

# Ski-Type Self-Balance Biped Walking for Rough Terrain

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**Abstract**—This paper introduces a new approach for humanoid robot quasi-static walking for improving stability performance, which is called *ski-type walking*. By adding two canes held by hands, the supporting region and stability margin are enlarged in comparison with biped walking. We first study the mechanism of cane-assisted walking by human beings. Based on the study, we develop two ski-type gaits, Crawl\_1 and Crawl-2, respectively for the humanoid robot Hubo. The stability performance for the two configurations is compared, which leads to the adoption of the Crawl\_2 gait. Furthermore the length of the canes is selected to support a feasible while stable Crawl\_2 gait. Finally simulation and experiments are performed to verify the new ski-type gait.

**Keywords**— ski-type gait, biped robot, rough terrain, Hubo, OpenRAVE.

## I. INTRODUCTION

In the past two decades, biped locomotion has been widely researched in the humanoid robot field. Although some of the well-known humanoid robots such as Hubo by KAIST [1-2], ASIMO by Honda [3-4], and Petman by Boston Dynamics [5], etc. have demonstrated reliable biped walking under some perturbations, most of the experiments were conducted on flat or modestly rugged terrains. In general, biped walking algorithms are still not perfectly suitable for humanoid robots to reliably walk on real rough terrains such as grass, sand, rocks, etc. Walking on rough terrains by humanoid robot has never been seriously addressed except some earlier works on biped climbing slopes [6] or stairs [7].

In this paper, we describe a new gait called *ski-type gait*. The idea comes from human beings in negotiating rough terrains. When people climb a mountain, they often use canes to help keep balance. The advantages of canes are threefold. First, canes are held by hands; therefore, robot hands can be flexible for either manipulation or locomotion without a permanent modification. Thus the advantages of using hands for accomplishing certain tasks are maintained. Secondly, with canes held by hands, biped locomotion can be turned into quadruped locomotion almost instantly. Quadruped gaits are much more stable than biped gaits even on flat floors. Let alone rough terrains. Also quadruped gaits are quasi-static locomotion, for which an accurate dynamic model of the system is not required. That is advantageous under the circumstances of model inaccuracy or sensor failure, which occur regularly to walking robots. To our surprise, we could not find any work dealing with cane-assisted locomotion for humanoid robots. Simply no publication exists for the proposed ski-type gaits in the published literature.

We believe that our technical and design approaches for the so called “ski-typed gait”, allowing the robot to hold canes in hands, can solve the stability problem of humanoid robots walking on rough terrains, while maintaining the manipulating capability of the hands. That will bring significant impacts to the use of humanoid robots in different applications. In this paper, we describe the ski-type gaits, which we started in our earlier work [8], but will be studied in more robust terms, and analyze how it improves the stability of a humanoid robot. As described in our previous paper [8], the humanoid robot we used in our study is Hubo designed and manufactured by KAIST in South Korea [1-2]. The current study is sponsored by DARPA for the DARPA Robotics Grand Challenge Program.

The paper is organized as follows. A brief study of cane-assisted human walking is described in Section II. In Section III, the general design and the stability performance of two ski-type gaits are presented. In Section IV, strategies for determining the length of the cane to achieve feasible while stable ski-type gait is discussed. In Section V, experimental and simulation results are presented. Finally, our conclusions and future work are given in Section VI.

## II. CANE-ASSISTED WALKING FOR HUMAN

Usually human being can perform biped walking very stably relying on strong muscles and accurate biological sensing feedback in the legs. When the legs suffer some injuries, it turns out to be difficult keeping balance using the two legs only. In order to overcome the difficulties caused by injuries, cane is invented to help people walk. Since humanoid robot is not stable executing biped locomotion in rough or uneven environments, it can be viewed as leg-injured human beings. Consequently, it is beneficial to look into cane-assisted walking by human beings for designing reliable cane-assisted gaits for humanoid robots.

