Ice Skating Humanoid Robot

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Abstract. Current humanoid walking gaits are ill-suited to traversing low-friction environments such as ice. For robots to be useful outdoors in the winter they must be able to move across ice without falling over. In this paper we present a skating gait for a small humanoid robot equipped with ice skates to enable it to traverse indoor and outdoor ice surfaces faster than an inverted pendulum-based walking gait would allow.

1 Introduction and Motivation

Over the past decade dynamically stable humanoid walking gaits have been developed to allow robots to traverse flat terrain. Such gaits generally make the assumption that the ground is level (or nearly level), generally free of debris, and has a surface with sufficient friction to prevent the robot's feet from slipping (e.g. smooth concrete, thin carpet, ceramic tiles). When any one of these assumptions is violated the gait becomes unstable and the robot may fall over.

To be practical in many applications humanoid robots must be able to traverse uneven terrain. For example, robotic firefighters must be able to traverse a debris field. Even domestic helper robots must be able to deal with common household obstacles such as carpet edges, stairs, wet linoleum, or toys left on the floor.

The ability of a robot to traverse completely unstructured environments is a long term goal. Further research in sensors, materials, power, and intelligent control is necessary to achieve this goal. As an intermediate step we consider the problem of an ice skating robot. Icy surfaces such as skating rinks, frozen lakes, and icy concrete have little friction, but are generally flat and free of debris.

Navigating over ice patches is a requirement for any robot that is supposed to be useful in outdoor environments in polar or sub-polar regions, including Canada during the winter months. By designing a stable gait to facilitate movement across ice or other low-friction surfaces, we move closer to designing a robot capable of traversing heterogeneous surfaces, transitioning between standard walking and skating gaits as needs dictate.

Furthermore, skating is the fastest method of humanoid locomotion without additional mechanical support. By allowing a humanoid robot to move not only over slippery environments stably, but to take advantage of these low-friction surfaces with a skating-style gait, we can ultimately make robots able to traverse terrain more quickly than a standard walking gait would allow.

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In this paper we present a simple gait that allows a humanoid robot to propel itself on ice skates across a smooth surface. We discuss the evolution of this gait from simply modifying the robot's walking gait to developing a new gait specifically-designed for moving on skates. This new gait relies entirely on motion in the frontal plane to propel the robot forwards. The design of the ice skates, and the development of a set of inline skates for use when ice surfaces are unavailable for testing are also explained.

2 Related Work

Most research concerning humanoid locomotion has focused on walking gaits. Dynamically stable walking gaits are typically modelled after the inverted pendulum [10]. This technique works very well when walking over flat terrain with a high level of friction in all directions, and serves as the baseline for our work on skating.

When the terrain is not flat, the standard inverted pendulum model ceases to be practical without modification. Push-recovery algorithms such as walking phase modification [1] and surface learners [11] have been used to good effect when walking over uneven surfaces.

However, relatively little work has been done concerning humanoid locomotion using skates. Research into skating has largely been done with non-humanoid robots [3,4]. Even in these cases the focus has been on wheeled skates and not ice skates.

3 Ground Reaction Forces

Standard humanoid walking gaits rely on consistent ground reaction forces in all directions. The ground reaction force is the force exerted by the ground on the foot of the robot. This includes the normal force pushing up against the sole of the foot to counteract gravity (vertical component) and lateral forces acting along the ground plane (tangential component). Figures 1–3 show how the horizontal and vertical components change when walking on normal ground, walking on ice, and skating.

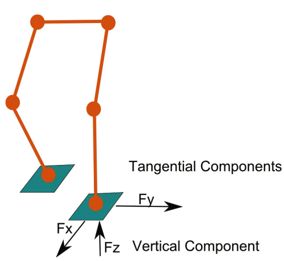

Fig. 1. Normal ground reaction forces. The tangential components are high in all directions. [2]

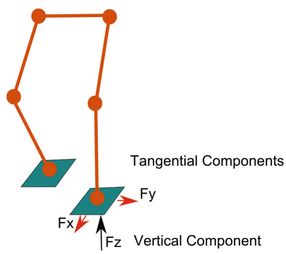

Fig. 2. Ground reaction force when walking on ice. The tangential components are significantly less in all directions when compared to normal walking. [2]

