A Comparison of a Passive and Variable-Damping Controlled
Leg Prosthesis in a Simulated Environment

JIE ZHAO∗, KARSTEN BERNS∗, ROBERTO DE SOUZA BAPTISTA† and
ANTÔNIO PADILHA L. BÔ†
∗Robotics Research Lab, University of Kaiserslautern,
Kaiserslautern, 67655, Germany
∗E-mail: {zhao,berns}@informatik.uni-kl.de
†Automation and Robotics Laboratory, University of Brasília,
Brasília, Brazil

This paper presents two control methods for a leg prosthesis: a passive based
and a variable-damping based. First, the concept of the mechanical design for
the leg prosthesis is described. A simulated environment is used to compare the
two control methods. The joint setup and its control scheme, in which a passive
or a variable-damping control can be easily implemented, are introduced for
the prosthetic leg in the simulated environment. Intelligent prosthesis require a
specific adjustment for each gait phase based on kinematic events of knee and
ankle joints along a gait cycle. A feasible damping profile is generated based
on kinematic and dynamical data of the knee joint along a gait cycle. This
data set was extracted from a simulated biped which is 1.8 m in height and
76 kg in weight with 21 degrees of freedom during normal walking. The data
show that the damping profile is critical between the toe-off and heel contact
events. Tests using the simulated biped with the passive and the variable-
damping controlled leg prosthesis during walking enables the comparison of
both control approaches.

Keywords: Leg prosthesis; Variable-damping control; Passive control; Rough
terrain

Introduction

Amputations of lower limbs, which can occur due to trauma, infections
or other diseases, significantly decreases a person’s quality of life. Among
all basic locomotion affected walking is critical when compared to other
movements. This paper addresses the use of new tools in the development
of control strategies for artificial legs and presents a comparison between
two distinctive control methods, since its merits and drawbacks are still not
clear. In the next sections, we start by describing the mechanical design of ongoing leg prosthesis, its working principles and hardware setups. Based on the mechanical setup, a passive control scheme for one joint will be briefly introduced. Next, by parsing captured kinematic and dynamical data from an existed simulated biped, a variable-damping controller is developed for the leg prosthesis. We test both controllers on a simulated human with a leg prosthesis and demonstrate their performances. Results demonstrate both merits and drawbacks of each control method.

Mechanical Design of Leg Prosthesis

The knee module of the ongoing leg prosthesis project is a polycentric knee mechanism with adjustable damping ratios. The main advantages of a polycentric mechanism is a combination of stability at full extension, i.e. in stance phase of gait, and better foot clearance in the swing phase of gait.\cite{1,2} As in various polycentric knee designs, our polycentric mechanism is based on a four bar linkage system.\cite{3} A magnetorheological piston is integrated to the prosthetic knee to provide damping adjustment of the mechanism. Magnetorheological fluids alter its viscosity in the presence of a magnetic field. A piston, or damper, filled with this type of fluid provides a continuously variable damping force controlled by a desired input.\cite{4} In our project we used a commercially available magnetorheological piston from Lord Corporation. In this device, the magnetic field through the magnetorheological fluid is induced by an electric current, which is the control input to adjust the damping coefficient of the system. The prosthetic knee module prototype is currently in the finishing phase of production as shown in Fig. 1. The goal of this project is to investigate different control strategies taking into account human in the loop for above the knee amputees.

![Fig. 1. Mechanical configuration of leg prosthesis in a simulated biped and prototype.](image-url)
Joint Setup and Control

The main feature of the joint setup is constant stiffness and damping, which makes the joint compliant. Each joint consists of a parallel elastic element and damper, except for prosthetic knee joint that has an additional variable-damping control. Figure 2 presents the torque computation applied to implement a constrained rotational movement of the prosthetic knee and the passive joints at the ankle. Given the constant equilibrium point $\theta_0$ of the spring and the actual joint angle $\theta$, the resulting torque is computed as

$$
\tau_{\text{spring}} = \text{sgn} (\theta_0 - \theta) \cdot K_{\text{spring}} \cdot (\theta_0 - \theta)^2.
$$

The combined torque for the joint can be computed as

$$
\tau = \tau_{\text{spring}} - \tau_{\text{damping}} - \tau_k,
$$

with $K_{\text{spring}}$ being the spring stiffness. Constant damping at each joint is represented by the torque $\tau_{\text{damping}}$ which is proportional to the joint’s angular velocity while $\tau_k$ represents the torque generated by the variable-damping controller at the knee joint if it is activated. Thus, for passive

![Diagram of variable-damping controlled knee joint](image2.png)

Fig. 2. A variable-damping controlled knee joint. Other two passive joints don’t contain elements inside dashed rectangle.
joints the combined torque should not include the last part of Eq. (2), i.e. $\tau_k$.

**Computation of Damping Coefficient at Knee Joint**

Kinematic data of the knee joint along gait cycle was obtained simulating a biped in a dynamic environment within the scenario of flat ground walking, as shown in Fig. 3. The power consumption profile at the knee joint after toe-off and before heel strike generally has negative magnitude. Associating this feature to the physical damper, the knee can be modeled as a variable-damper in this phase.

![Fig. 3. Knee angle, velocity, torque and power along gait cycle.](image)

The effective damping variable $B_k$ is the ratio between the knee torque $\tau$ and knee velocity $\dot{\theta}_k$. By using the data set illustrated in Fig. 3, the damping coefficient can be directly calculated, as shown in Fig. 4.

