International Journal of Advanced Mechatronics and Robotics (IJAMR)
Vol. 3, No. 1, January-June 2011; pp. 1-7; © International Science Press, ISSN: 0975-6108

Dynamic Mechanisms of Kneecap, Compliant Ankle and Passive Swing Leg to Simulate Human Walking Robot

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ABSTRACT

The dynamic mechanisms can be exploited in the control of human walking robots. The dynamic mechanisms have been tried for the swing leg to swing freely, kneecap to prevent the leg from inverting, and compliant ankle to transfer the center of pressure along the foot and help in toe off. A simple control algorithm has been described using these mechanisms. The required inputs are joint angles and velocities, body pitch and angular velocity, and ground reaction forces. In this paper, a walking robot having configuration of seven links with twelve degrees of freedom was controlled and simulated using three proposed dynamic mechanisms.

Keywords: Dynamic Mechanisms, Walking Robot.

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1. INTRODUCTION

Passive human walkers have limitations such as limited capabilities and the need to walk down a slope [1, 2]. Powered human robots can avoid these limitations. However, the control of powered robots is very complicated and the resultant motion often looks unnatural and is inefficient. Many of the controllers used for powered robots are model based. They require an accurate model of the dynamics of the robot. Several of the robots use trajectory planning, which require pre-specified trajectories of either the body or the joints [3, 4].

In this paper, three dynamic mechanisms have been presented for human walking robot. Three dynamic mechanisms are as follows:

- Walking robot with a kneecap to prevent the leg from inverting.
- Walking robot with a compliant ankle limit to transfer the center of pressure on the foot travels forward with the center of mass of the body.
- Walking robot with swing dynamics.

An algorithm was developed to stabilize lateral motion through foot placement and ankle torque.

2. THE DYNAMIC MECHANISMS

2.1 Kneecap

Walking with straight support legs is more efficient than with bent legs since energy requirements in muscles and motors are proportional to the torque at the joint, even if there is no velocity [5]. As the leg is to support the weight of the body, a straight leg poses an interesting challenge. Figure 1 illustrates the advantages of kneecap. When the body is directly over the foot (A), no torque is required at the knee. But, this is an unstable latch configuration. If the knee moves slightly either way, the leg buckles (B or C). A kneecap (D) can greatly simplify the control and make the resultant motion smoother and more efficient. A very simple control technique to keep the leg straight is to apply a constant torque so that the knee pushes against the stop.

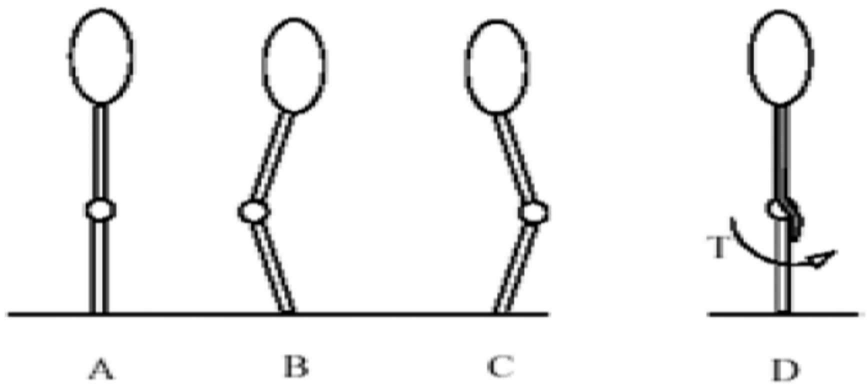

Figure 1: Diagram Illustrating Kneecap Advantages

2.2 Compliant Ankle

Feet and ankles provide many benefits to human walking. They reduce velocity fluctuations since the center of pressure on the foot can travel forward, staying below the center of mass of the body. They also help to control speed and to inject energy at the end of the stride through toe off. However, the torque requirements can be quite high, since the foot provides a significant lever arm when the center of pressure is near the toe. A compliant ankle provides most of the benefits of a foot and ankle but without the torque requirements. An actuator can then be used in addition to the passive ankle for fine control and energy injection at toe off as shown in figure 2. In configuration A, the center of mass is behind the foot and there is zero ankle torque. In configurations B and C, the center of mass is traveling forward. The ankle torque increases, thereby moving the center of pressure of the foot forward from the heel to the toe. In configuration D, the robot goes into toe off, releasing the energy stored in configurations B and C and perhaps injecting some more, through active torques, to maintain walking. A quadratic spring configuration that could give the ankle the desired compliance was used.