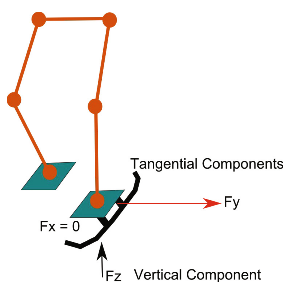

Fig. 3. Ground reaction force when skating. The forward component is zero, while the lateral component is very high. [2]

When the tangential ground reaction forces are insufficient to prevent the foot from slipping we must modify the gait. A robot on ice skates will experience a very high tangential ground reaction perpendicular to the skate blade (lateral component) and very low tangential ground reaction parallel to the skate blade (forward component). It is this high/low reaction force discrepancy that leads to the "push and glide" motion seen in skaters. By exploiting the low forward component a skating robot can sustain higher forward speed while moving, resulting in a higher overall speed when compared to walking.

4 Hardware Used

In this section we discuss the hardware used to develop our skating gait, including the physical properties of the robot and of the skates.

4.1 Robot

For this project we used a standard DARwIn-OP humanoid robot, manufactured by Robotis [9]. The robot has 20 degrees of freedom, as shown in figure 4. Of particular importance for this project are the six degrees of freedom in each leg: three in the hip (pitch, roll, yaw), one in the knee, and two in the ankle (pitch and yaw). Each point of articulation is controlled by an electric servo motor that can provide position, speed, and load information.

4.2 Ice Skates

We designed several prototype ice skates before settling on the final shape and material. Our first prototype was made of 1mm aluminium, cut by hand and bolted to the robot's feet. We quickly discovered that the first prototype had insufficient length; the front point of contact between the skate and the ice was several millimetres behind the robot's toe. If the skate dug into the ice surface this point acted as a pivot, causing the robot to fall forwards. Furthermore, the skate was approximately 5cm tall, significantly raising the robot's centre of gravity causing problems maintaining lateral stability.

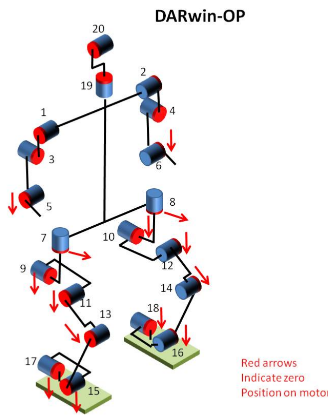

Fig. 4. A schematic showing the motor configuration of the humanoid robot used in our work [8]

Our second prototype moved the curve of the skate in front of the robot's toe to prevent the robot falling forward if the skate dug into the ice. The height of the skate blade was lowered from 5cm to 2.5cm. These changes improved the stability, but we discovered that the narrow aluminium cut into the ice, preventing any sort of gliding motion.

Our third prototype was the same shape as the second, but made of 1.5mm aluminium – the limit of what we could comfortably cut by hand with the tools available in the lab. The wider aluminium improved the gliding, but still cut into the ice too much.

The final skates were designed on a computer and machine-cut to shape. They were modelled after an ice hockey goalie's skate. The skates were made from 3mm aluminium and feature shallow curves at the front and back to allow us to experiment with skating both forwards and backwards. The skates run parallel to the midline of the foot, and are placed such that they are approximately inline with the main axis of the shin when in a standing position.

4.3 Inline Skates

To facilitate testing during the summer months when outdoor ice surfaces have melted and indoor rinks are unavailable we also developed a simple set of inline skates. The inline skates are made out of Lego and use small rubber wheels on axles to simulate the low-friction properties of ice. The rubber wheels grip the

Fig. 5. The robot's ice skates (left) and inline skates

concrete floor of our lab when pushed sideways (similar to how an ice skate digs into the ice when pushed sideways), but are free to roll when pushed forwards and backwards.

The Lego skates, shown in figure 5, are attached to the side of the ice skates using plastic cable ties. This allows us to quickly install or remove the inline skates as circumstances dictate without affecting the ice skates.

The inline skates are approximately 7mm taller than the ice skates, raising the robot's centre of gravity slightly. Because the inline skates are affixed to the side of the ice skates, the centre of pressure of each foot is moved approximately 10mm towards the outside edge of the foot. Despite these small changes to the centres of gravity and pressure, we have found that no changes to the skating gait were necessary.

5 Skating Gait Development

The development of the skating gait was an evolutionary process. We began with a keyframing approach. This was quickly determined to be ill-suited to the dynamic nature of skating; the skate blades are too narrow to allow for a statically-balanced gait and keyframing did not allow us to adjust the gait on-the-fly to maintain dynamic stability.

