_1.\cos q_1 + l_2.\cos q_2 + a_3.\cos q_3 \\
x_{c4} &= -l_1.\sin q_1 - l_2.\sin q_2 - l_3.\sin q_3 + (l_4 - a_4).\sin q_4 \\
y_{c4} &= l_1.\cos q_1 + l_2.\cos q_2 + l_3.\cos q_3 - (l_4 - a_4).\cos q_4 \\
&\ldots.
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
x_{c1} &= -a_1.\sin q_1 \\
y_{c1} &= a_1.\cos q_1 \\
x_{c2} &= -l_1.\sin q_1 - a_2.\sin q_2 \\
y_{c2} &= +l_1.\cos q_1 + a_2.\cos q_2 \\
x_{c3} &= -l_1.\sin q_1 - (l_2 + a_3 - q_3).\sin q_2 \\
y_{c3} &= +l_1.\cos q_1 + (l_2 + a_3 - q_3).\cos q_2 \\
x_{c4} &= -l_1.\sin q_1 - (l_2 + l_3 - q_3).\sin q_2 + (l_4 - a_4).\sin q_4 \\
y_{c4} &= +l_1.\cos q_1 + (l_2 + l_3 - q_3).\cos q_2 - (l_4 - a_4).\cos q_4 \\
&\ldots.
\end{aligned} \tag{2}
$$

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:

$$
v = \sum_1^9 v_i = \sum_1^9 m_i g y_{ci} \tag{3}
$$

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:

$$
M_s(q)\ddot{q} + V_s(q,\dot{q}) + G_s(q) = T_l \tag{4}
$$

Where M_s is a 9×9, symmetric, positive-definite inertia matrix, V_s is a 9×1 column vector containing the effects of the Coriolis and centripetal torques, G_s is a 9×1 column gravity vector, T_l is a 9×1column 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 matrixes (M_s) is written below. For Robot I:

$$
\begin{aligned}
M_s(1,2) = (m_2 \frac{a_2}{l_2} + m_3 + m_4 + m_5 + m_6 + m_7 + m_8 \\
+ m_9).l_1 l_2.\cos(q_1 - q_2)
\end{aligned} \tag{5}
$$

And for Robot II:

$$
\begin{aligned}
M_s(1,2) = \{[m_2 a_2 + m_3(l_2 + a_3) + (m_4 + m_5 + m_6 + m_7 + m_8 \\
+ m_9)(l_2 + l_3)].l_1 - [(m_3 + m_4 + m_5 + m_6 + m_7 + m_8 \\
+ m_9).l_1].q_3\}.\cos(q_1 - q_2)
\end{aligned} \tag{6}
$$

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_b should be added to x_{ci} and y_b should be added to y_{ci} as follows:

$$
\begin{aligned}
x_{c1} &= x_b - a_1.\sin q_1 \\
y_{c1} &= y_b + a_1.\cos q_1 \\
x_{c2} &= x_b - l_1.\sin q_1 - a_2.\sin q_2 \\
y_{c2} &= y_b + l_1.\cos q_1 + a_2.\cos q_2 \\
&\ldots.
\end{aligned} \tag{7}
$$

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

$$
M_f(q)\ddot{q} + V_f(q,\dot{q}) + G_f(q) = T_l \tag{8}
$$

Note that, for both robots we have:

$$
\begin{aligned}
M_f(q) &= M_s(q) \\
V_f(q,\dot{q}) &= V_s(q,\dot{q}) \\
G_f(q) &\neq G_s(q)
\end{aligned} \tag{9}
$$

3.3 Joint Torques and Ground Reaction Force

In Eqs (4) and (8), T_l 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_l and T_j for Robot I, and Eqs (11) show the relation between T_l and T_j for Robot II. It can be seen that T_j is an 8×1 column vector because the angle q_1 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.

$$
T_j = \begin{bmatrix} T_{j1} \\ T_{j2} \\ T_{j3} \\ T_{j4} \\ T_{j5} \\ T_{j6} \\ T_{j8} \\ T_{j9} \end{bmatrix} = \begin{bmatrix} T_{l2} - T_{l3} + T_{l7} - T_{l8} - T_{l9} \\ T_{l3} - T_{l7} + T_{l8} + T_{l9} \\ T_{l7} - T_{l8} - T_{l9} \\ T_{l4} - T_{l5} + T_{l6} \\ T_{l5} - T_{l6} \\ T_{l6} \\ T_{l8} \\ T_{l9} \end{bmatrix} \tag{10}
$$

$$
T_j = \begin{bmatrix} T_{j1} \\ F_{j2} \\ T_{j3} \\ T_{j4} \\ F_{j5} \\ T_{j6} \\ T_{j8} \\ T_{j9} \end{bmatrix} = \begin{bmatrix} T_{l2} - T_{l7} + T_{l8} + T_{l9} \\ F_{l3} \\ T_{l7} - T_{l8} - T_{l9} \\ T_{l4} - T_{l6} \\ F_{l5} \\ T_{l6} \\ T_{l8} \\ T_{l9} \end{bmatrix} \tag{11}
$$

