Robotics and Autonomous Systems 62 (2014) 306–318

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Gait design for an ice skating humanoid robot

Chris Iverach-Brereton *, Jacky Baltes, John Anderson, Andrew Winton, Diana Carrier

Autonomous Agents Laboratory, University of Manitoba, Winnipeg MB R3T2N2, Canada

HIGHLIGHTS

- Unmodified ZMP-based walking gaits are unsuitable for walking on low-friction surfaces.
- A skating-style gait for a humanoid robot using only lateral motions is possible and improves stability.
- Modified ZMP-based walking gaits maintain higher speeds, but are less stable than skating-style gaits.

ARTICLE INFO

Article history:
Available online 12 October 2013

Keywords:
Humanoid robotics
Skating
Bipedal walking

ABSTRACT

Basic walking gaits are a common building block for many activities in humanoid robotics, such as robotic soccer. The nature of the walking surface itself also has a strong affect on an appropriate gait. Much work is currently underway in improving humanoid walking gaits by dealing with sloping, debris-filled, or otherwise unstable surfaces. Travel on slippery surfaces such as ice, for example, greatly increases the potential speed of a human, but reduces stability. Humans can compensate for this lack of stability through the adaptation of footwear such as skates, and the development of gaits that allow fast but controlled travel on such footwear.

This paper describes the development of a gait to allow a small humanoid robot to propel itself on ice skates across a smooth surface, and includes work with both ice skates and inline skates. The new gait described in this paper relies entirely on motion in the frontal plane to propel the robot, and allows the robot to traverse indoor and outdoor ice surfaces more stably than a classic inverted pendulum-based walking gait when using the same skates. This work is demonstrated using Jennifer, a modified Robotis DARwIn-OP humanoid robot with 20 degrees of freedom.

1. Introduction

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), 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.

While such basic gaits remain very common building blocks to current humanoid robot applications (e.g. robotic soccer, or basic locomotion for more advanced FIRA HuroCup challenges such as the obstacle run), such gaits must be greatly improved to make humanoid robots more broadly applicable to the real world. Most of the real world involves uneven terrain—robotic firefighters must be able to traverse a debris field, for example. Even in relatively forgiving environments such as domestic service, humanoid robots must contend with common household obstacles such as carpet edges, stairs, or toys left on the floor.

The ability of a humanoid robot to traverse completely unstructured environments with the ease of humans is a long term goal. Further research in sensors, materials, power, intelligent control, and the interactions between all these, will be necessary to achieve this. In the nearer term, however, there is much we can do to improve walking gaits in order to move towards this goal. Challenges such as those in the FIRA HuroCup [1], which force robots to make broader use of upper body movements and complex motion planning, challenge walking gaits to be more adaptive, for example [2]. Much work is being done on adaptations to various types of uneven or unstable terrain (e.g. [3–5]), including debris and slopes.

In addition to these types of variations, it is equally important to consider variations in the nature of the walking surface and their effects on gait. Humans walk differently on a surface that can be slippery, such as wet linoleum indoors or ice outdoors—or rather, there is a significant danger of falling if a human gait is not adapted for such conditions. The most obvious adaptations are for stability; even children readily see that it is possible to travel much faster on slippery surfaces than normal indoor terrain, provided

* Corresponding author. Tel.: +1 204 898 4622.
E-mail addresses: chrisib@cs.umanitoba.ca, umiverac@cc.umanitoba.ca (C. Iverach-Brereton).

0921-8890/$ – see front matter
http://dx.doi.org/10.1016/j.robot.2013.09.016

that expectations of the ability to stop or change direction quickly are relaxed. The types of human gaits required to travel on ice or other slippery surfaces quickly are modified further through the addition of specialised footwear such as speed or figure skates, which support greater speed and control.

In this paper, we describe the development of Jennifer, the world's first ice skating humanoid robot. Areas that support skating, such as skating rinks, frozen lakes, and icy concrete have little friction, but are generally assumed to be flat and free of debris. Our goal in this work is to explore gaits that support controlled travel on skates, in order to better support a broader range of walking motions. 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, shifting between walking and skating gaits as needs dictate.

Beyond this goal, however, there are also practical reasons for supporting gaits for travel on ice. Navigating over ice patches is a requirement for any humanoid robot that is intended to be useful in outdoor environments in polar or sub-polar regions, or in temperate regions during the winter months. The geography of Canada includes all of these regions. Furthermore, skating is the fastest method of humanoid locomotion without additional mechanical support. Partly because of the speed afforded, travel on skates has historically been an important means of everyday human transportation, such as on frozen canals in the Netherlands in the 16th and 17th centuries [6]. By allowing a humanoid robot to move over slippery environments stably, while taking 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.

The remainder of this paper is organised as follows. Section 2 relates our work to the state of the art in humanoid robotics. Section 3 relates the differences between travel on slippery vs. non-slippery surfaces, and Section 4 follows this with a description of the robot hardware used in this work, including the design of ice skates and a modification supporting inline skates for use when ice surfaces are unavailable for testing. Section 5 describes a gait that allows a humanoid robot to propel itself on ice skates across a smooth surface, and discusses the evolution of this gait from attempts to modify an existing robot walking gait to the development of 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. Experimental results comparing the speed and stability of the skating gait with a standard walking gait are presented in Section 6.

2. Related work

Humanoid walking gaits for robots have seen significant development over the last decade. Dynamically stable gaits based on the linear inverted pendulum model [7,8] have become the current standard. These gaits model the robot as an inverted pendulum; the robot's support foot contains the fulcrum, the support leg forms the rod, and the upper body forms the mass, as shown in Fig. 1. By varying the length and angle of the rod – flexing or extending the ankle, hip, and knee joints – and by manipulating the location of the zero moment point (ZMP), the robot's centre of mass (CoM) can be controlled, propelling it forward or backward, or keeping it stationary in a stable position.

Gaits based on the inverted pendulum model consist of two distinct phases: the single support phase (SSP) and the double support phase (DSP). During the DSP the robot is statically stable with both feet on the ground with the CoM located above the support polygon formed by the feet. During the SSP the robot is unstable: the front foot is the support leg and the robot pivots

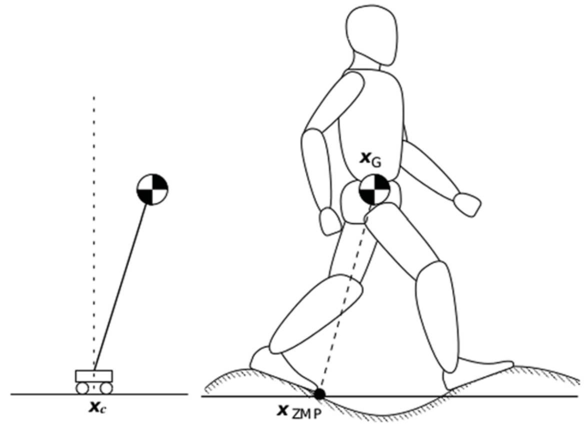

Fig. 1. An inverted pendulum (left) and a humanoid system, showing the fulcrum, rod, and mass of the pendulum (Sugihara et al. [8]).

about the ZMP, falling forwards. While the robot is falling forward, it swings its non-support leg (the "swing leg") forward as well. The SSP terminates when the swing leg lands, beginning a new DSP. These phases are illustrated in Fig. 2 (taken from Baltes and Lam [9]).

Because walking gaits such as that described above are cyclical in nature, they rely on an internal timer to control the timing of transitions between SSP and DSP, and vice versa. On level terrain with good traction this does not cause problems. However, when presented with uneven terrain (e.g. inclines, variable-level terrain) the gait can become unstable [5]: when the gait's internal timing no longer corresponds to the robot's physical state the robot can fall over. One strategy for stabilising the gait is the use of gyroscopic sensor data with walking phase modification [10,9,11,3].

