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Ski-Type Self-Balance Biped Walking for Rough Terrain

Hongfei Wang, Shimeng Li and Yuan F. Zheng
Electrical and Computer Engineering
The Ohio State University
Columbus, OH 43210 USA
Email:zheng@ece.osu.edu

Taegoo Kim and Paul Oh
Mechanical Engineering and Mechanics
Drexel University
Philadelphia, USA
Email: paul.yu.oh@drexel.edu

***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 Craw-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.

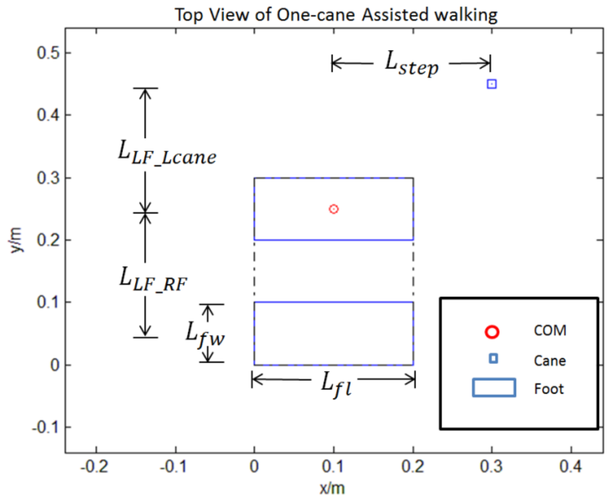


Fig. 1 Top view of one-cane assisted walking showing variables

The gait and supporting region when $L_{fw} = 0.1$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.

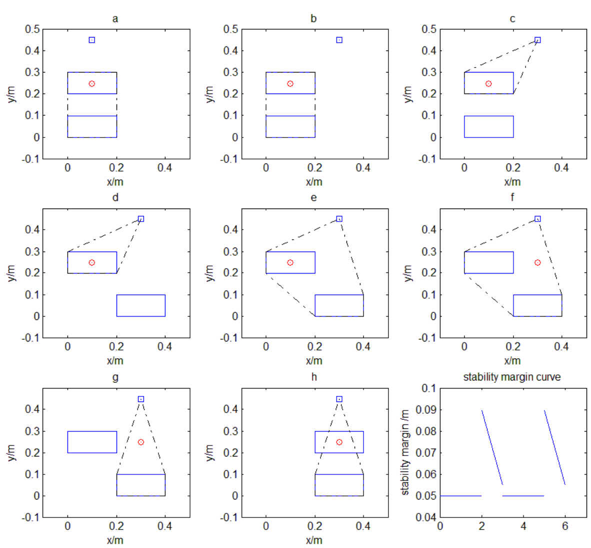


Fig. 2 Stability margin curve for one-cane assisted walking

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

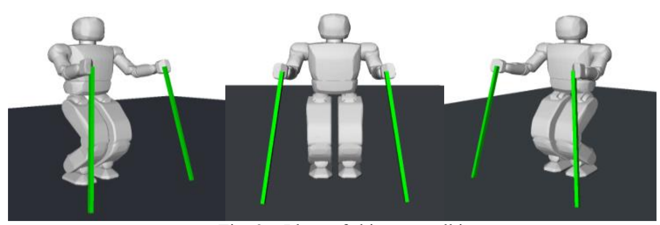


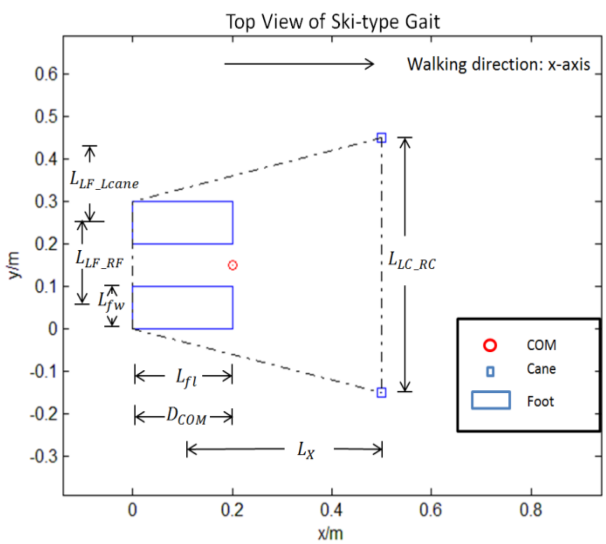
Fig. 3 Ideas of ski-type walking.