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.

$$F_n = \frac{T_{j1} - T_{l1}}{l_1} \tag{12}$$

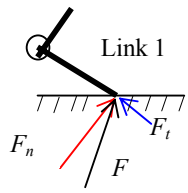

Fig 3: Ground reaction force

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).

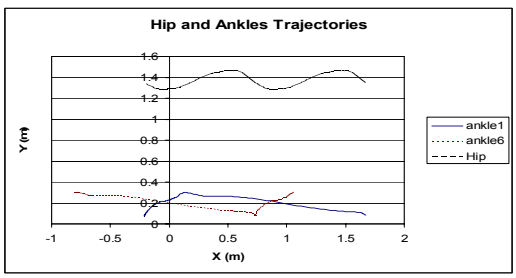

Fig 4: Hip and ankles trajectory (one cycle)

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

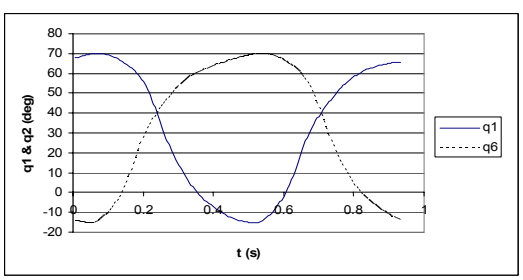

Fig 5: Feet trajectory (one cycle)

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).

It is assumed that hands motion is corresponding to thighs motion, and then for Robot I:

$$q_8(t) = q_4(t), q_9(t) = q_3(t) \tag{13}$$

And for Robot II:

$$q_8(t) = q_4(t), q_9(t) = q_2(t) \tag{14}$$

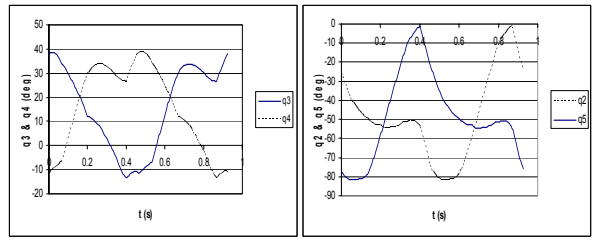

Fig 6: Robot I Links trajectory (one cycle)

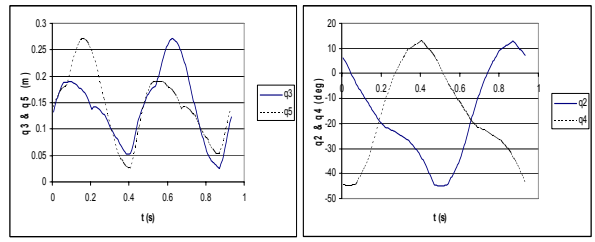

Fig 7: Robot II Links trajectory (one cycle)

Having dynamic model and trajectory of robots, joint torques and forces can be calculated.

