INTRODUCTION

Over the past years, several studies have investigated how much of the human walking motion can be modeled with passive dynamics (e.g. Garcia et al., 1998; Kuo, 2002; Wisse et al., 2004). However, only a few studies have been done on a flat foot shape in passive dynamic models (e.g. Kwan Hubbard, 2007). These studies proposed that the flat foot with a geometric parameter (foot length) can introduce a toe-strike collision in addition to the heel-strike impulse and influence the passive dynamics of walking. It has been investigated that flat feet can distribute the energy loss per step over these two collisions. Additionally, experiments on human subjects and robot prototypes revealed that the tendon in ankle joint is one mechanism that favors locomotor economy (Fukunaga et al., 2001; Collins et al., 2005). However, no effort has been made to analyze the adaptability and stability of adding compliant ankles to passive dynamic models that have flat feet.

The general goal of this study was to provide insight on the role of ankle compliance in human walking, by using a passivity-based bipedal locomotion model that is more close to the human motion in view of walking stability and adaptability.

MODEL

We proposed a 2D passivity-based bipedal locomotion model that consists of two three-segmented rigid legs interconnected through a passive hinge with a rigid upper body connected at the hip, as shown in Fig.1. The foot is mounted on the ankle with a torsional spring. A kinematic coupling is used to keep the body midway between the two legs.

![Figure 1. Model and walking sequence of the passive dynamic walker with flat feet and compliant ankle joints.](image-url)
by the spring on the swing leg should be considered as external force.

RESULTS AND DISCUSSION
By introducing flat feet and ankle compliance, the bipedal walking has a specific resistance of 0.06 at a scaled speed of 0.45 (walking speed/leg length). It is more efficient than not only the passive dynamic model with upper body (Wisse et al., 2004), but also human beings walking at the similar speed (Ralston, 1958). We found that the model is stable for small disturbance, with parameter values from Table 1 and a certain combination of initial conditions (\(\alpha_1(0)=-0.20203, \alpha_3(0)=-0.89034, \dot{\alpha}_3(0)=-0.17253\)). In addition, by applying the cell mapping method, we found that the model performs well in the concept of global stability. This can be inspected by the evaluation of the basin of attraction as shown in Fig.2(a). One can find that such cyclic walking emerges even if the initial step is nearly fourfold as large. Fig.2(b) indicates that a relatively small ankle compliance \(k\) will lead to more stable points and an inappropriate \(k\) may be worse than a stiff ankle in the view of walking stability.

![Figure 2. Results of walking stability.](image)

By adding compliance to ankle joints, the adaptability of bipedal walking is no surprise: the passive dynamic walker can achieve adaptive bipedal locomotion with larger ground disturbance on uneven terrain. Having the hip torque 0.38Nm and ankle spring 8.65Nm/rad, the passive walker performs a stable walking on the ground with -10mm disturbance with no active control. It indicates that by adding ankle compliance, bipedal walking can keep stable on uneven terrain with no active control. Fig.3(a) presents the results of terrain adaptability of walking with different ankle compliance. The relation between maximum allowable disturbance and ankle compliance is nearly linear. Big ground disturbance needs a small \(k\). Fig3(b) reveals that more ankle compliance results in more visible sensitivity to the hip torque.

![Figure 3. Results of terrain adaptability.](image)

Table 1. Parameters in simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>mass</th>
<th>length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body</td>
<td>0.81kg</td>
<td>0.62m</td>
</tr>
<tr>
<td>Pelvis</td>
<td>15.03kg</td>
<td>-</td>
</tr>
<tr>
<td>Thigh</td>
<td>0.56kg</td>
<td>0.45m</td>
</tr>
<tr>
<td>Shank</td>
<td>0.56kg</td>
<td>0.35m</td>
</tr>
<tr>
<td>Foot</td>
<td>2.05kg</td>
<td>0.15m</td>
</tr>
</tbody>
</table>

SUMMARY
In this paper, we presented a passivity-based bipedal locomotion model with flat feet and compliant joints. Both the theoretic analysis and the simulation results show that ankle compliance can improve the stability and efficiency of bipedal walking, which may reveal the role of ankles in human walking.

REFERENCES