Our next approach was to try using the robot's walking gait to move on skates. This proved moderately successful with small modifications to the gait. The robot was able to shuffle forward on skates.

Finally we developed a new gait specifically designed for use with skates. This gait relies entirely on motion in the frontal plane, pushing against the sides of the skate blade to produce forward momentum.

5.1 Stock Walking Gait

The DARwIn-OP robots come with a highly configurable, open-source module to allow walking over flat surfaces. We tried to use the unmodified walking gait on skates. This formed the base-line from which our later work was developed.

Unsurprisingly the standard walking gait, with a stride length of 2cm, step height of 2cm, and period of 600ms, proved highly unstable. The narrow surface provided by the skate blades proved insufficient for balance, and the robot fell over sideways after only one or two steps [7]. Furthermore, placing the skates directly in line with the direction of travel resulted in effectively zero ground reaction force, meaning the robot could not propel itself forward at all.

As shown in figure 6, the accelerometer and gyroscope data is highly erratic when attempting to use the standard walking gait on skates. This highly irregular pattern of acceleration makes the gait unstable, and the robot is prone to falling after one or two steps.

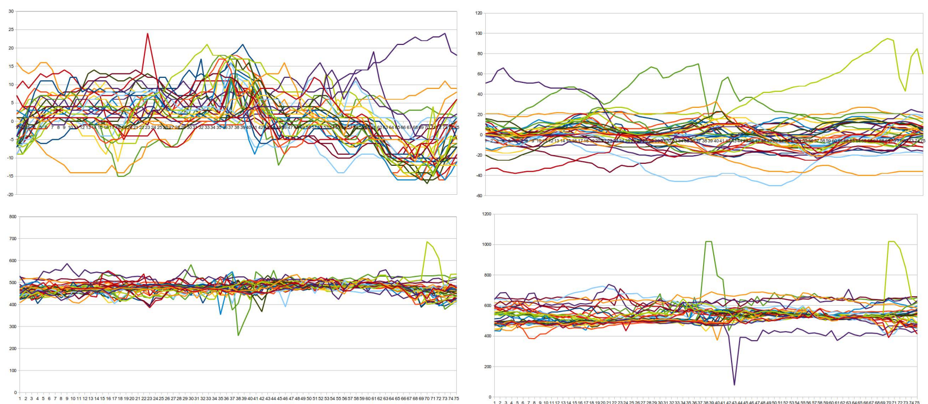

Fig. 6. Raw accelerometer and gyroscope data vs time collected while using the standard walking gait on skates. No clear cyclical patterns are visible. Clockwise from top-left: front/back gyroscope, right/left gyroscope, right/left accelerometer, front/back accelerometer.

5.2 Modified Walking Gait

Given the poor performance of the robot's stock walking gait when applied to skating we began experimenting with modifying the walking gait's parameters in an attempt to increase the robot's stability. The two primary problems to address were the lack of lateral stability and the negligible traction between the robot's foot and the ice.

To address the problem of lateral stability we modified the stride height such that the two feet are in almost constant contact with the ice. This ensured that if the robot began to fall over sideways, the other foot was close enough to the ground to catch the robot. Lowering the stride height also had the benefit of lowering the force with which the robot pushed off the ground. This in turn significantly reduced the amplitude of the side-to-side oscillations in the torso, further increasing stability.

The problem of traction was simply solved by taking advantage of the high level of friction between the edge of the skate blade and the ice. By simply

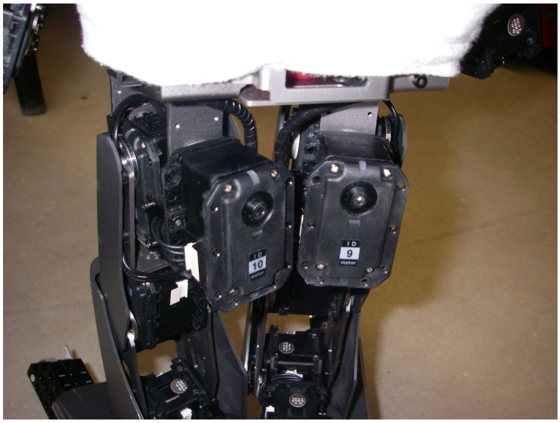

Fig. 7. The motors in the robot's hips can collide if the legs are turned outwards too far

turning the robot's toes outward by approximately 25 degrees we were able to achieve sufficient friction against the side of the skate blade that the robot could propel itself forward [5]. Due to hardware limitations we were unable to splay the feet apart more than 25 degrees; as seen in figure 7 the hip motors collide with one another if the legs are turned outwards too far.