According to [9-10], the cane is usually held at the contralateral side of the injured leg. Here are some variables for specifying the gait.  $L_{fw}$  and  $L_{fl}$  are width and length of the foot pedal,  $L_{LF\_RF}$  is the distance between the centers of the two foot pedals,  $L_{LF\_Lcane}$  is the distance between the left cane and the center of the left foot pedal along the y-axis, and  $L_{step}$  is the step length. The variables are shown in Fig. 1. Some reasonable assumptions are made as follows:

1.  $L_{fl} = 2L_{fw}$
2.  $L_{step} = L_{fl}$
3.  $L_{LF\_Lcane} = L_{LF\_RF} = L_{fl}$
4. Projection of the center of mass (COM) is at center of un-injured foot pedal (left foot in this case) at the initial posture.

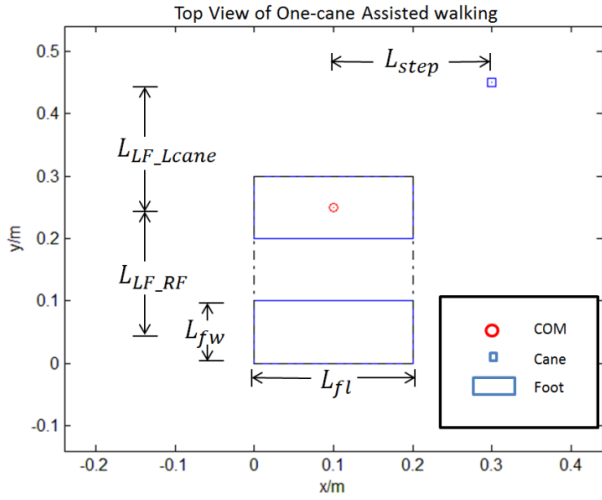


Fig. 1 Top view of one-cane assisted walking showing variables

The gait and supporting region when  $L_{fw} = 0.1\text{m}$  is shown in Fig. 2 (a)-(h). Starting from the initial posture, the cane is the first to move forward, and the COM is within the left foot. Then the right leg moves forward by the same distance as the cane, while the COM moves forward in the supporting area formed by the left foot and the cane tip. Then the right foot swings forward by the step-length with the COM in the supporting polygon formed by the cane tip and right foot. After three steps of motion, it is back to initial posture.

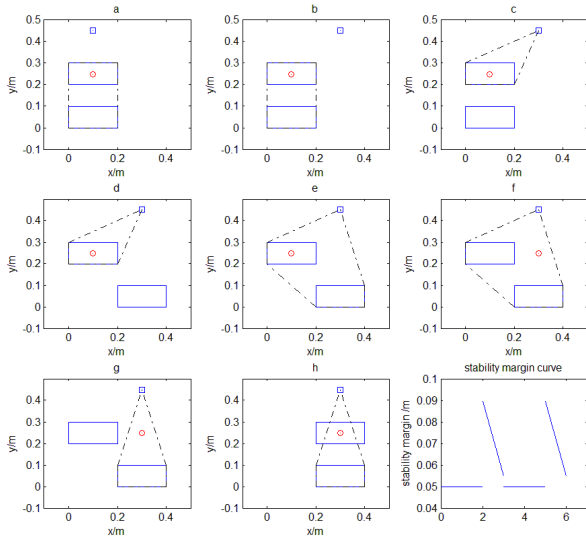


Fig. 2 Stability margin curve for one-cane assisted walking

From the stability margin curve in Fig. 2 (lower right corner), the minimum stability margin is  $0.5L_{fw}$ , which is greater than that of biped walking with the same walking parameters but without cane. One may notice a sudden change of the stability margin. That is due to the lifting and dropping of the cane tip bringing in instant change of the supporting area. So by introducing a cane to assist walking, the stability performance is improved. However, this cane-assisted walking is asymmetric with only one cane held

at the uninjured side. For humanoid robot, we introduce two canes held in both hands for two reasons. First, the gait can be symmetric which will make the gait planning simpler. And secondly the robot can be more stable with two canes. The details of the gait development are described in the next session.