If a robot is traversing uneven terrain, it is likely that the transition from SSP to DSP may occur at unexpected times: a slight elevation in the terrain may cause the swing leg to touch the ground early. Likewise, a depression may cause the swing leg to touch the ground too late. In either case, the gait's internal timing no longer corresponds with reality, and the robot can become unstable.

Walking phase modification allows the robot to dynamically control the start and end timing of each phase. By using gyroscopes to measure a robot's angular velocity along the X, Y, and Z axes, it is possible to detect when a robot has transitioned from the SSP to DSP and vice versa. If the sensors detect that the swing leg has touched the ground earlier than anticipated, the remaining time in the SSP can be discarded, and the robot can begin the DSP. Similarly, if the SSP time expires but the sensors indicate that the swing leg has not yet touched the ground, the SSP can be continued. This technique has been shown to stabilise statically stable gaits [11] as well as dynamic gaits [10].

Skating robots are relatively uncommon, though some work has been done on non-humanoid robots equipped with inline skates [12,13]. Statically stable gaits using 4-DOF robots equipped with inline skates have been demonstrated to be able to propel themselves forward and turn in either direction by swinging the skates in cyclical patterns [13]. These robots rely on a central, omnidirectional caster for balance, unlike a humanoid robot which must balance on skates.

3. Mechanical differences between skating and walking

Skating and walking are both forms of bipedal motion, but differ significantly when analysed from a mechanical perspective. The differences lie primarily in how they exploit ground reaction forces: walking uses high-traction surfaces to push the subject

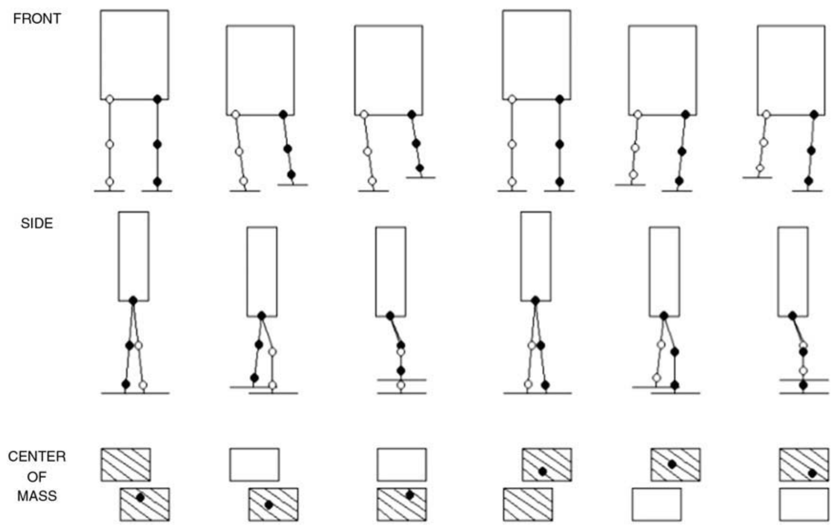

Fig. 2. The walking gait used by a simple humanoid robot, showing the single support and double support phases.
Source: Baltes and Lam [9].

forward; skating uses skate blades or wheels, initially to provide impulse by exploiting high lateral ground reaction forces and subsequently to reduce friction moving forward, allowing the subject to glide forward.

Ground reaction forces describe the forces acting in three dimensions against a robot's foot while walking. These forces can be summarised as the normal force pushing vertically against the bottom of the robot's foot (*vertical* component) and lateral forces acting along the ground plane (*tangential* components) [14]. The tangential components consist of two forces: one acting parallel to the robot's direction of travel (*forward* component) and one acting perpendicularly to the direction of travel (*lateral* component).

The linear inverted pendulum model used by most modern humanoid robots assumes strong, consistent ground reaction forces in all directions. This ensures that the robot's foot does not slip while walking. However, these assumptions are not always reliable. For instance, a robot walking on a slippery surface (e.g. ice, slick ceramic tiles, wet linoleum) will experience significantly reduced tangential ground reaction forces, as shown in Figs. 3 and 4. A robot moving on ice skates will experience very low forward ground reaction force, but a very high lateral ground reaction, as shown in Fig. 5. This difference in the lateral and tangential forces experienced on skates is explained by the design of the skate blade. Inline skates have wheels that roll in the tangential direction but grip the ground when pushed laterally. The metal blades of ice skates are designed to form a thin film of water between the blade and the ice. This film acts as a lubricant, allowing the skate blade to glide forwards and backwards. When pushing sideways the corners of the skate blade cut into the ice, preventing lateral slipping, as shown in Fig. 6.

A robot using a walking gait based on a linear inverted pendulum model will keep its centre of mass (CoM) between its own feet. Unlike a statically stable gait, where the robot's CoM is always directly over the support polygon formed by the robot's feet, a dynamically stable gait allows the CoM to oscillate back and forth much more freely. As the robot walks, the zero moment point (ZMP) moves from the heel of the support foot forward towards the toe, while staying as far away from the edges of the support polygon as possible in order to maintain stability. When the support foot changes, the ZMP moves along from the heel to the toe of the other foot, as shown in Fig. 7.

While it is possible to perform a walking motion on skates, effective skating is entirely different than walking in that force is not applied in the direction of motion. The basic motion involved in

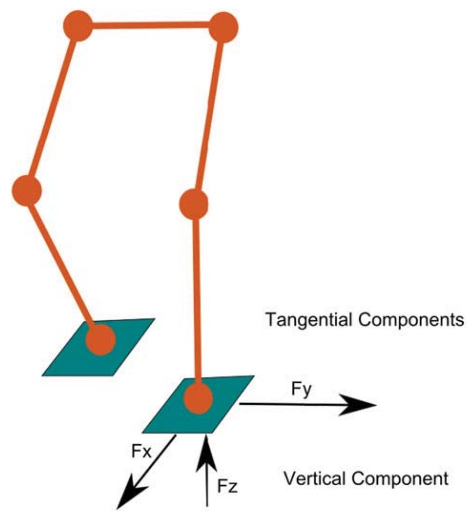

Fig. 3. Ground reaction forces experienced when walking. The tangential components are high in all directions.

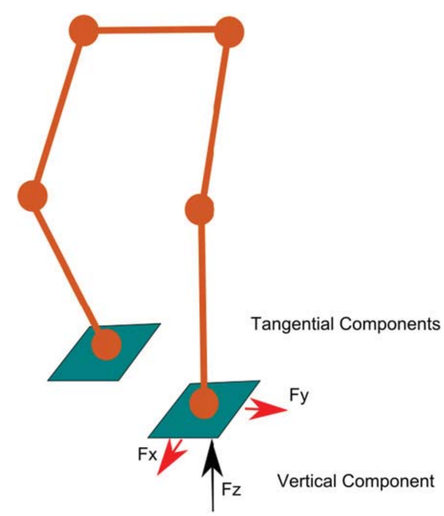

Fig. 4. Ground reaction forces experienced when walking on ice. The tangential components are near zero all directions, resulting in slipping.

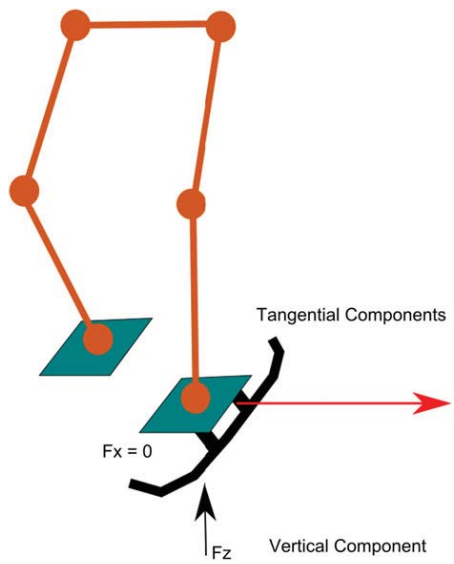

Fig. 5. Ground reaction forces experienced when skating. The forward component is effectively zero, while the lateral component is very high.

