

Crutch-assisted swing-through exoskeleton

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1 Introduction – Tool-assisted Humanoid Locomotion

Humanoid locomotion is the motion performed by a subject in humanoid shape. It can be a human being, a humanoid robot or a hybrid system consisting of human being and some robotic devices. Biped locomotion is the most common type of humanoid locomotion in daily practice. However, in case of some challenging terrains or people suffering injuries, the introduction of some tools to help with the locomotion is the most popular approach. The tools can provide more contact points with the ground to render the possibilities of dealing with the challenges.

The tool-assisted locomotion in human beings appears in many cases. When climbing mountains, the terrain is rugged and can bear characteristics of slippery and deformation. Biped walking in this case may not provide satisfying stability performance. Trekking poles are then introduced to extend the arm and enable ground contacts of the upper body. Locomotion with the additional contacts can be viewed as a variety of quadruped gait. Thus falling is less possible to happen. Another case is when human is carrying heavy loads. With the help of a stick, a closed-chain system exists no matter one leg or the stick is in the air. Consequently, the load redistribution is possible between upper and lower bodies to alleviate the high torque required in legs. Also for people with impaired visual capabilities, a stick can help with the detection of terrain conditions. On the other hand, tools are helpful in case of human injuries. When one leg cannot provide reliable contacts with the ground, axillary crutches can help the injured people to recover walking. The synchronized crutches can be viewed as the substitute of injured leg to provide contacts with the ground.

As for humanoid robots, the focus has been primarily on biped locomotion. The prevailing approach is to design gaits and controllers for stable and natural walking. Few works have been done to realize tool-assisted locomotion on humanoid robots. The only related research is the crawling motion on small-size humanoid robots like NAO. With hands on the ground, the resulting quadruped gait provides better stability. However, such crawling motion is not suitable for full-size humanoid robots like ASIMO or HUBO. The heavy weight of such robot can cause potential damage to the robot. Enlightened by human walking with trekking poles, introducing two canes held by hands in assisting the locomotion is believed to be advantageous for humanoid robots especially in rough terrain walking. In [1], we call this Ski-type gait and studied the

stability improvement. Canes are designed and comparison experiments with biped gait are performed on the grass terrain. The results validate the benefits of introducing tools to improve stability.

Lower-extremity prostheses and exoskeletons can also be categorized as tools to provide more contacts with the ground. Such prostheses are used to replace the missing leg and recover the original reliable contact with the ground. Lower-extremity exoskeletons are designed for paraplegic people. Suffering from the spinal cord injury, the patients are capable of controlling the lower body. Exoskeletons are attached on legs and thighs to make them move. Two typical exoskeletons are designed by ReWalk and Vanderbilt University, respectively. The ReWalk exoskeleton [2], which is approved by U.S. Food and Drug Administration (FDA) purely rely on the exoskeleton to drive people's motion [3]. Both exoskeletons are designed to recover biped walking in the paraplegic people. Consequently, both hip and knee joints exist. One typical feature is that the forearm crutches are necessary to move around. The crutches function in two aspects. Firstly, the motion control of exoskeleton is not perfect so crutches can help maintain stability with the help of human upper body interaction. Also the crutches function as the human intention sensing like a forward walking or climbing stairs is to be performed. Since both hip and knee consist of active joints, the power supply of such devices is usually huge. Consequently, a backpack battery is necessary to ensure the operation duration. The large battery will definitely harm the mobility of such devices. Moreover, the costs of these exoskeletons are high because as many as four joints need to be actuated.

To improve the energy efficiency and lower the costs of lower-extremity exoskeleton, we propose to apply the swing-through gait with axillary crutches. The emphasis is more interaction between human upper body and lower extremity exoskeletons.

2 Swing-through exoskeleton

In human crutch-assisted walking, the synchronized pair of crutches acts as one leg and the uninjured leg act as the other one. The two effective legs swing forward and touch the ground alternatively and then people can move forward. This kind of motion can be modeled as a synthetic rimless wheel. The most typical example of this type is the passive walker developed by McGeer [4]. A fully passive walker can move downslope purely driven by gravity. In our design, the system should walk on flat surface so

we need actuation. In our exoskeleton design for performing crutch-assisted gait, active knee joint is proposed to enable the possibility of standing and to ensure leg clearance in more complex cases than level walking.

As shown in Fig. 1, we separate the walking cycle into two phases. It is Phase-A when crutches are on the ground and human body swings, and Phase-B when crutches are swinging in the air. The separation is due to the fact that crutch is a whole piece of rigid body with no effective knee joint. Then the gait looks like a typical biped motion with human shoulder joint as the ‘hip joint’.