### III. DEVELOPING SKI-TYPE GAIT

#### A. Why ski-type walking is better?

For biped walking robot, only the two foot pedals form the contact area. For relatively flat surface, current humanoid robots perform well enough for stable walking. But humanoid robots are challenged when they are expected to perform really tough tasks like rough terrain walking. In this scenario, biped walking gaits may not be enough because two contacting foot pedals provide relatively small supporting area. When stepping on debris, the zero moment point (ZMP) may fall out of the supporting area, thus the robot lose balance.

On the other hand, quadruped walking is much more stable than bipedal walking. Unfortunately performing quadruped walking on humanoid robot platform faces challenges as well. For instance, one has to bend forward or lie backward the body for hands touching the ground to perform quadruped walking. One problem is that arms are not strong or long enough to be used as legs for supporting. Furthermore the lengths of arm links are usually limited, so step-size range is limited by the singularity problem. Another challenge is that biped walking is more flexible and effective than quadruped walking, especially when the humanoid robot needs to perform manipulation tasks. So transitions between these two gaits are required if we periodically use quadruped walking for negotiating rough terrains. But transition consumes extra time and energy. Ski-type gait is developed to overcome the difficulties while respecting the limits of humanoid robot.

#### B. Considerations

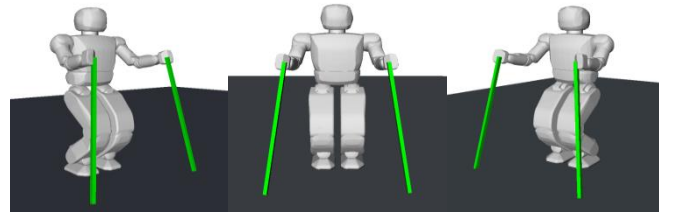


Fig. 3 Ideas of ski-type walking.

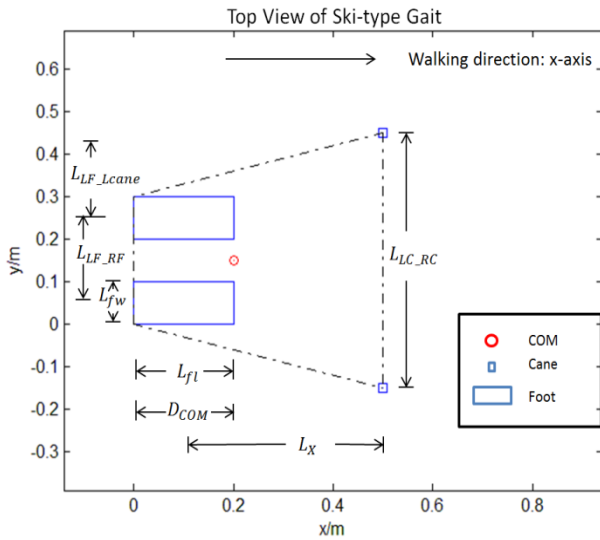
Fig. 3 shows the idea of ski-type walking. By holding two canes in the hands, the larger supporting area formed by two foot-pedals and two cane tips makes it more stable than biped walking. Compared with the bending forward or lying backward, the transition between biped and ski-type walking is more feasible and flexible by simply grasping the canes when the new gait is used. The canes can also be easily dropped when the hands need to perform manipulation tasks.

In the procedure of designing the ski-type walking, we start from making the canes vertically touching the ground. This is for the robot to keep balance easier. Since the cane tips touching the ground are considered to be point-contact

model, if the cane is not vertical, there will be a tangential force along the surface of terrain. To keep balance, the ground needs to provide enough friction force to prevent the tips from slipping. This requires the surface to have certain friction coefficient. So by making canes vertical, we assume there is no sliding at cane tips throughout the gait.

The second consideration is the COM position in the supporting polygon in the initial posture. When the robot is in the initial posture, the robot is a close-chain system thus the weight distribution has multiple solutions. The first consideration indicates that the canes are assumed to be vertically touching the ground, so the weight distribution depends on the reaction force at cane tips and the COM position. For humanoid robots, the arms usually have less power supply than legs. It is reasonable to put the COM near the feet rather than the cane tips. In this section, we assume the COM lies along the front edge of the foot pedals as shown in Fig. 4.