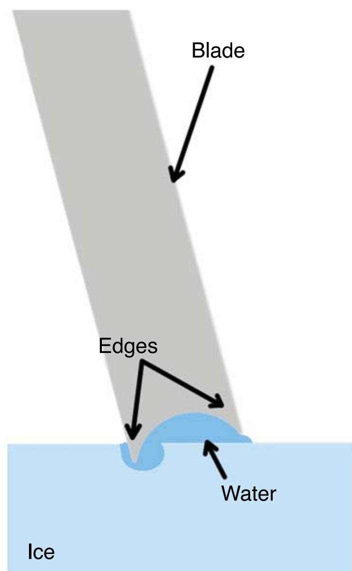

Fig. 6. Cross-section of a skate blade. The concave surface in contact with the ice traps a small film of water that acts as a lubricant between the skate and the surface of the ice when gliding. When pushing laterally the corners of the skate blade cut into the ice, creating high friction. (Wikimedia Commons [15].)

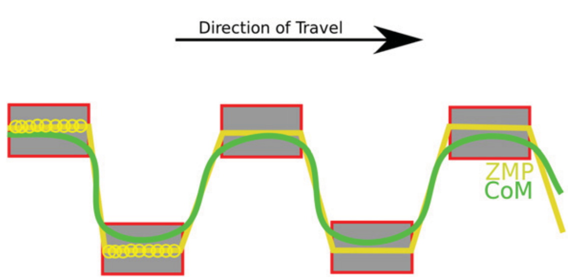

Fig. 7. A robot's centre of mass and zero moment point while walking. The foot remains stationary, but the ZMP moves along the length of the foot.

skating involves a constant rotation around the edge of the contact point, and force is instead generated perpendicular to the direction of travel. Because skating relies on the support foot gliding forward,

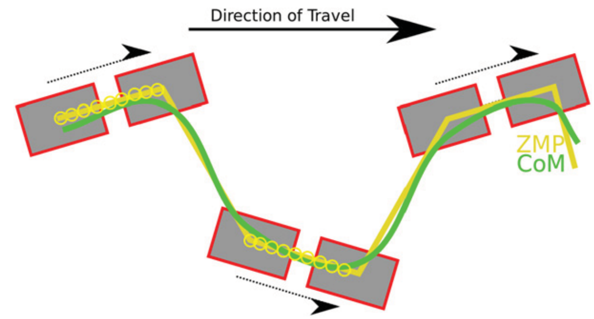

Fig. 8. A robot's centre of mass and zero moment point while skating. The ZMP remains fixed under the centre of the skate blade, but the skate itself slides forward.

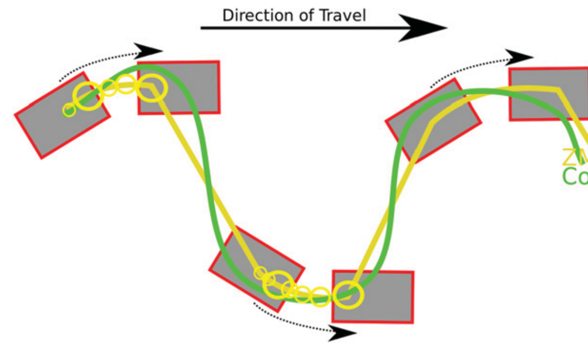

Fig. 9. Double push skating motion. The large ZMP circles indicate when a push occurs.

the ZMP behaviour is different. When skating, the ZMP remains in the middle of the skate blade; as the skate moves forward along the ice, the ZMP moves with it until the support foot changes, as seen in Fig. 8.[1] The CoM follows a similar path as seen when walking; the CoM moves from side to side, but stays between the two feet.

This basic skating motion is, of course, not the only one possible. Advanced human skaters can use even more efficient motions, such as a double push (Fig. 9). In a classic skating motion, the skater pushes out with one leg, and when that leg gets to full extension, uses the other leg as a support and glides on it while returning the original extended leg to its starting position. The skater also performs a similar set of steps with the other leg. In such a motion, each leg pushes consistently in one direction (e.g. the left leg only pushes to the left). In a double-push, rather than only gliding on the opposing leg while recovering the previously extended leg, the opposing leg does useful work by pushing in the opposite direction (e.g. the left leg pushes right) as the extended leg is recovered. Because of these opposing motions, the CoM must travel over the leg to the outside (Fig. 9). The motion is inherently less stable because of the greater shift in CoM, but is more efficient in that it allows additional useful force to be applied through the overall cycle. This technique is used extensively in competitive inline skating [16] and has been adapted to other sports such as cross country sprint skiing [17]. In the latter, skiers were shown to be up to 6.9% faster using an analogous technique.

4. Hardware used

In this section we discuss the humanoid robot we used to conduct our experiments and the development of ice skates and inline skates used by the robot.

[1] Both Figs. 8 and 9 were developed by one of the authors (Baltes) based on his experience as an Olympic speed skater and through analysis of footage of speed skating competitions.

Fig. 10. Jennifer, the robot used in our experiments, 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 helmet, shirt and trousers helped protect the motors from cold and moisture.

4.1. Robot

In our experiments we use Jennifer,[2] a commercially available DARwIn-OP humanoid robot, manufactured by Robotis [18], shown in Fig. 10. In its stock configuration the robot has 20 degrees of freedom (DOF). Single-DOF hands were added to the robot as an after-market addition partway through our work on skating to facilitate other ongoing research projects. The hands are visible in some photographs, but not all. The presence (or absence) of hands did not present any significant challenges as far as skating is concerned.

To allow the robot to interact with a small foam ball, a hockey stick was duct-taped to the robot's arm in several of our early experiments. The stick was not used as a balance aid at any point in our experiments.

We equipped the robot with a miniature hockey uniform to help protect it from cold and moisture. The uniform consisted of a foam-lined helmet (which also helped protect the robot from damage due to falls), foam-lined trousers, and a shirt.

Each leg contains six degrees of freedom: three in the hip (pitch, roll, yaw), one in the knee, and two in the ankle (pitch and yaw), as seen in Fig. 11. Each DOF is controlled by a single MX-28 electric servo motor. The motors provide position, speed, and load information about each joint.

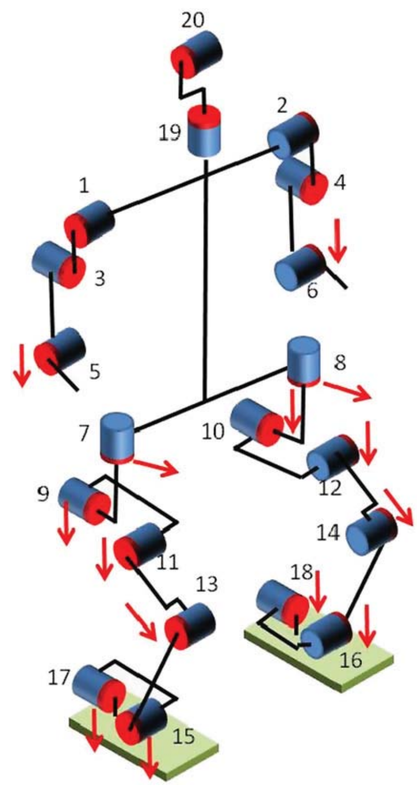

Fig. 11. A schematic showing the stock configuration of the humanoid robot used in our work (RoboSavvy [19]). The legs have six degrees of freedom: hip pitch (motors 11 and 12), hip roll (motors 9 and 10), hip yaw (motors 7 and 8), knee (motors 13 and 14), ankle roll (motors 17 and 18), and ankle pitch (motors 15 and 16). The red arrows indicate the zero position of each motor.

4.2. Skates

Throughout our experiments we have designed and tested several different styles of skate, including plastic roller skates and hand-cut aluminium ice skates. After initial experimentation with these possibilities, we decided upon a pair of machine-cut aluminium skates that can be converted into inline skates by attaching rubber wheels to the side of the blades, shown in Fig. 12.