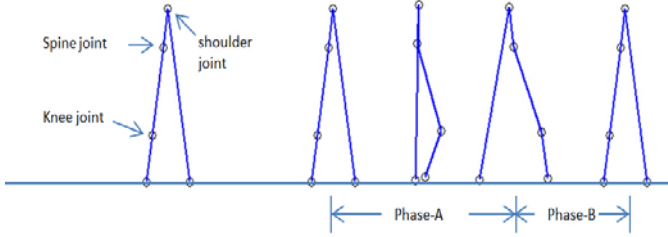


Figure 1 Proposed crutch-assisted walking

Another creative thing is the addition of the spine joint and elimination of hip joint on human body in our modelling. The prevailing exoskeleton design consists of hip joints to enable normal biped walking. In the crutch-assisted gait, the shoulder joint pins the two links together. Thus an active hip joint is unnecessary. So the number of actuation and weight of the system are reduced. The addition of spine joint can provide more possibilities in collaboration from the human upper body. Though the bending limit of the spine is small it is very powerful. We model the torso to be two rigid bodies of same length connected by the spine joint.

Suppose the state of the system is x , which is a vector consists joint angles and angular speed, we use x_A^-, x_A^+ , x_B^-, x_B^+ to denote the end point state of Phase-A and Phase-B, respectively, where the superscript “-” and “+” mean the phase beginning and ending points. Then we have the following system equations:

$$x_A^+ = f_A(x_A^-, T_A(t_A)) \quad 0 \leq t_A \leq \tau_A \quad (2.1)$$

$$x_B^+ = f_B(x_B^-, T_B(t_B)) \quad 0 \leq t_B \leq \tau_B \quad (2.2)$$

$$x_B^- = f_{AB}(x_A^+) \quad (2.3)$$

$$x_A^- = f_{BA}(x_B^+) \quad (2.4)$$

Eqn. 2.1 models the dynamics of Phase-A relating the beginning and ending state. τ_A stands for the duration of the phase and $T_A(t_A)$ is the time dependent active torque input. The notations are similar in Eqn. 2.2 for Phase-B. Eqn. 2.3 and 2.4 models the support transfer from Phase-A to Phase-B and the other way, respectively. Also after two steps the state repeats, which ensures a periodic motion. To determine the optimal periodic motion, we choose the criterion minimizing the required active torque provided both by the exoskeleton and human body. If C is the weight coefficient matrix for the active torques, the optimal can be fixed by:

$$\min_{x_A} C(T_A + T_B) \quad \text{subject to Eqns. 2.1 – 2.4}$$

As illustrated in Fig. 1, we make the hip joint passive by locking it using some devices like hip brace for easy installation. For the active knee joint, we decide to attach it to human body using belts or knee braces, which is the prevailing approach. The most crucial problem is the design and motor choice of the knee joint. We hope to make it compact in size for users’ convenience. So we make motor and speed reducer two separate parts which are aligned using pulleys for transmission. Through a preliminary dynamic simulation of Phase-A based on human of 175cm and 75kg with the body segmentation data in [5]. We found that for the clearance of swing forward motion, the maximum torque is around 3 Nm.

To make our gait more natural and comfortable, we propose a passive damping strut across the rear part of foot. It can store energy in landing and push the rear part of foot pedal to help take off as shown in Fig. 2.

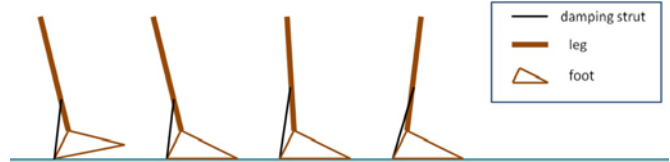


Figure 2 Passive damping strut cross ankle joint

References

- [1] H. Wang, S. Li, Y. Zheng, and P. Oh, “Ski-type self-balance humanoid walking for rough terrain,” *IEEE Int. Conf. Robotics and Automation (ICRA)*, vol. 2, 2014, pp. 1620–1626.
- [2] G. Zeilig and et. al., “Safety and tolerance of the ReWalk™ exoskeleton suit for ambulation by people with complete spinal cord injury: A pilot study,” *J. Spinal Cord Medicine*, vol. 35, no. 2, pp. 96-101, 2012
- [3] FDA approval of ReWalk: <http://www.fda.gov/NewsEvents/Newsroom/PressAnnouncements/ucm402970.htm>.
- [4] T. McGeer, “Passive dynamic walking,” *Intl. J. Robotics Research*, vol. 9, no. 2, pp. 62–82, 1990.
- [5] Human body segment data: <http://www.exrx.net/Kinesiology/Segments.html>