Fig. 4 Variables to specify ski-type gait.



The third assumption is about COM shift sequence throughout the ski-type gait. In traditional quadruped walking, there is no difference between arms and legs, and the COM moves forward whichever limb is swinging [11]. But in ski-type walking, the arms are supposed to bear less weight than legs. So the COM only shifts forward with the swinging legs. This pattern of COM shift is also valuable for rough terrain walking. Since there is no COM shifting during cane swing, the phase of cane motion can be used for detection the environment.

The last assumption is no sway throughout the whole walking period. This is for better comparison of the stability performance of different gaits.

### C. Step sequence choice.

With all the assumptions made in the previous section, another factor is the step sequence of the gait. Since ski-type gait is one kind of quadruped and quasi-static gait, one possible step sequence is like the creep/crawl gait. It is hand motion and leg motion of one side then the symmetric motion of the other side. However, there is another possible crawl/creep gait of sequence: right hand, left leg, left hand,

right leg, etc. Here we call the two step sequence Crawl-1 and Crawl-2, respectively.

#### C.1 Variables to specify ski-type gait

The variables for specifying ski-type gait is shown in Fig. 4 and listed as follows:

1.  $L_{fw}$ : width of the foot pedal.
2.  $L_{fl}$ : length of the foot pedal.
3.  $L_{LF\_RF}$ : length between the centers of the two foot pedals along the y-axis.
4.  $L_{LF\_Lcane}$ : length between the centers of the left foot and the left cane along the y-axis.
5.  $L_{LC\_RC}$ : length between two cane tips along the y-axis.
6.  $D_{COM}$ : length between COM and cane tips along the x-axis at the initial posture. According to the previous assumption for COM,  $D_{COM} = L_{fl}$ .
7.  $L_x$ : length between cane tips and the center of the foot pedal along the x-axis.
8.  $L_{step}$ : step length.

#### C.2 Comparison of Crawl\_1 and Crawl\_2

In this part, only one side of motion is shown because the gait is symmetric for both sides. And  $S_{min}$  stands for the minimum value of the stability margin.

The parameters are chosen as follow:  $L_{fw} = 0.1m$ ,  $L_{fl} = 0.2m$ ,  $L_{step} = 0.2m$ ,  $L_{LF\_Lcane} = 0.2m$ ,  $D_{COM} = 0.2m$ ,  $L_x = 0.5m$ ,  $L_{LC\_RC} = 0.6m$ ,  $L_{LF\_Lcane} = 0.2m$ .

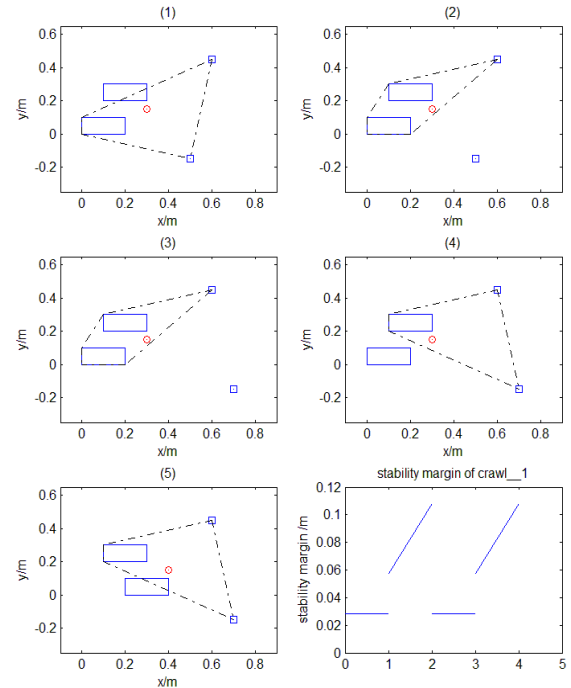


Fig. 5 Step sequence and stability margin of Crawl\_1

In Fig. 5 and Fig. 6, there is a jump in stability margin when switching end-effectors (canes and foot pedals) to swing. That is the result of a sudden change in the supporting polygon. Also the minimum stability margin occurs when a

cane is moving to the next position. In both Crawl\_1 and Crawl\_2, when the right cane is swinging, the stability margin is minimal. In Crawl\_1, the x-position of the right foot is smaller than that of Crawl\_2. So the supporting polygon results in smaller stability margin compared with Crawl\_2.