Our first experiments with statically stable gaits used a pair of plastic roller skates designed for a toy bear. The roller skates were designed primarily for decoration, and proved ill-suited to our research; the wheels provided little traction and had unacceptably high-friction axles, and the plastic construction was prone to bending under the weight of the robot. Furthermore, because roller skates place one wheel at each corner of the skate, the ZMP is no longer directly under the skate blade: it can move anywhere within the polygon formed by the wheels of the support foot.

Because of the limitations of the roller skates our focus shifted quickly to ice skating and we began developing a pair of aluminium ice skates for the robot. Our goal was to create a pair of ice skates that were as realistic as possible when compared to human skates. Specifically, we needed skates that could exploit the thin film of water that is formed between the skate blade and the ice, as discussed in Section 3.

[2] The robot is named after Canadian three-time Olympic gold medallist and five-time world champion in women's ice hockey, Jennifer Botterill.

Fig. 12. The robot's ice skates (left) and inline skates.

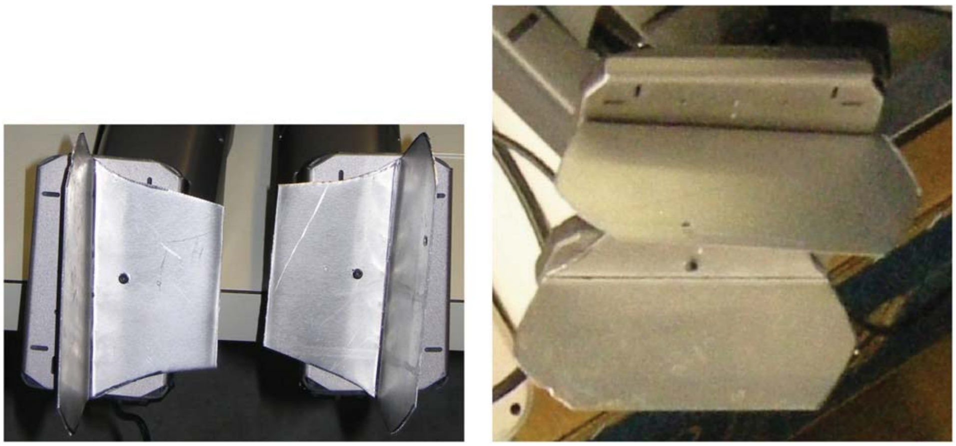

Fig. 13. The first pair of prototype skates. These skates were flawed in several ways: the blade material was too narrow and cut into the ice rather than glide upon it, the blades themselves were too tall, and the curved front and rear surfaces created contact area that was too short to provide sufficient support when moving.

We tried several prototype ice skates before deciding on the final design and material. Our first prototype, shown in Fig. 13 was made of hand-cut 1 mm aluminium. A single screw attached the skate to the centre of the robot's foot. Our initial tests revealed that these skates were too tall and had insufficient length: the curved surface at the front of the blade meant that the skate made contact with the ice several millimetres behind the robot's toe. This contact point acted as a pivot and caused the robot to fall forwards very easily. The extreme height of the skate (approximately 5 cm, compared to the robot's total height of 40 cm) raised the robot's centre of gravity significantly, further aggravating the issue of balance. Finally, the material was too thin to serve the purpose of an ice skate: the material sliced into the ice rather than melting a film of water to glide on.

The second prototype was longer and lower than the first, and made from hand-cut 1 mm aluminium. The point of contact between the skate and the ice was moved ahead of the robot's toe to improve stability, and the overall height was reduced to 2.5 cm. These changes improved stability dramatically, but did not address the issue of the skate cutting into the ice.

The third prototype used the same shape as the second, but was made from heavier material: 1.5 mm aluminium. This was the heaviest material we could comfortably cut by hand using the tools available in our lab. The thicker aluminium improved the skates' ability to glide on ice, but were still too thin to prevent cutting.

The final skates were designed using CAD software and machine-cut from 3 mm aluminium. Two screws attach them to the robot's feet. The skates themselves are styled after a hockey goalie's skate, allowing us to experiment with skating both forwards and backwards. The skates are attached so that they run parallel to the midline of the robot's foot. The skate blade itself is positioned underneath the robot's ankle motors, forming an approximately straight line from the robot's hip to the skate blade; the skate is positioned slightly towards the outside edge of the robot's foot due to the location of the holes used for the mounting screws. To reproduce the concave surface of modern skate blades, as shown in Fig. 6, we hand-filed a shallow groove along the blade.

To facilitate research when both indoor and outdoor skating rinks are unavailable, we developed a simple set of inline skates that can be affixed to the robot's ice skates using plastic cable ties. The inline skates, shown in Fig. 12 are constructed out of Lego Technic frames and wheels. These wheels have rubber tyres that provide a high degree of lateral traction, but are free-spinning forwards and backwards. This adequately simulates the ground reaction forces seen when ice skating, provided the axles are kept clean; the plastic axles are prone to jamming if exposed to dirt or grit, necessitating frequent cleaning.

When affixed to the ice skates, the inline skates raise the robot an additional 7 mm above the ground. This raises the robot's centre of gravity slightly, but the effect was not noticeable in any of our experiments.

Because the inline skates are positioned along the outside edge of the skate blades, the centre of pressure of each foot is moved approximately 10 mm towards the outside edge. This disrupts the straight line from the hip to the skate blade's point of contact with the ground and increases the torque on the ankle roll motors. Despite these differences we have found that no changes to the robot's gait were necessary when moving from ice skates to inline skates.

5. Skating gait development

Developing a stable skating gait was an evolutionary process. Initially we tried keyframing, but quickly discovered that such an

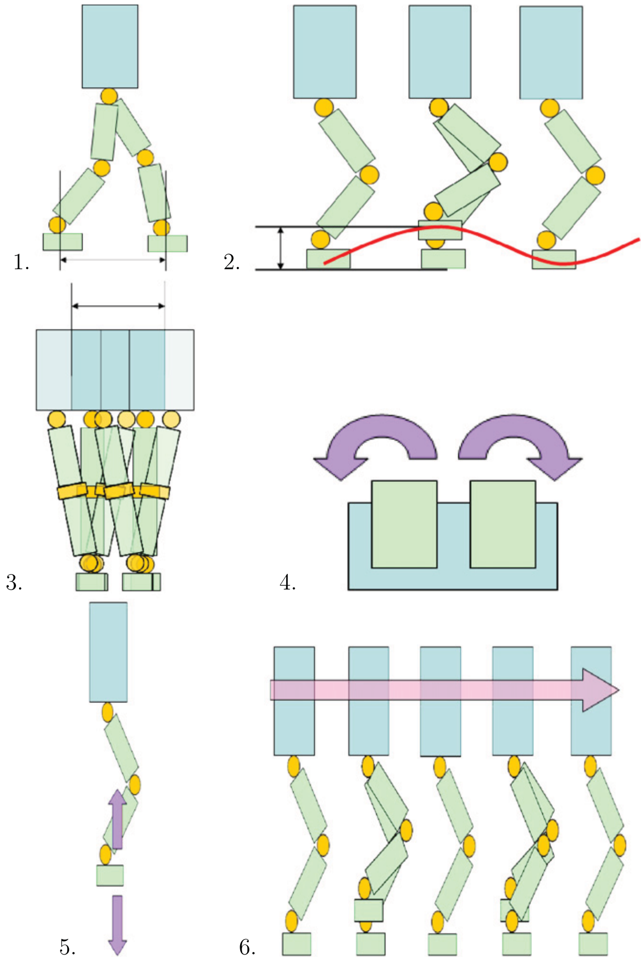

Fig. 14. The major walking parameters modified over the course of our experiments (illustrations from Springnote [21]): 1. step length, 2. step height, 3. left/right swing (used to modify the skating gait's glide length), 4. yaw offset (changes the skating gait's glide and push angles), 5. hip height, 6. period.

approach is infeasible when skating due to the complex balancing required. Our next approach was to use the robot's stock walking gait to literally "walk on skates". This approach proved moderately successful with modifications to the gait. Finally, we developed a new gait based on the inverted pendulum model that relies entirely on motion in the frontal plane: the robot moves its legs side to side to generate traction against the edges of the skates, propelling the robot forwards.