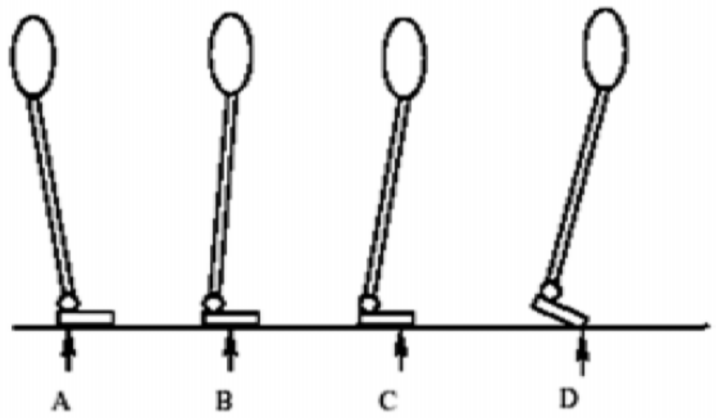

Figure 2: Diagram Illustrating Compliant Ankle

2.3 Passive Swing Leg

The human walkers use control techniques to control the swing leg along a trajectory to a desired landing position. However, with a suitable leg, the swing dynamics are such that once the swing starts, the leg will continue without any intervention, as illustrated in Figure 3. Gravity alone can be used to initiate swing, as in the case of the passive dynamic walkers. Hip torque can be added in order to make the leg swing faster. In this work, the passive swing properties of the leg were employed in the control. The hip was driven forward to a desired angle and the knee was allowed to swing freely. At the end of the swing, moderate damping was added to the knee to prevent from banging into the kneecap and finally it was locked once it hit the kneecap.

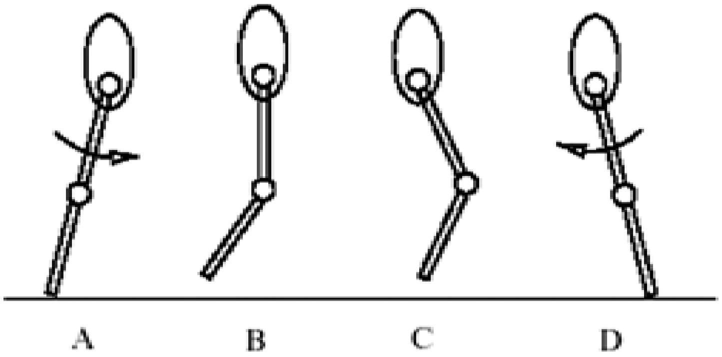

Figure 3: Diagram Illustrating Passive Swing

3. THE SIMULATION ALGORITHM

The dynamic mechanisms described above were employed in the control of a virtual human walking robot having seven links with twelve degree of freedoms. The simulation had an actuated hip, knee, and ankle on each leg.