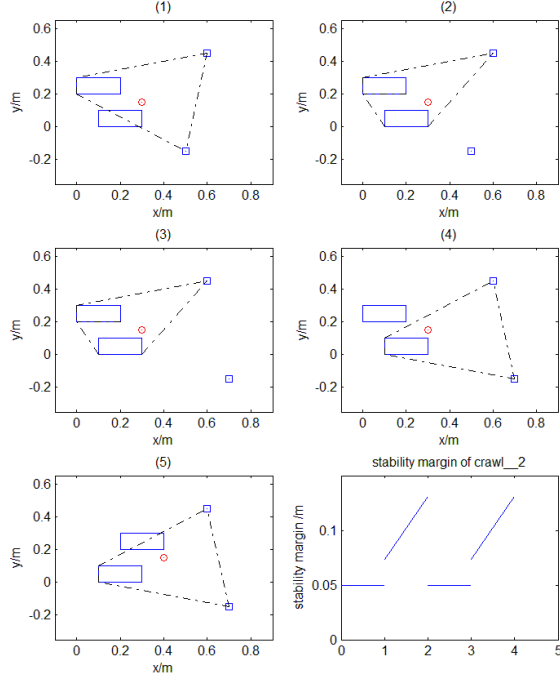


Fig. 6 Step sequence and stability margin of Crawl\_2

In conclusion, with the same walking parameters, the Crawl-2 step sequence results in larger  $S_{\min}$  and thus provides better stability performance for the ski-type gait. This conclusion is different from the optimal step sequence in [11]. In [11], the arms are treated as legs and the contacting points are all treated as point-contacting. But humanoid robots usually have foot pedals and only cane tips can be viewed as point. So Crawl-2 is chosen to be the step sequence of ski-type walking.

#### D. Different configurations for ski-type walking

From Fig. 4, once the dimensions of the foot pedal are fixed, the remaining variables that will affect the stability of ski-type gaits are:  $L_{\text{step}}$ ,  $D_{\text{COM}}$ ,  $L_x$ ,  $L_{\text{LF\_RF}}$ . In this part, the relationship between stability and each of the five variables is evaluated. If the variable is not considered a variable, the value is the same as that in the previous part.  $S_{\min}$  is selected as the stability performance criterion.

##### D.1 Relationship between $S_{\min}$ and $L_{\text{step}}$

The step size will directly change the supporting polygon of the triple supporting phase, so  $S_{\min}$  will change consequently. Fig. 7(a) shows the relationship between  $S_{\min}$  and  $L_{\text{step}}$ . The range of  $L_{\text{step}}$  is chosen to be 0 to 0.60m, three times the length of the foot pedals.

When  $L_{\text{step}}$  is relatively small,  $S_{\min}$  is constant because the shape of the supporting polygon is determined by  $L_x$ ,  $L_{\text{LF\_RF}}$ , especially where the  $S_{\min}$  occurs. But when  $L_{\text{step}}$  is large enough, the cross edge of supporting area, which is the line between left cane and right foot in Fig. 6(d), will change like rotating clockwise. Consequently, COM is closer and closer to this edge. When  $L_{\text{step}}$  increases to 0.6m, COM lies on this cross line. Thus  $S_{\min}$  becomes 0.

From the discussion above, when  $L_{\text{step}}$  is too large, the stability performance becomes worse. On the other hand, with larger  $L_{\text{step}}$ , both the supporting area and the walking speed can be increased. In practice,  $L_{\text{step}}$  should be chosen carefully based on the trade-offs to maximize the supporting area and traversing speed, and meet the stability criteria.