The robot has six degrees of freedom in each leg (three in each hip, one in each knee, and two in each ankle). This is sufficient to allow the robot to mimic a human-like walking gait. Based on our analysis of videos of human skaters, the robot should not require additional degrees of freedom to mimic a human skating gait.

5.1. Parameterised motions

The difference between skating and walking for humanoid robots is highlighted by the fact skating requires several additional parameters in comparison to walking. Many researchers have proposed parameterised walking gaits for humanoid robots [20]. The dominant commonly used parameters for the description of walking gaits are: period, hip height, step length and step height, as shown in Fig. 14. Skating, on the other hand, uses the following parameters: period, hip height, glide length, glide angle and push angle. Glide angle refers to the angle of the blade when the swing leg is brought down on the ice, and push angle is the angle of the

Fig. 15. The robot using a statically stable gait on roller skates.

blade when the support leg is fully extended and pushing sideways to move the centre of gravity.

Fig. 14 illustrates the walking and skating parameters modified over the course of our experiments. Tables 1 and 2 describe the effects of the various parameters on walking and skating.

5.2. Keyframing statically stable gaits

Our early keyframing experiments resulted in two gaits, neither of which proved effective. The first was a statically stable gait using roller skates (not inline skates). The second was a statically stable gait suitable for ice skates or inline skates.

The roller skating gait exploited the fact that a roller skate has one wheel positioned at each corner of the foot. This allows the robot to balance on one foot easily. The robot would shift its weight over one foot (the support foot), and turn the other foot (the push foot) outwards and push straight back against the edge of the wheels. The robot would then rotate the push foot such that the toe points forwards again and place the push foot on the ground beside the support foot. The robot's weight is shifted over the push foot. At this point the support and push feet swap roles, and the robot pushes off against the edge of the other foot as described above (see Fig. 15).

When we tried to use this gait on ice and inline skates it proved ineffective; the narrower skates did not offer sufficient support to allow for a statically stable gait.

This failure led to the development of a statically stable gait that was suitable for use with both ice skates and inline skates. This gait kept both skates in contact with the ice at all times and was inspired by one often used by children when they first learn to ice skate. The gait, seen in Fig. 16, is composed of four steps:

1. With the toes of the skates pointing outward, the legs are spread apart from the hip. The force acting on the skates forces the feet to move forward and outward.
2. The feet are turned so that the toes point inward.
3. The legs are brought together from the hip. The force acting on the skates forces the legs forward and inward.
4. The feet are turned so that the toes point outward.

Table 1
Walking parameters. Values indicate those used in the DARwIn-OP's stock walking gait (see Section 5.3).

Parameter	Value	Effect
Period	600 ms	Lowering the period increases the gait's overall speed, but puts more strain on the motors; the motors need to accelerate and decelerate more quickly in order to keep up. Changing the period too much (increasing or decreasing it) requires changing other parameters in order for dynamic stability to be maintained.
Hip height	20 cm	Determines the height of the hip above ground. To simplify the mathematical model of the humanoid robot, most ZMP based walking approaches use a constant hip height throughout the walk. Increasing the hip height also increases the centre of mass of the robot, which reduces stability of the robot.
Step length	20 mm	Determines length of stride. Increasing the step length will make the robot walk faster coupled with a loss of stability due to the ZMP moving closer to the edge of the foot support area.
Step height	40 mm	Determines the height of the foot above ground. Increasing the step height is necessary when the robot is walking on soft carpet to ensure that the robot does not stub its toes while walking. This usually leads to reduced stability, since additional time is required to raise the foot higher, increasing the length of the single support phase.

Table 2
Skating parameters. Values are those used in the final skating gait (see Section 5.5).

Parameter	Value	Effect
Period	600 ms	Like walking gaits, a lower period results in a faster overall gait, but large changes to the period require changing additional parameters to ensure that the robot maintains dynamic stability. For simplicity of comparison we kept the period the same as the stock walking gait.
Hip height	20 cm	Similar to the range of motion of a piston in an engine, the hip height determines the amount of power that the skater can transfer on the ice. A lower hip height has an additional advantage: lowering the hip height also lowers the centre of mass of the robot, which improves the stability of the skating. In human skaters, a low hip height results in high torque on the knee and hip joints, which is why skaters have powerful quadriceps (thigh) and glutaeus maximus (hip) muscles. However, limitations in the hardware of our robot (max. torque of the knee servos) limited the hip height to 20 cm. We are currently planning on redesigning the legs of the robot to add more powerful knee servos, which will allow us to reduce the hip height dramatically.
Glide length	30–50 mm	This parameter is similar to the step length in walking, but determines the length of the glide. In contrast to walking, the foot of the swing leg is always placed directly underneath the hip of the robot and remains there. An increase in glide length will only result in an increase in the skating speed if the other leg continues to accelerate the centre of mass. Otherwise, the skate will simply glide on the ice and it will be slowed down by friction and air resistance.
Glide angle	22.5°	The glide angle is the angle at which the foot of the swing leg is brought down on the ice. The larger the angle, the more the centre of mass will move to the side. The angle resulting in the fastest skating is the angle that aligns the direction of the blade with the direction of the push generated by the support leg. Limitations in the robot's hardware forced us to limit this angle (see Fig. 17).
Push angle	22.5°	The push angle is the angle of the blade when the support leg is fully extended. The optimal push angle is 0°, as this results in a maximum push sideways for the centre of mass. Due to limitations in the torque of the hip transversal servos, we kept this angle to the same as the glide angle during our experiments.

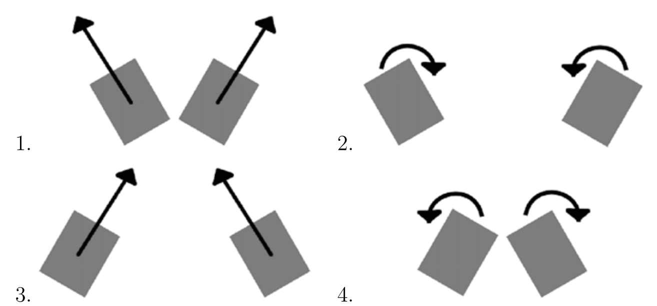

Fig. 16. An overhead view of the foot positions and motions for a statically stable skating gait.

Unfortunately, the robot's hip motors were unable to provide sufficient torque to force the legs to move inward during step 3. The weight of the robot's torso pushing down forced the legs apart, and the hip motors were unable to overcome both the force of gravity acting on the robot's body and the friction of the skates against the ice. Furthermore, the robot was unable to point its toes outward sufficiently. The hip motors collide in the back if the toes are pointed outward beyond approximately 25°, as seen in Fig. 17. Ideally the toes should be pointed out by approximately 45°: a shallow angle means that the robot is pushing sideways against the high-friction axis of the blade, requiring a large amount of torque. A wider angle reduces the torque on the hip motors when spreading the legs.

5.3. Stock walking gait

The DARwIn-OP robots come with an open-source, configurable walking program. This gait is stable when walking over flat terrain.

Fig. 17. The motors in the robot's hips can collide if the legs are turned outwards too far.

We attempted to use this gait, unmodified, to walk on skates. These experiments formed the baseline for the rest of our work.

The stock walking gait uses a stride length of 2 cm with a step height of 4 cm and period of 600 ms. The robot spends 90% of each cycle in the SSP, with the remaining 10% in the DSP. While these parameters are suitable for walking on concrete or thin carpet, the gait proved highly unstable when used with skates. The thin skate blades did not provide sufficient lateral support, and the robot fell over almost immediately.