Figure 4: Human Walking Robot

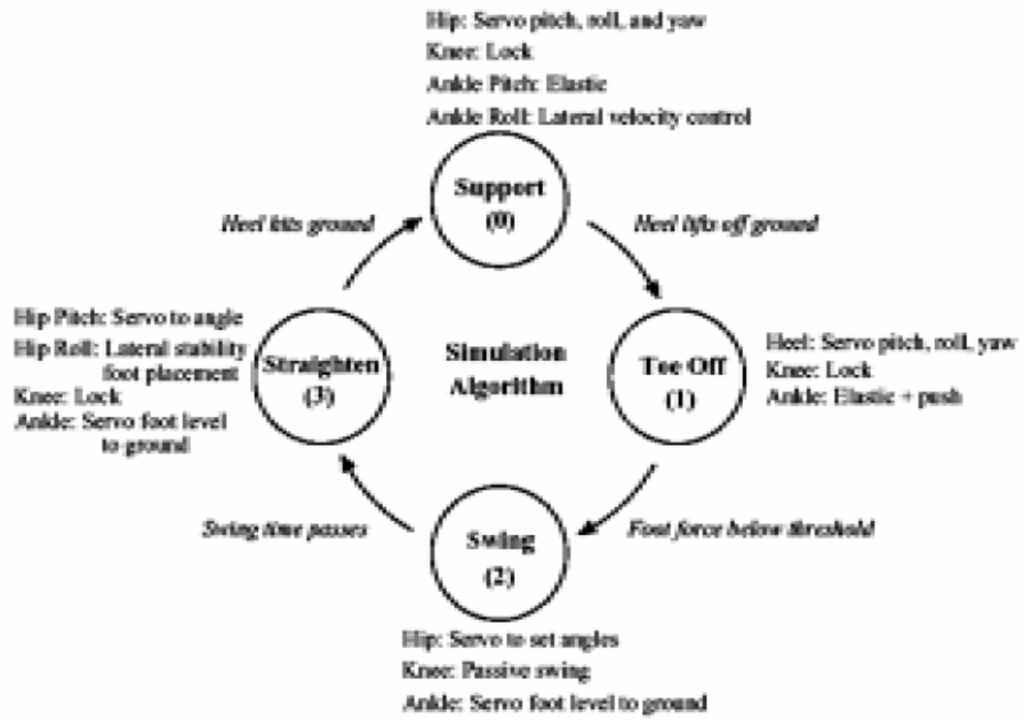

Figure 5: Simulation Algorithme

The simulation algorithm is summarized in Figure 5. Each leg acts separately and has a simple state machine. The leg can be in either support, toe-off, swing, or straighten states. In Support and Toe Off states, the hip is used to servo body pitch to maintain balance and the knee is locked to maintain height. In Support state, the ankle pitch is unactuated (only the passive ankle compliance is present). The ankle roll is used to dampen lateral velocity.

During Toe Off state, the ankle is servoed to an angle using a Proportional-Derivative (PD) controller in addition to its passive compliance. The transition from Support to Toe Off occurs when the heel lifts off the ground due to the passive compliance of the ankle.

The human robot transitions from Toe Off to Swing when the force on the foot falls below a certain threshold. In both Swing and Straighten states the hip pitch is servoed to an angle using a PD controller and the foot is servoed to be level with the ground so that the robot does not stub its toe. In Straighten state, the hip roll is used for lateral foot placement, to control lateral velocity. In Swing state, the knee is damped while in Straighten state the knee is locked straight using a PD controller. The human robot transitions from Swing to Straighten state after a constant amount of time passes. Finally, the human robot transitions from Straighten to Support state when the heel of the swing leg hits the ground.

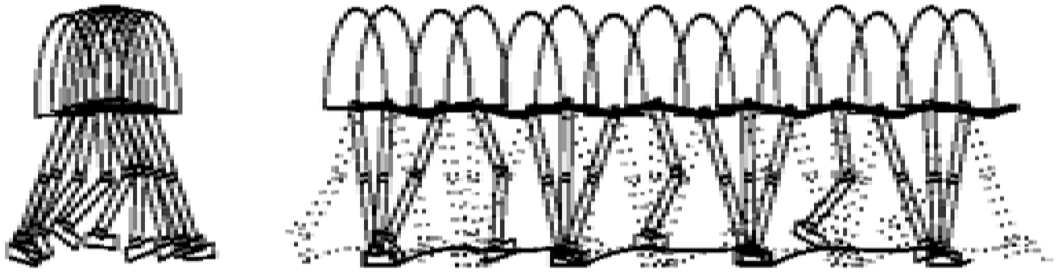

Figure 6: Elapsed Time Snapshot of the Simulated Robot Walking Data. The Right Leg is Dotted While the Left Leg is Solid. Lines Show the Path of the Tips of the Feet and the Hip Trajectory. The Robot Walks from Left to Right.

4. RESULTS AND DISCUSSION

The simulation parameters were first manually tuned, and then fine tuned using a genetic algorithm with efficiency as its cost function. Efficiency was computed as distance traveled divided by total joint energy after ten seconds of walking. Total joint energy was computed by integrating the total joint power, which is the sum of the absolute values of the mechanical power at each joint:

$$E_{total} = \int P_{total}\,dt \quad = \sum_{joints} \left| P_{joint} \right| \quad \text{where,} \quad P_{joint} = \tau_{joint}\,\dot{\theta}_{joint}$$

After a couple generations, the walking resulted. A time-elapsed animation is shown in Figure 6. The drawings on the left show the swing phase of one leg. The drawings on the right show several steps. The right leg is dotted while the left leg is solid. Lines show the path of the tips of the feet and the hip trajectory. The results are plotted graphically in Figure 7. It can be observed that the simulated robot walked at a moderate speed (approximately 0.8 m/s). It is interesting that the algorithm does not contain any explicit speed control mechanism, yet speed is stabilized. This is due to the dynamic mechanisms.