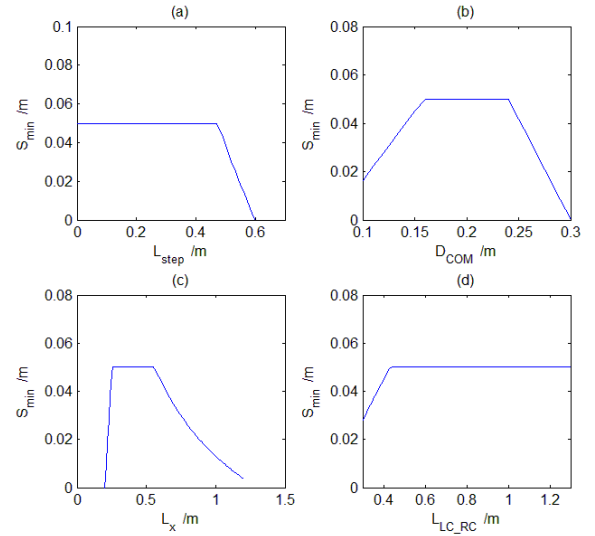


Fig. 7 Relationship between  $S_{\min}$  and  $L_{\text{step}}$ ,  $D_{\text{COM}}$ ,  $L_x$ ,  $L_{\text{LF\_RF}}$

##### D.2 Relationship between $S_{\min}$ and $D_{\text{COM}}$

$D_{\text{COM}}$  reflects the COM position with respect to the supporting area. Since ski-type walking should be different from bipedal walking, in our scenario, COM should lie before the center of the foot pedals:  $D_{\text{COM}} \geq 0.10\text{m}$ . As mentioned in the previous part, the arms of humanoid robot should bear less weight than legs. Although  $D_{\text{COM}}$  only reflects the weight distribution to some extent instead of determining it directly, it is reasonable to make COM at rear part of the supporting area at the initial posture. We choose  $0.10\text{m} \leq D_{\text{COM}} \leq 0.30\text{m}$ .

From Fig. 7(b), when COM moves from center to front edge of the foot pedal,  $S_{\min}$  increases to a constant. In the ski-type gait, COM only shifts forward when leg is swinging. In Fig. 6(d), if  $D_{\text{COM}}$  is smaller, COM will be closer to the edge between the left cane and the right foot. As a result,  $S_{\min}$  decreases.

On the other hand, if COM moves further over the front edge of the foot pedal,  $S_{\min}$  decreases to zero at some  $D_{\text{COM}}$ . In Fig. 6(d), increase of  $D_{\text{COM}}$  is better but in Fig. 6(c) it will make COM out of the supporting area. In practice, it will be best to choose some  $D_{\text{COM}}$  resulting in

the maximal  $S_{\min}$ . If the constant area exists, the best choice will be in the middle of it. Choosing  $D_{\text{COM}}$  by this strategy can not only make sure  $S_{\min}$  reach the maximum, but also allow a variation in  $D_{\text{COM}}$  without changing  $S_{\min}$ .

#### D.3 Relationship between $S_{\min}$ and $L_X$

Similar to  $L_{\text{step}}$ ,  $L_X$  will also affect the shape of the supporting area directly. It is reasonable to assume that canes are stretching forward. So  $L_X > 0.20\text{m}$ .

In Fig. 7(c), when  $L_X$  increases within a range,  $S_{\min}$  keeps unchanged. But further increase will result the drop of  $S_{\min}$ . The reason for the drop is similar to that in  $S_{\min}$  and  $L_{\text{step}}$ . However in practice,  $L_X$  cannot be arbitrarily large because of the link length constraints of robots. In most cases,  $L_X$  will not affect the stability performance too much.