Because the stock walking gait keeps the feet pointed straight forward, the skate blades were parallel with the robot's direction of travel. This produced effectively zero traction—even when holding

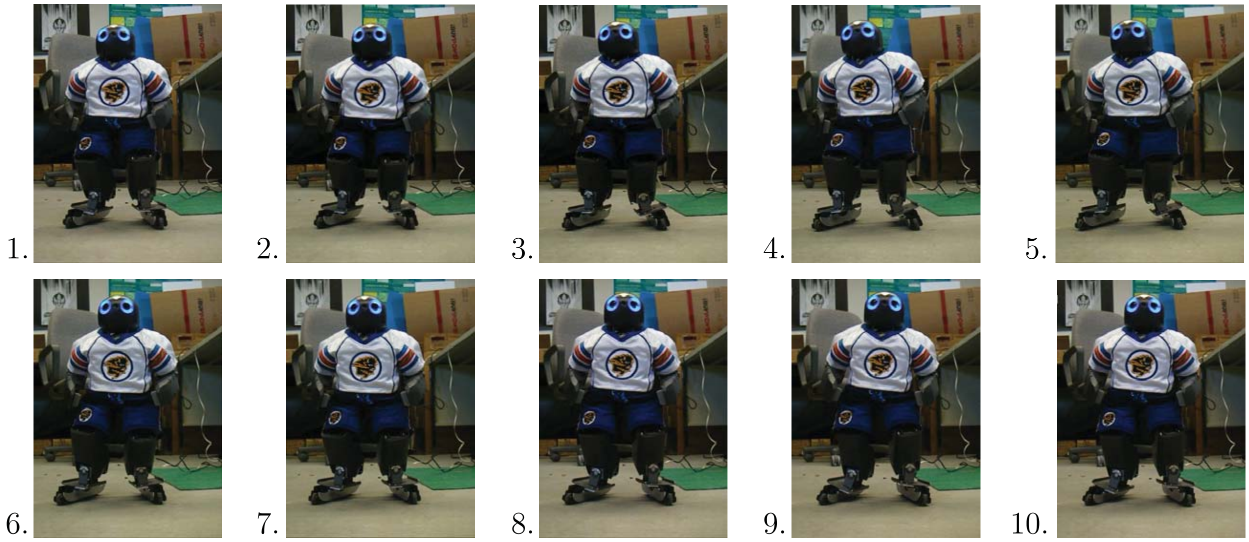

Fig. 18. Still images from a video of the robot's skating gait. The interval between each image is approximately 60 ms.

the robot to keep it from falling over, the robot was unable to generate sufficient forward momentum to propel itself.

5.4. Modified walking gait

Our experiments with the stock walking gait revealed two shortcomings:

1. the orientation of the skates relative to the direction of travel produced insufficient traction, and
2. the robot showed no lateral stability and was unable to balance on a skate during the SSP.

The first issue was trivially resolved by adding a 25° yaw offset to the legs. A higher offset would have been desirable, but was impossible due to the design of the robot's hips. (See Section 5.2.) Ideally the skates should form a 90° angle, allowing the robot to push directly against the high-friction axis of one skate and glide directly along the low-friction axis of the other. However, even the 50° angle allowed the robot to push against the edge of the skate blade to some extent.

To resolve the second issue, we reduced the stride height to 1 cm. This ensured that the robot's swing leg was close enough to the ground that if the robot fell it would enter a de facto DSP without any additional phase manipulation required. Lowering the stride height also reduced the force with which the robot pushed off the ground, reducing the amplitude of any side-to-side oscillations.

This gait was successfully tested on both a well-maintained indoor hockey rink and a well-used outdoor skating rink (such an outdoor rink would be expected to have more natural variation in ice smoothness, as well as thin, inconsistent snow cover). The robot was able to shuffle-walk forwards on skates, albeit at low speed.

5.5. Skating gait

Having established that a walking-style gait was possible, we set about developing a gait that was closer to what a human skater would use. Human skaters rely largely on moving their legs side to side, parallel to the frontal plane, pushing sideways against the edges of their skates. The modified walking gait, in contrast, relied on moving the swing leg forwards along the sagittal plane.

In order for a skater to glide forward on the support leg, a strong initial push is required. This push must provide sufficient inertia to overcome both air resistance and friction between the skate and the ice. Once given sufficient inertia from the push the robot must balance on a single skate for an extended period of time while gliding forward. Without a strong push the skater cannot glide: air resistance and ground friction slow the skater to a stop almost instantly.

Because of the importance of a strong push, we focused our efforts on the push phase, accepting that the glide phase would have to be short to maintain stability. A sustained glide phase is planned for future work.

The skating gait we developed is a further refinement of the parameters of the stock walking gait. However, because we eliminate all motion in the sagittal plane, the gait bears little resemblance to a true walking gait. Virtually all leg motion occurs in the frontal plane, as shown in Figs. 18 and 20. The skating gait uses the same 600 ms cycle as the walking gait and a stride height of 2 cm. The left/right swing is increased to 5 cm (up from the default 2 cm). As with the modified walking gait, the skating gait uses a yaw offset of 25°. The stride length is set to 0 cm.

Fig. 18 shows a series of images taken from a video of the robot skating. The interval between each image is approximately 60 ms. Initially, the robot's left foot is the push foot and the right foot is the glide foot. Frames 2–5 show the robot pushing against the left foot while the right foot glides forward. Frame 6 shows the robot shifting its weight back to the right, swapping the roles of the push foot and glide foot. Finally, frames 7–10 show the robot pushing against the right foot while the left foot slides forward. The cycle begins again with the robot shifting its weight back to the left and returning to the state shown in frame 1.

Of particular interest is the exaggerated rolling motion shown by the ankles when pushing. In order for the robot's skates to dig into the ice, the ankle is rolled so that the corner of the skate blade points directly into the ice. This disrupts the film of water formed between the ice and the skate and produces high friction, allowing for a strong push. The glide foot, meanwhile, stays in a relatively neutral position with the skate blade positioned near vertically. This creates the lowest friction between the ice and the skate (or the lowest rolling friction in the axles of an inline skate).

In our experiments we did not specifically create the ankle rolling motion. This motion is a result of the way the skate is mounted to the foot and the natural compliance of the motor. Because the skate blade is mounted towards the outside edge of the foot the mass of the robot pushing down on the foot will naturally

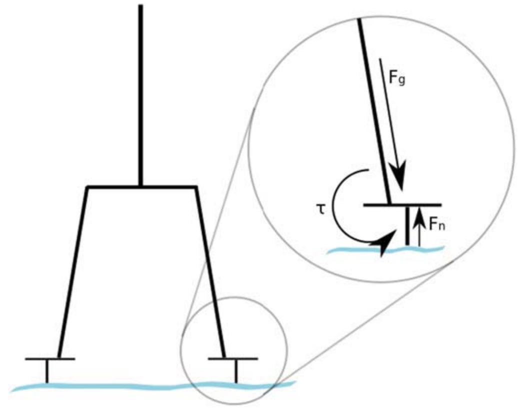

Fig. 19. Torque (τ) is naturally applied to the ankle. Gravity (F_g) acts downward through the leg. The normal force (F_n) acts upward through the skate. Because the skate is offset to the outside the ankle will roll.

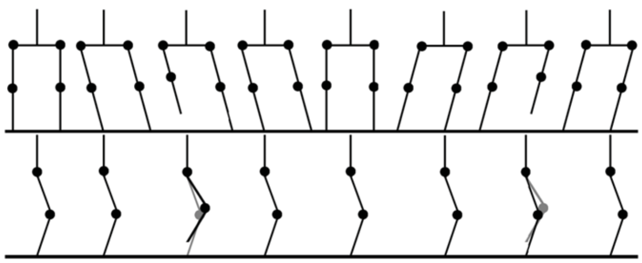

Fig. 20. Key positions in the robot's gait as seen in the frontal plane (top) and sagittal plane. These images do not take the effect of gravity into consideration. The interval between each position is approximately 75 ms.

tend to torque the ankle outwards, as shown in Fig. 19. The Robotis MX-28 servo motors used in the DARwIn-OP robots use a PID controller to control the speed at which the motor spins to its goal position. In their default configuration the motors use (P, I, D) gains of $(32, 0, 0)$. By using a lower P gain we increased the compliance in the ankle motor, allowing the foot to roll naturally, rather than directly controlling the roll motor's position through software.