5. SIMULAION 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.

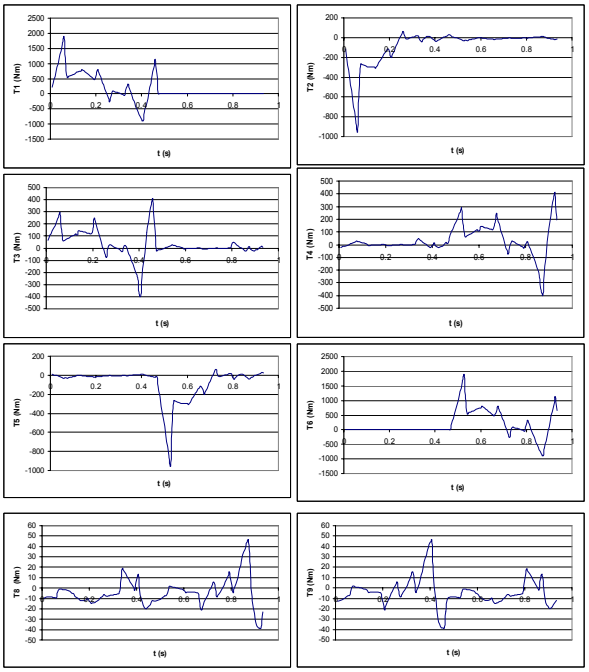

Fig 8: Robot I joint torques

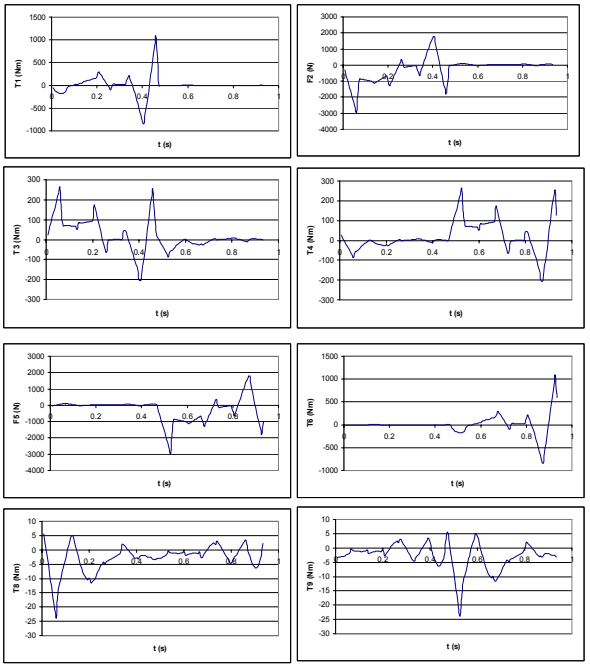

Fig11: Robot II joint torques and forces

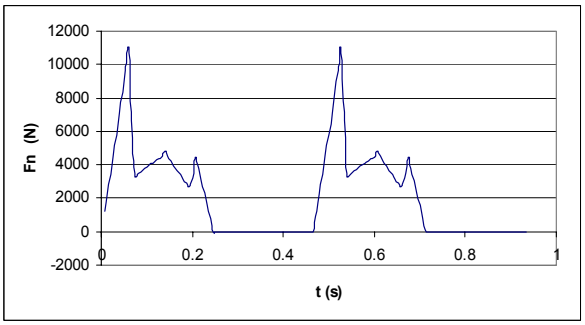

Fig 9: Robot I normal ground reaction force

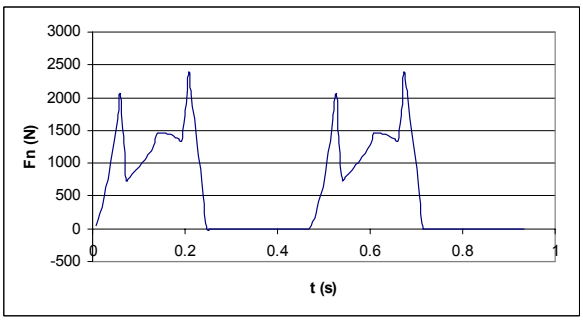

Fig 12: Robot II normal ground reaction force

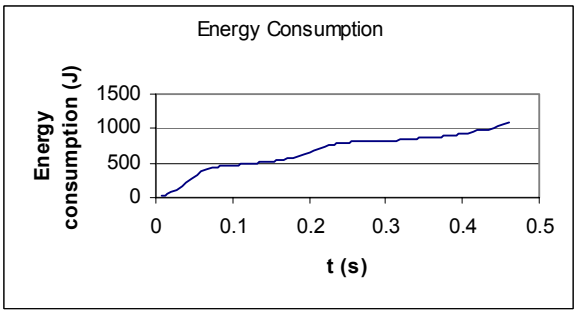

Fig 10: Robot I energy consumption during one stride

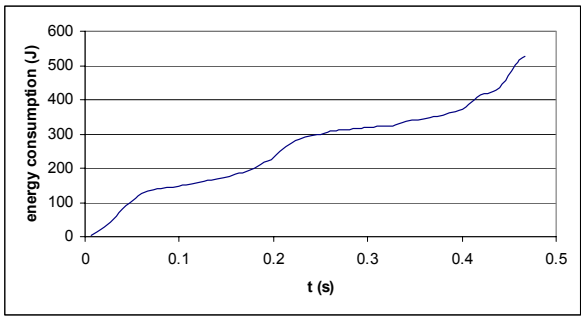

Fig 13: Robot II energy consumption during one stride

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