#### D.4 Relationship between $S_{\min}$ and $L_{\text{LC,RC}}$

$L_{\text{LC-RC}}$  is the distance between two cane tips at the initial pose. Usually it should be larger than the value between the left edge of the left foot and the right edge of the right foot. So  $L_{\text{LC-RC}} \geq 0.30\text{m}$ .

In Fig. 7(c),  $L_{\text{LC-RC}}$  starts from  $0.30\text{m}$ , and  $S_{\min}$  increases to some constant value. In practice,  $L_{\text{LC-RC}}$  should be chosen somewhere leading to the constant  $S_{\min}$  based on kinetic constraints of the system.

In this section, it is obvious that the stability performance of ski-type walking is determined by several variables as  $L_{\text{step}}$ ,  $D_{\text{COM}}$ ,  $L_X$ ,  $L_{\text{LC-RC}}$ . In practice, the values of these variables are usually constrained by the kinetic model of the humanoid robot. Section IV is one practical example in the designing of the ski-type gait.

### IV. CANE LENGTH DESIGN

In this section, we consider the cane length to optimize the performance of the ski-type gait.

#### A. variables of ski-type gait

Fig. 8 shows the side view of the Hubo stick model holding two canes. The dimensions are based on the real robot. The following parameters are used to specify a gait:

1. Lean angle ( $\theta_{\text{Lean}}$ ): the degree between torso and vertical axis. This can be used to tune the center of mass (COM) position with respect to the supporting area. This position affects the torque required for each joint.
2. Ankle angle ( $\theta_{\text{ankle}}$ ): the angle between lower leg and vertical line. That parameter will affect the singularity of the legs significantly. A small angle leads more likelihood of singularity planning the ski-type motion.
3. Cane length ( $L_{\text{cane}}$ ): the effective cane length held in the hands.
4.  $L_X$ : the distance between the cane tips and the foot pedals when no step is made. This parameter directly

changes the shape of supporting area and thus affects the stability margin.

5. Step size ( $L_{\text{step}}$ ): the size of one step.

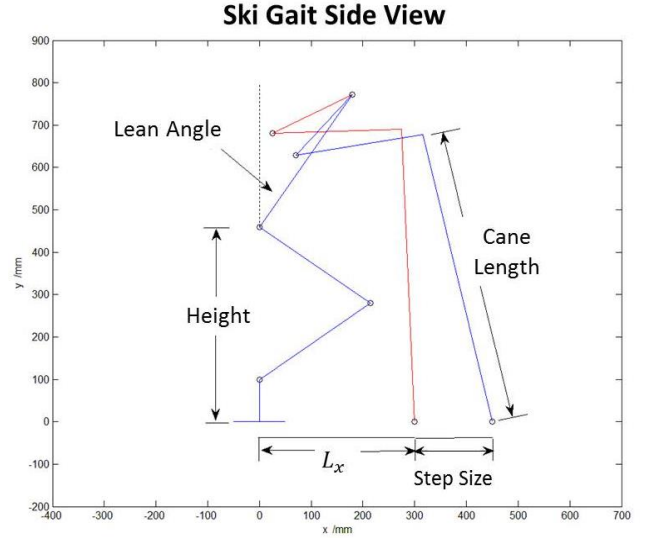


Fig. 8 Variables for developing ski-type gait

There is an assumption here: the hip joint is always above the ankle joint in the  $z$  direction. Since the lower leg and upper leg have the same length, we have  $\theta_{\text{knee}} = 2\theta_{\text{ankle}}$ . This assumption is made out of the following considerations. For humanoid robots, arms are usually not as strong as legs. That is true to Hubo which has relative small power supply in arms. To respect the power limit of humanoid, the weight should be sustained mainly by the legs. By making  $\theta_{\text{knee}} = 2\theta_{\text{ankle}}$ , the position of COM within the supporting area is basically near the feet end, but still can be tuned by the variable of  $\theta_{\text{Lean}}$ . So this assumption respects the power limits of humanoid robots and does not affect the flexibility of the ski-type gait. In the following two parts, the relationship between stability and  $L_{\text{step}}$ ,  $\theta_{\text{Lean}}$  is calculated respectively. And the step sequence is Crawl-2.