Fig. 20 shows an abstract representation of the robot's gait, ignoring the effects of gravity. The robot begins in a neutral standing position and shifts its weight over the push foot. The robot lifts the glide foot, causing the entire robot to pivot around the push foot. This pivoting generates forward momentum in the same way as an inverted pendulum falling forward. Because the skates are angled outwards, the angle of rotation is normal to the push skate. This causes the robot to move forwards and sideways. The robot then straightens out its glide leg and shifts its weight over the other foot. The pattern then repeats with the push and glide legs reversed.

6. Evaluation

To evaluate the effectiveness of the modified walking gait and skating gait, we compare the speed and stability of each to the robot's stock walking gait on ice. Our experiments show that both the modified walking gait and skating gait improve stability on ice. When used on concrete with inline skates, both gaits are stable but slower than the standard walking gait without skates.

Each gait was tested using a modified version of the FIRA HuroCup sprint event [1]: the robot must move forward 3 m without falling over while staying within a 1 m wide lane. The robot uses a visual marker placed at the end of the lane to help guide it, as shown in Fig. 21. If the robot falls over the trial is marked as a fall and the distance and speed are calculated based on the robot's performance before falling over. If the robot crosses either side of the lane the trial is marked as a fault, and the distance and speed are calculated based on the robot's performance up to the point where it crosses the line.

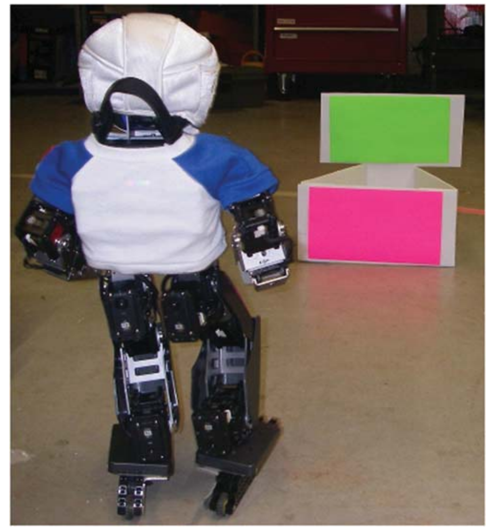

Fig. 21. The robot using a visual marker to guide it down a 3 m course using inline skates on a concrete floor.

Table 3
The results of the five trials per gait using ice skates on an indoor hockey rink.

Gait	Falls	Faults	Success	Distance (cm)	Speed (cm/s)
Stock walking (no skates)	3	1	1	171.8 (90.96)	11.20 (0.72)
Stock walking (skates)	5	0	0	0	0
Modified walking	2	1	2	191.4 (121.35)	8.36 (0.80)
Skating	1[a]	0	4	284.0 (35.78)	2.91 (0.26)

[a] A hardware fault caused the robot to lose power during one trial.

Table 4
The results of the five trials per gait using inline skates on a concrete floor.

Gait	Falls	Faults	Success	Distance (cm)	Speed (cm/s)
Stock walking (no skates)	1[a]	1	3	237.4 (97.43)	14.87 (0.48)
Stock walking (skates)	5	0	0	0	0
Modified walking	0	1	4	285.4 (32.65)	11.56 (0.37)
Skating	0	2	3	252.2(96.61)	2.58 (0.46)

[a] A piece of debris on the floor caused the robot to fall over backwards.

Each gait was tested five times, with the results shown in Table 3. The distance indicated is the average distance travelled in all five trials. The speed is the average speed across all five trials. The value in parentheses is the standard deviation.

The experiment was conducted on a well-maintained indoor ice rink. Low-quality ice results in higher ground reaction forces, which makes walking easier and hinders a skate's ability to glide. Because the quality of outdoor ice can vary significantly from day to day – and even hour to hour – depending on temperature, humidity, and precipitation, we used indoor ice to ensure more consistent results.

For comparison, we also conducted the same experiment on a concrete floor using inline skates. The results of these trials are shown in Table 4. During the trials on concrete the some of the inline skates' wheels jammed. This increased the forward ground reaction experienced by the robot when compared to the trials on ice.

6.1. Speed analysis

In both experiments the stock walking gait (without skates) was fastest, with the modified walking gait second. The skating gait was the slowest by a wide margin. The speed of the stock walking gait on skates is impossible to determine; the robot made insufficient forward progress before falling over for any meaningful data to be recorded.

Both the stock walking gait and modified walking gait were slower on ice by 24%–27%. This is likely due to both gaits relying heavily on ground reaction forces parallel to the direction of travel to produce traction. The robot's feet were observed to slip with each stride when using these gaits on ice, lowering the robot's forward speed.

The skating gait exhibited the opposite behaviour; it was 11% faster on ice than on concrete. The skating gait is specifically designed to maximise traction by pushing against the edges of the skate, limiting the foot's ability to slide when pushing. The lower friction of the ice allows the glide foot to move forward more easily, increasing the robot's forward speed and reducing energy wasted combating friction.

6.2. Stability analysis

The stability of each gait is evaluated using two criteria: the number of falls and the number of faults. Falls indicate that the gait is laterally unstable and unable to keep the robot upright, making it ill suited for use under the test conditions. Faults indicate that the gait is prone to moving the robot off course, requiring further refinements or dynamic adjustments to maintain the robot's orientation.

6.2.1. Directional stability

During the trials on concrete all gaits displayed good directional stability; all faults recorded on concrete were the result of the robot consistently moving to the left and crossing the lane boundary after moving 1.5–2.5 m. This indicates a systematic error – likely a slight depression in the floor – or a calibration error with the robot.

On ice the skating gait performed best, with no faults recorded. The skating gait was able to maintain the robot's orientation throughout the course. By contrast the stock walking gait (without skates) exhibited very poor directional stability. The robot's feet slid constantly, causing the robot to slide side to side and pivot. Several of the falls recorded were very close to the edge of the lane; if the robot had not fallen over the trials would have been recorded as faults. The modified walking gait was more stable than the stock gait, but still displayed some pivoting behaviour, resulting in a single fault and several near-faults.

6.2.2. Lateral stability

On ice all walking-style gaits show a lack of lateral stability compared to the skating gait. The stock walking gait without skates suffered from a lack of traction, impeding the robot's ZMP manipulation. This caused the robot's feet to slide wildly, causing the robot to fall over frequently. The modified walking gait showed some improvement on ice; the robot was able to successfully complete the course twice, and had a single fault. However, the lack of traction in line with the direction of travel caused the robot's feet to slide forward and backward. This sliding caused the robot to fall over twice and veer off-course once. The skating gait in contrast showed no lack of lateral stability, and kept the robot upright in all but one trial. The single fall exhibited by the skating gait was due to a hardware failure that resulted in a loss of power during the trial.