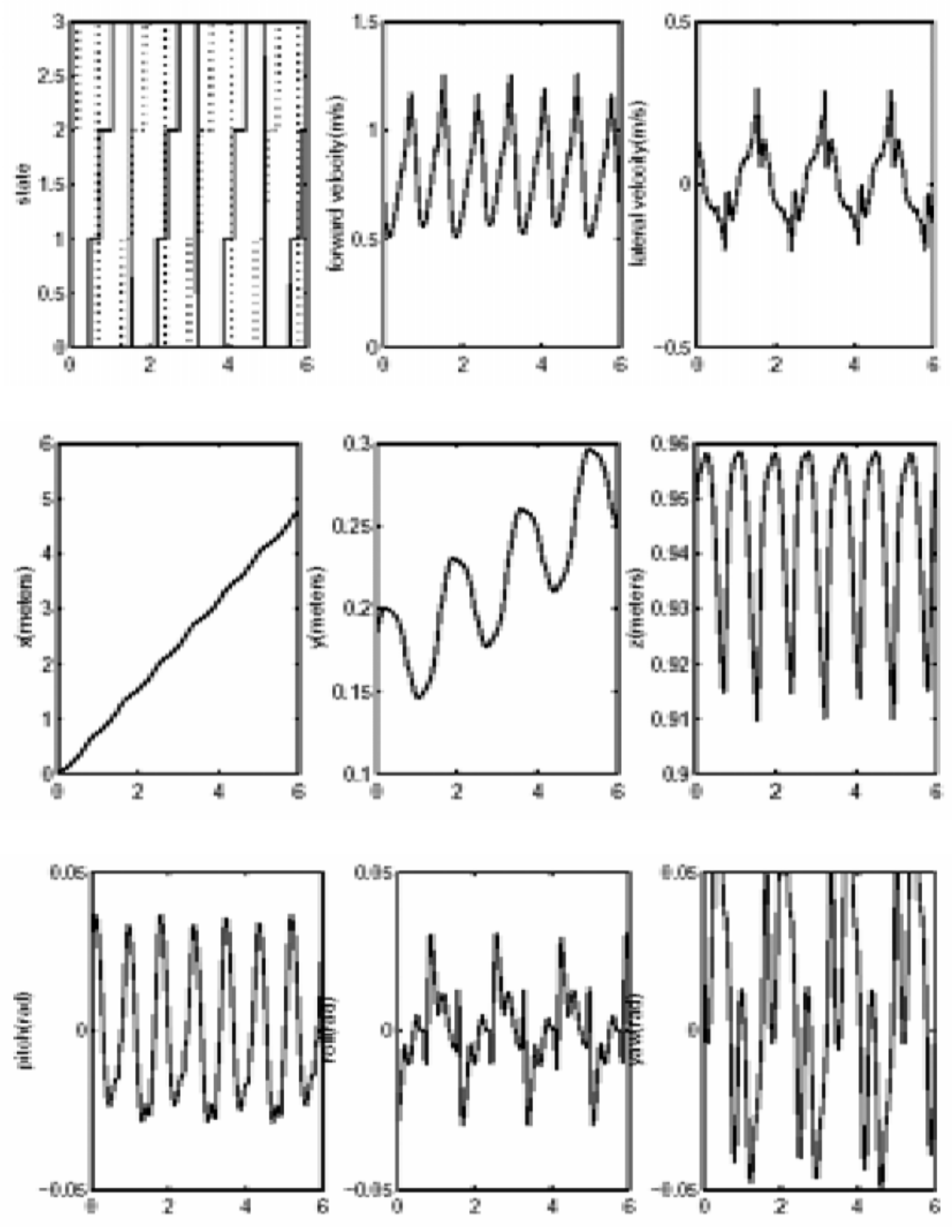

Figure 7: Simulation Data. The First Row Contains, Left to Right, State of the Legs, Forward Velocity, and Lateral Velocity. The Second Row Contains Forward Distance, Lateral Motion, and Body Height. The Last Row Contains Body Pitch, Roll, and Yaw.

5. CONCLUSIONS

The human walking can be achieved by a simple control algorithm, which exploits the dynamics of a kneecap, compliant ankle, and passive swing leg. The resultant motion is fairly smooth and efficient. This work may help bridge the gap between passive dynamic walkers and powered bipedal robots. The simulation settles on a stable speed of walking of approximately 0.8 m/s. It is believed that the speed is stabilized in a similar way to passive dynamic walking machines. That is, if the robot goes too fast, it takes a longer step due to the swing leg dynamics and hence slows down on the next step. Similarly, if the robot moves too slowly, it takes a shorter step and hence speeds up on the next step.

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