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: $L_{fw} = 0.1$m, $L_{fl} = 0.2$m, $L_{step} = 0.2$m, $L_{LF_Lcane} = 0.2$m, $D_{COM} = 0.2$m, $L_x = 0.5$m, $L_{LC_RC} = 0.6$m, $L_{LF_Lcane} = 0.2$m.

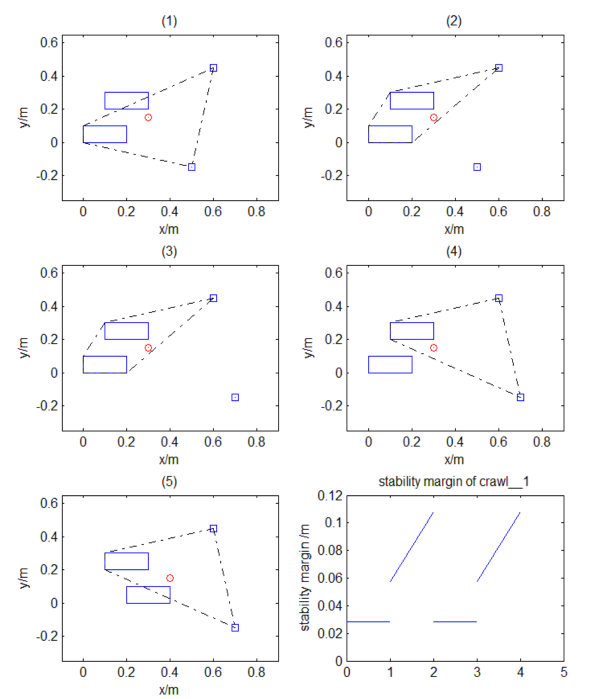


Fig. 5 Step sequence and stability margin of Crawl_1

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.

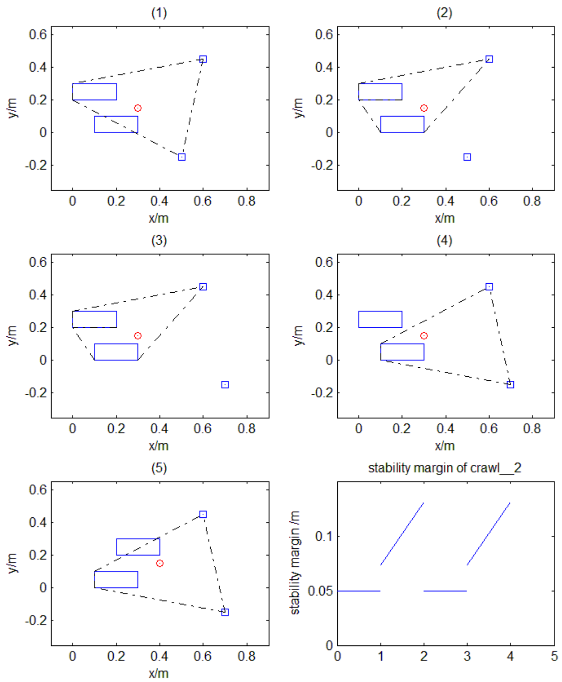


Fig. 6 Step sequence and stability margin of Crawl_2

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_{step}, D_{COM}, L_X, L_{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_{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_{step}. The range of L_{step} is chosen to be 0 to 0.60m, three times the length of the foot pedals.

When L_{step} is relatively small, S_{min} is constant because the shape of the supporting polygon is determined by L_x, L_{LF_RF}, especially where the S_{min} occurs. But when L_{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_{step} increases to 0.6m, COM lies on this cross line. Thus S_{min} becomes 0.