The modified walking gait was successfully tested both indoors on a university ice hockey rink and on an outdoor community skating rink located on the University of Manitoba campus. To help protect the leg motors from cold and moisture

Fig. 8. The robot skating on an indoor (left) and outdoor (right) ice surface. The hockey stick was used to interact with a foam ball and did not serve as a balance aid. The shirt and pants helped protect the motors from cold and moisture.

we equipped the robot with a small ice hockey uniform, as shown in figure 8. A small hockey stick was taped to the robot's arm to allow it to manipulate a foam ball, but was not used as a balance aid.

The modified walking gait was also successfully tested with the inline skates, indicating to us that there is minimal practical difference between inline skating and ice skating for this kind of gait. This gait yielded a top speed of between 0.5cm/s and 2cm/s on an outdoor ice rink. Ice conditions were highly variable due to precipitation and changes in temperature and humidity which impacted the robot's speed.

5.3 Skating Gait

Once we established that a stable walking gait on skates was possible, we began developing a gait that was closer to a true skating gait. The modified waliking gait relied on lifting the back foot and placing it on the ground in front. This requires that force be exerted backwards to propel the robot forwards. Our aim was to develop a gait wherein the robot's leg movements are almost entirely lateral. With the skating gait the robot pushes off against the edge of one skate blade, gliding along on the other foot for a short distance before pushing off again with the other skate.

Without a strong push it is impossible to generate sufficient inertia to sustain a glide. Therefore we chose to focus our research primarily on the push phase of skating, accepting that the glide phase would be short. A sustained glide phase is planned for future work.

Unlike the walking gaits used earlier, there is very little motion in the saggital plane; almost all leg motion occurs in the frontal plane. The gait's motions in the frontal and saggital planes are shows in figure 10.

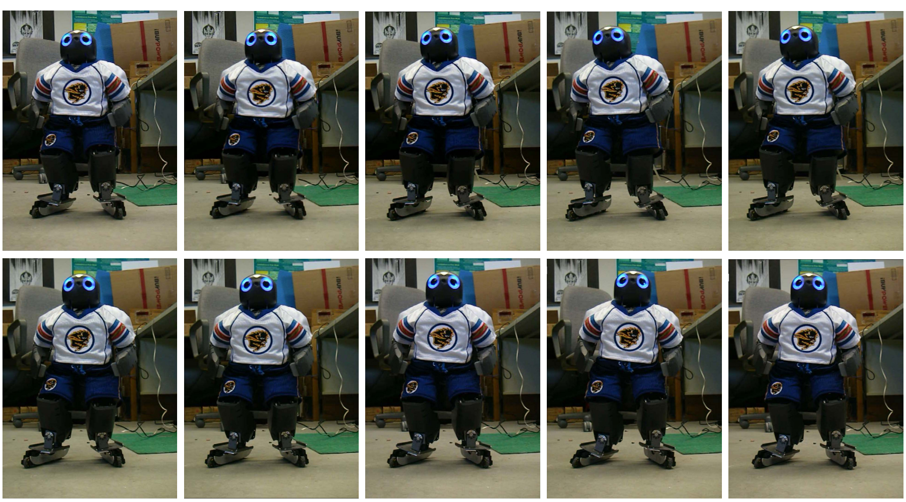

Fig. 9. Still images from a video of the robot's skating gait. The interval between each image is approximately 60ms.

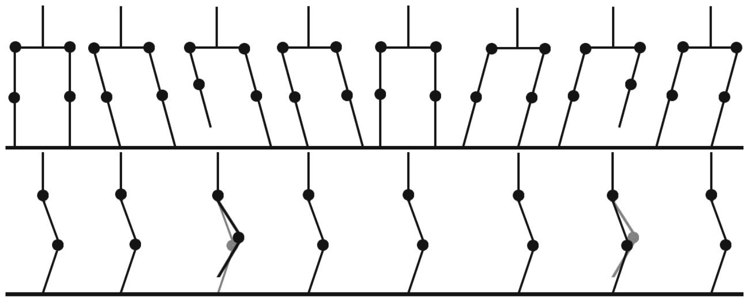

Fig. 10. Key positions in the robot's gait as seen in the frontal plane (top) and saggital plane. These images do not take the effect of gravity into consideration. The interval between each position is approximately 75ms.