According to Fig. 4, the damping coefficient can be characterized as a function of knee angle:

$$B_k(\theta_k) = \begin{cases} 
B_{k_{\text{low}}} + \frac{B_{k_{\text{up}}}}{\theta_{k_{\text{up}}} - \theta_{k_{\text{low}}}} \cdot (\theta_k - \theta_{k_{\text{low}}}), & \text{if } \theta_k > \theta_{k_{\text{low}}} \\
\infty, & \text{otherwise}
\end{cases}$$

In Eq. (3) $\theta_{k_{\text{low}}}$ and $\theta_{k_{\text{up}}}$ represent a range in which knee joint can be modeled as a variable damper whereas $B_{k_{\text{low}}}$ and $B_{k_{\text{up}}}$ indicate the damping

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*The detailed control architecture, i.e. biologically inspired control of a dynamically walking bipedal robot can be found in*\(^5\)
Fig. 4. Knee damping coefficient along the knee angle during gait cycle.

The variable-damping controlled leg prosthesis consists of one knee joint and ankle joints in both sagittal and frontal plane. Except for the variable-damping controlled knee joint, others joints are passive elements with fixed stiffness and damping. A sliding joint is placed between top of the amputee’s stump and the knee joint, whereas another is situated between knee and ankle joint. Those two sliding joints, which are shown in Fig. 1, provide a constant stiffness and lock mechanism that is used to lock knee angle during late swing phase and stance phase.

Fig. 5. A simulated biped with a left prosthetic leg.

Meanwhile, the mechanically passive prosthesis consists of three passive joints, e.g. knee joint, ankle joint in sagittal and frontal plane. The stiffness coefficient at $\theta_{k_{low}}$ and $\theta_{k_{up}}$, respectively.

Simulation Results

The variable-damping controlled leg prosthesis consists of one knee joint and ankle joints in both sagittal and frontal plane. Except for the variable-damping controlled knee joint, others joints are passive elements with fixed stiffness and damping. A sliding joint is placed between top of the amputee’s stump and the knee joint, whereas another is situated between knee and ankle joint. Those two sliding joints, which are shown in Fig. 1, provide a constant stiffness and lock mechanism that is used to lock knee angle during late swing phase and stance phase.
and damping ratio for each joint are predefined and can not be adjusted during the walking phase as shown in Fig. 2.

**Walking on the Even Ground**

We first simulated the normal walking at a speed of 1.21 m/s on an even platform without the presence of external disturbances. The results allow a detailed evaluation of the calculated damping coefficient for the variable-damping controlled leg prosthesis and the capability of the passive leg prosthesis.

The kinetic data set of both types of prosthesis in this walking scenario is illustrated in Fig. 6. Figures 6 (a) and (b) show the joint angles of passive and variable-damping controlled prosthesis respectively. One can observe that the courses of the kinematic data of the passive controlled joints are actually more stable during gait cycle. Those curves present nearly similar course during the gait cycle, which means that the choice of the damping constant for passive prosthesis is also proper. The joint torques of passive and variable-damping controlled prosthesis are shown in Fig. 6 (c) and (d), respectively. The courses of torque generated in the passive joints have nearly similar profiles as those in variable-damping controlled prosthesis.
which means they have almost the same performance on energy consumption. However, while the variable-damping controlled prosthesis requires extra mounting of electronic devices and thus more energy consumption, the variable-damping controlled prosthesis exhibits no advantage in this aspect.

Walking on the Rough Terrain

We have also tested walking in scenario of an uneven terrain with the unevenness up to about 3.3 mm. Simulation results show that the variable damping controlled prosthesis is more adaptable to unknown rough terrain than the passive prosthesis. Figures 7 (a) and (b) show the joints angles of passive and variable-damping controlled prosthesis individually. The variances of joint angles of passive controlled prosthesis are clearly larger than those in variable-damping controlled prosthesis. The joint torques of passive and variable-damping controlled prosthesis are shown in Fig. 7 (c) and (d), respectively. The curves representing the passive controlled prosthesis show greater dynamic variations of joint angles along a gait cycle, which means more energy is required for keeping stability.

Table 1 exhibits standard deviations of the joints in prosthetic legs in walking scenarios of flat ground and uneven terrain respectively. All joint variables are captured from experiment of 10 gaits. One can observe that the passive controlled prosthesis shows more deviations than the variable-
damping controlled one. Also, walking on the uneven terrain introduces more deviations on each joint due to unevenness of terrain. This result gives us a clue that using variable-damping controlled prosthesis will improve the stability of walking on unknown rough terrain compared to the passive one.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Flat Ground</th>
<th>Uneven Terrain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>passive</td>
<td>variable-damping</td>
</tr>
<tr>
<td>Hip Y</td>
<td>1.30°</td>
<td>1.24°</td>
</tr>
<tr>
<td>Knee Y</td>
<td>1.50°</td>
<td>1.34°</td>
</tr>
<tr>
<td>Ankle Y</td>
<td>1.50°</td>
<td>1.40°</td>
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<tr>
<td>Ankle X</td>
<td>1.32°</td>
<td>1.26°</td>
</tr>
</tbody>
</table>

**Conclusion and Future Works**

In this paper we described the development of a variable damping controlled for a lower leg prosthesis using a simulated environment. We then presented a comparison between a passive controlled and a variable-damping controlled prosthesis in different walking scenarios. Simulation results show that there is no obvious difference between two approaches on flat ground walking, but the variable-damping controlled prosthesis may need more energy due to extra electrical instrumentation. On the other hand, the variable-damping controlled prosthesis is more stable than the passive controlled prosthesis on rough terrain walking.

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**References**


\(^b\)http://www.capes.gov.br/
\(^c\)https://www.daad.de