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

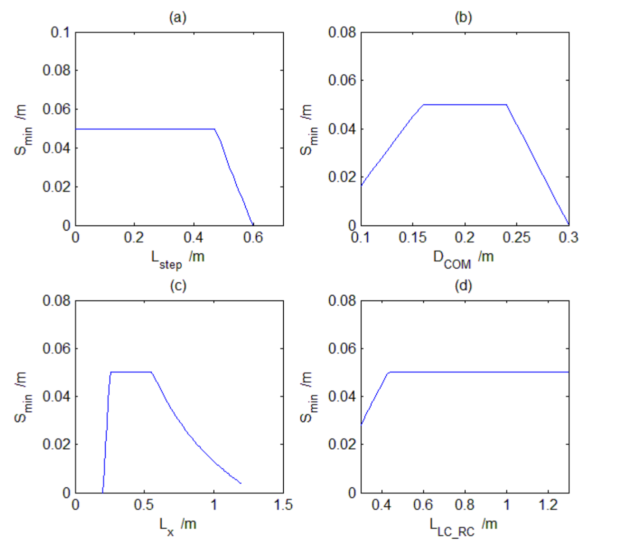


Fig. 7 Relationship between S_{min} and L_{step}, D_{COM}, L_X, $L_{LF_{RF}}$

D.2 Relationship between S_{min} and D_{COM}

D_{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 lies before the center of the foot pedals: $D_{COM} \geq 0.10$m. As mentioned in the previous part, the arms of humanoid robot should bear less weight than legs. Although D_{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 $0.10\text{m} \leq D_{COM} \leq 0.30\text{m}$.

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_{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_{COM}. In Fig. 6(d), increase of D_{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_{COM} resulting in the maximal S_{min}. If the constant area exists, the best choice will be in the middle of it. Choosing D_{COM} by this strategy can not only make sure S_{min} reach the maximum, but also allow a variation in D_{COM} without changing S_{min}.

D.3 Relationship between S_{min} *and* L_X

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

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_{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_{LC_RC}

L_{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 $L_{LC_RC} \geq 0.30$m.

In Fig. 7(c), L_{LC_RC} starts from 0.30m, and S_{min} increases to some constant value. In practice, L_{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_{step}, D_{COM}, L_X, L_{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 (θ_{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 (θ_{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_{cane}): the effective cane length held in the hands.
4. Lx: 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_{step}): the size of one step.

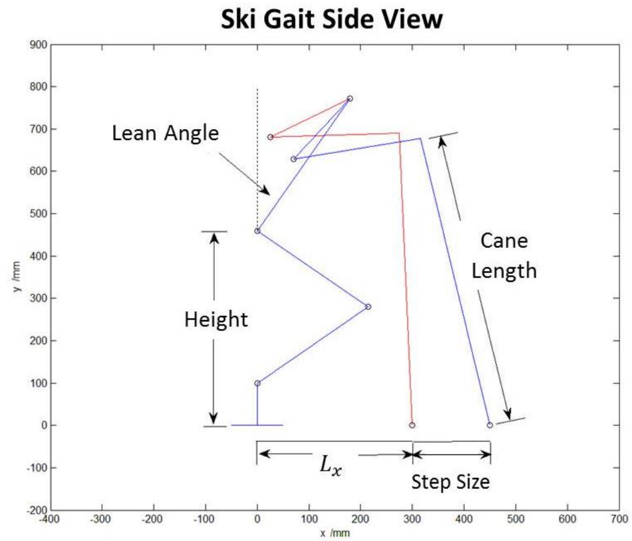


Fig. 8 Variables for developing ski-type gait

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 $\theta_{knee} = 2\theta_{ankle}$. 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 $\theta_{knee} = 2\theta_{ankle}$, the position of COM within the supporting area is basically near the feet end, but still can be tuned by the variable of θ_{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_{step}, θ_{Lean} is calculated respectively. And the step sequence is Crawl-2.

B. Relationship between L_{cane} *and* L_{step} *range*

The joint limits for Hubo are set to be:

(1) Ankle pitch: 0° - 88°
(2) Knee pitch: 0° - 160°
(3) Hip pitch: 0° - 88°
(4) Shoulder pitch: -90° - 90°
(5) Elbow pitch: 0° –170°.