Figure 9 shows images of the robot's skating gait at regular intervals. The robot begins with its weight over the left foot, ready to execute a push to the right. Over the next four images the robot is seen shifting its weight over the right foot while pushing against the edge of the left skate. The final three images show the robot shifting its weight to the left foot, pushing against the edge of the right skate. Of particular interest is the high degree of motion in the robot's ankles when pushing. In order for the ice skate blade to dig into the ice and provide maximum traction we angle the foot such that the corner of the skate blade is pointed down. The support foot meanwhile is positioned in a more neutral position, keeping the flat bottom of the skate blade (or the wheels in the case of inline skates) vertical to minimise gliding or rolling friction.

Figure 10 shows a wireframe representation of the robot's gait. The robot begins in the neutral position before shifting its weight over the right foot. The

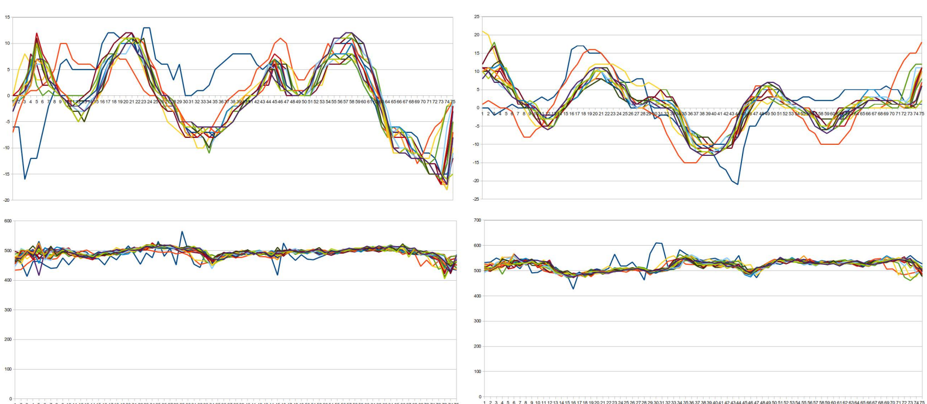

Fig. 11. Raw accelerometer and gyroscope data vs time collected while using the skating gait. These graphs show stable, cyclical patterns. Clockwise from top-left: front/back gyroscope, right/left gyroscope, right/left accelerometer, front/back accelerometer.

push phase is accomplished by bending the knee of the support leg, lowering the robot's centre of gravity and causing the entire robot to pivot around the left skate blade. Because the feet are angled outwards by 45 degrees this pivoting forces the robot to move ahead and to the right. The robot then straightens the support leg once again and shifts its weight over the left foot, pushing against the right skate.

The accelerometer and gyroscope data recorded while using the skating gait illustrates the stability of the gait; regular patterns in the angular velocity along the left/right and front/back axes are clearly visible in figure 11. The accelerometer data, while relatively flat, shows much less variation than the unmodified walking gait data, seen in figure 6.

The skating gait allowed the robot to skate at a top speed of approximately 3cm/s on inline skates, indicating that even without a sustained glide phase the skating gait is faster than the modified walking gait.

6 Conclusion

We have shown that a dynamically stable skating gait is possible, and that by pushing laterally against the edges of skate blades, a small humanoid robot can traverse indoor and outdoor ice surfaces. Through our experiments we have also shown that an unmodified inverted-pendulum model results in a gait unsuited for skating. With minor modifications such a gait can be made to allow the robot to shuffle on ice. However, a skating gait relying on lateral movements results in a higher forward speed.

7 Future Work

Having established an effective push phase to the skating motions our next step is to focus on the glide phase. By increasing the strength of the push phase and lengthening the glide phase we hope to increase the speed of the robot's skating to the point where it is faster than the stock walking gait.

Our research to this point has been focused on moving forwards. We plan to explore turning, moving backwards, acceleration, and deceleration. To guide this area of our future work we will be using ice hockey as the framework. Ice hockey offers many of the same challenges as robot soccer (identifying the ball/puck, finding the goal, manoeuvring into position to pass or shoot), but is designed specifically for a low-friction surface. By mounting a small hockey stick to the robot we have already demonstrated the robot's ability to manipulate a small ball in an ice hockey setting [6]. We plan on continuing this work, ideally to the point where we will see international robot ice hockey competitions similar to current-day robot soccer events.

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