#### B. Relationship between $L_{\text{cane}}$ and $L_{\text{step}}$ range

The joint limits for Hubo are set to be:

- (1) Ankle pitch:  $0^\circ - 88^\circ$
- (2) Knee pitch:  $0^\circ - 160^\circ$
- (3) Hip pitch:  $0^\circ - 88^\circ$
- (4) Shoulder pitch:  $-90^\circ - 90^\circ$
- (5) Elbow pitch:  $0^\circ - 170^\circ$ .

We set  $\theta_{\text{Lean}} = 30^\circ$ ,  $L_X = 300\text{mm}$ ,  $H_{\text{Max}} = 25\text{mm}$ , and study the relationship between  $L_{\text{cane}}$  and  $L_{\text{step}}$  with different  $\theta_{\text{ankle}}$  values:  $20^\circ, 30^\circ$  and  $40^\circ$ . The results are shown in Fig. 9. Based on the results in Fig. 9, we choose  $L_{\text{cane}} = 750\text{mm}$  out of the following considerations. First, as ankle degree changes, the height and the valid step size range change accordingly. The value  $750\text{mm}$  can promise large step range for all scenarios. Secondly, we assume the cane touching the ground vertically. So  $750\text{mm}$  is around the height of torso which is a reasonable value. In the next section, we use  $750\text{mm}$  to be the cane length and added the



cane model in simulation for motion planning. And in experiment, the canes are exactly 750mm.

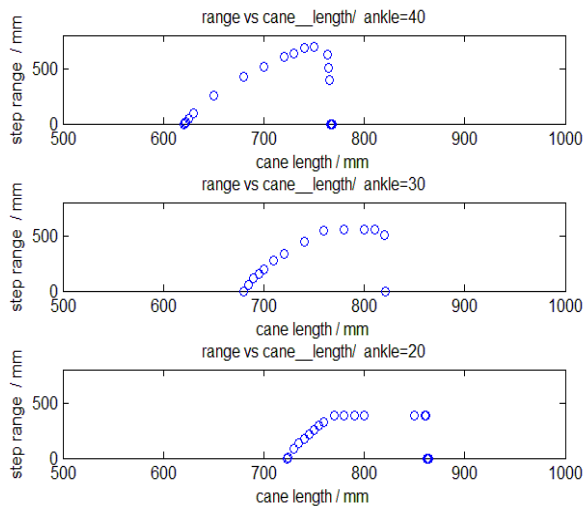


Fig. 9 Variables for developing ski-type gait

## V. SIMULATION AND EXPERIMENTS

Simulation is performed in OpenRAVE. The simulator OpenRAVE is developed by Rosen Diankov of CMU Robotics Institute. Based on OpenRAVE, Robert Ellenberg from Drexel University developed supplementary packages for simulation dealing with Hubo model. The simulation involves ODE physics engine for dynamics; therefore, the result is close to real-robot operation. Fig. 10 shows snapshots of simulation and the proposed ski-type gait is stable using the step sequence of Crawl\_2. As described earlier Crawl\_2 gait has better stability margin than Crawl\_1.

Succeeding in simulation, we further tested ski-type gaits on Hubo. The software used for controlling Hubo is Hubo-Ach [12-13], which is available in our laboratory. The experimental result is shown in Fig. 11 which also shows a stable walking using the Crawl-2 sequence.



Fig. 10 Hubo ski-type walking on flat surface in OpenRAVE.



Fig. 11 Hubo ski-type walking on grass

## VI. CONCLUSIONS

We have presented a new quadruped walking gait called ski-type gait for humanoid robots. By holding two canes in the hands, robot has larger supporting area than biped walking and has improved stability performance. Step sequences for the ski-type gaits have been studied and performances are compared. The result dictates the employment of the Crawl-2 gait. Furthermore, the effect of the cane length to the gait performance is also studied. From our simulation and experimental results, ski-type walking is proved smooth on flat floors and on grass.

## ACKNOWLEDGEMENTS

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