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

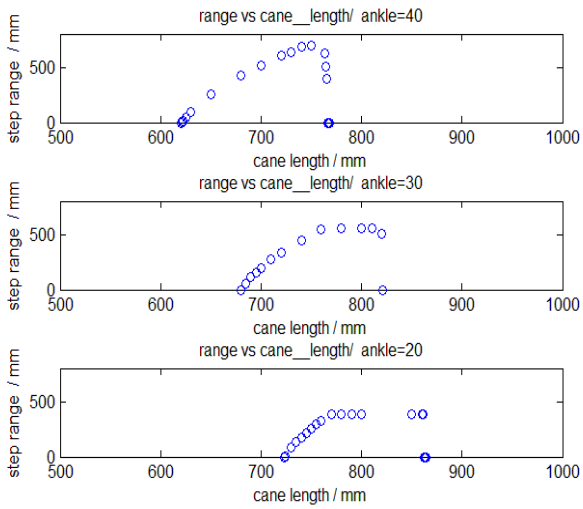


Fig. 9 Variables for developing ski-type gait

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.

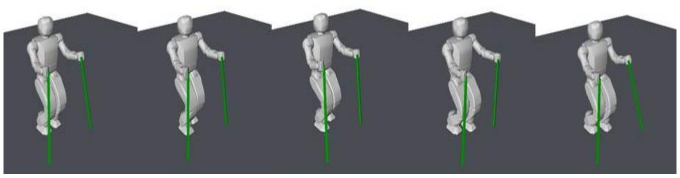


Fig. 10 Hubo ski-type walking on flat surface in OpenRAVE.

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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REFERENCES

[1] Ill-Woo Park, Jung-Yup Kim, Jungho Lee, and Jun-Ho Oh, "Online free walking trajectory generation for biped humanoid robot (KHR-3 (HUBO)," in *Proc. the IEEE Int. Conf. Robotics and Automation*, pp. 1231-1236, May 2006.

[2] Hubo Humanoid Robot, http://www.ros.org/wiki/Robots/HUBO.

[3] K. Hirai, M. Hirose, Y. Haikawa and T. Takenaka, "The development of Honda humanoid robot," in *Proc. IEEE Int. Conf. Robotics and Automation* , vol. 2, pp. 1321-1326, May 1998

[4] Asimo - The World Most Advanced Humanoid Robot, http://asimo.honda.com.

[5] Boston Dynamics, http://www.bostondynamics.com.

[6] Y. F. Zheng and J. Shen, "Gait Synthesis for the SD-2 biped robot to climb sloping surface," *IEEE Trans. Robotics and Automation*, vol. 6, no. 1, pp. 86-96, Feb. 1990.

[7] Jung-Yup Kim, Ill-Woo Park, and Jun-Ho Oh, "Realization of dynamic stair climbing for biped humanoid robot using force/torque sensors," *IEEE J. Intelligent and Robotic Systems*, vol. 56, no. 4, pp. 389-423, Nov. 2009.

[8] Y. F. Zheng et. al., "Humanoid robots walking on grass, sands and rocks," in *Proc. IEEE Int. Conf. Technologies for Practical Robot Applications*, pp. 136-141, 2013.

[9] J. F. Lehmann and B. J. De Lateur. "Gait analysis: diagnosis and management," *Krusen's Handbook of Physical Medicine and Rehabilitation*, Philadelphia, PA, 1990.

[10] W. P. Blount, "Don't throw away the cane," *J. Bone Joint Surg Am*, vol. 28, pp. 695-703, 1956.

[11] R. B. McGhee and A. A. Frank, "On the stability properties of quadruped creeping gait," *Mathematical Boisciences,* vol.3, no.2, pp.331-351, 1968.

[12] D. Lofaro, "Unified algorithmic framework for high degree of freedom complex systems and humanoid robots," *Ph.D. dissertation,* Dept. Elect. Eng., Drexel Univ., Philadelphia, PA, May 2013.

[13] M. Grey et. al., "Multi-Process Control Software for Humanoid Robots," in *Proc. IEEE Int. Conf. Technologies for Practical Robot Applications,* pp. 177-182, 2013.