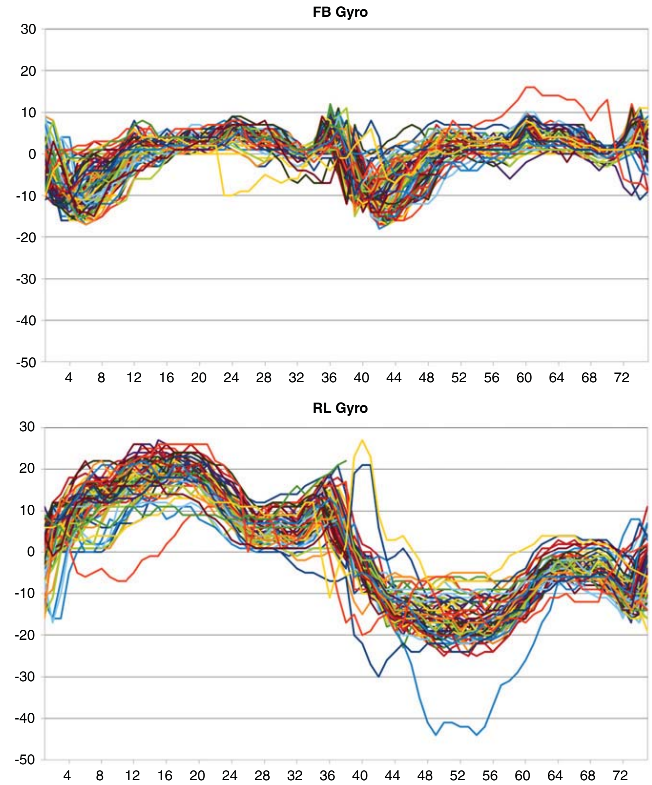

Fig. 22. The robot's angular velocity through several strides in the sagittal plane (top) and frontal plane when walking on concrete. Note the strong, cyclical pattern indicative of a stable gait.

On concrete the stock and modified walking gaits performed well in terms of lateral stability. The stock walking gait suffered a single fall due to a piece of debris in the testing area, but was otherwise stable. The modified walking gait and skating gait exhibited no falls.

To further reinforce our observations we used the robot's on-board gyroscopes to record data during the trials. Fig. 22 shows the robot's gyroscope data recorded when walking on a concrete floor. Note that the graphs show strong, cyclic patterns, indicative of a stable gait. When we use the stock walking gait on skates (the most unstable of the gaits tested) we can easily see that the angular velocity is highly erratic, as shown in Fig. 23. The stock walking gait on skates was a universally poor performer. As described in Section 5.3, the lack of lateral support in the skates causes the stock gait to become unstable very quickly, falling over after only one or two strides.

Both the modified walking gait and the skating gait show significant improvement over the stock walking gait from a stability perspective. Both gaits were able to propel the robot forwards stably. Fig. 24 shows the robot's angular velocity in the frontal and sagittal planes over several strides using the skating gait. Note that like Fig. 22 a clear, cyclical pattern is visible.

Because the skating gait relies on lateral motion to produce forward momentum, the angular velocities in both the sagittal and frontal planes are largely synchronised and have comparable magnitudes. This is contrasted with the walking gait which shows very large sine-wave-shaped curve in the frontal plane, but a flatter curve in the sagittal plane. Further analysis of the shape of the skating envelope is planned in the hope that it can be used to further stabilise the gait and aid in the development of a sustained glide phase.

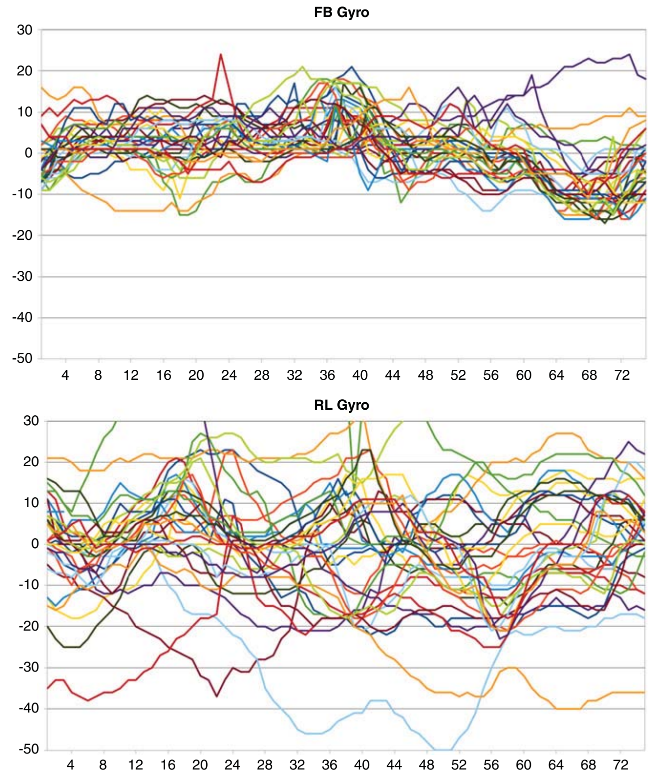

Fig. 23. The robot's angular velocity through several strides in the sagittal plane (top) and frontal plane when using the stock walking gait on skates. Note the lack of any clear, cyclical patterns.

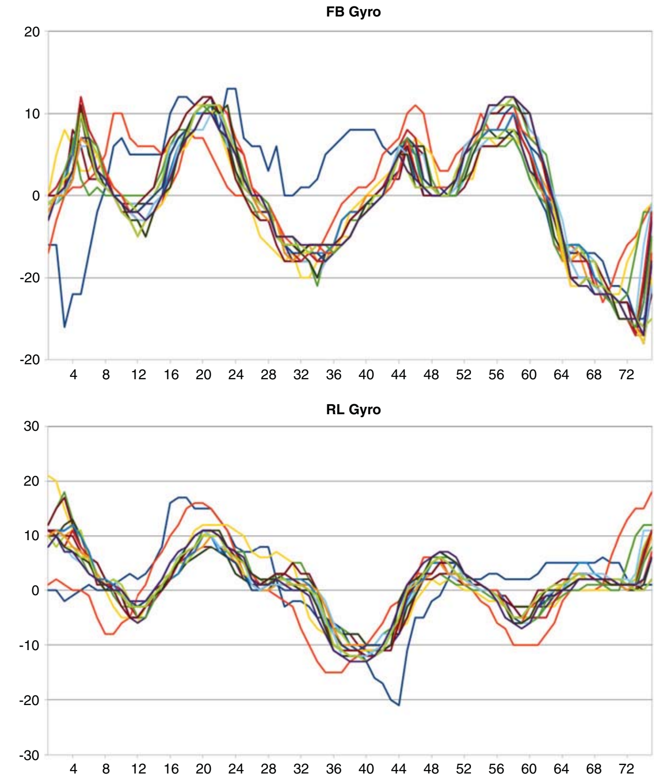

Fig. 24. The robot's angular velocity through several strides in the sagittal plane (top) and frontal plane when using the skating gait. Note that the data shows strong, cyclical patterns.

7. Conclusion and future work

In this paper, we have shown that a small humanoid robot can propel itself on ice skates using a dynamically stable gait based on the inverted pendulum model. Unmodified walking gaits are unsuited for traversing icy surfaces: the low friction impedes ZMP manipulation, causing the robot to slide off course or fall over. With modifications such a gait can be made to allow the robot to shuffle on ice skates. Through our experiments we have demonstrated that a gait composed primarily of lateral motions can be used to propel a robot forward on either ice skates or inline skates with higher stability than a more conventional walking gait.

Our research on humanoid robot skating to this point has produced several possible avenues of future research. Most important is the development of a sustained glide phase, where the robot balances on one skate while gliding forward. We hope to further increase the strength of the push phase to the point where the robot is able to skate on ice faster than it can walk on concrete.

Because the stock walking gait succeeded on ice in one of our experiments the development and evaluation of specialised walking footwear for walking on slippery surfaces (e.g. crampons, cleats) may have long-term benefits. Alternatively, research into balancing in dynamic, unstable environments (e.g. balancing on a rolling surface) may improve the robot's stability when walking or skating.

We have not yet examined the problem of turning and how the limitations of gliding on a skate blade will influence complex path-planning. A walking robot is able to stop, pivot on the spot, and continue, similar to a differential-drive wheeled robot. Skating robots must move in arcs with a minimum turning radius, similar to a conventional car. At this point it is not known what the relationship between forward velocity and turning radius is, nor what leg motions are required to execute an optimal turn.

In order to ensure to a broad range of real-world problems, and ensure that results in one area (e.g. control) must consider factors in other areas as well (e.g. perception, teamwork), much current robotic research is organised around challenge problems [2]. To this end, we intend to use ice hockey as a framework to guide our future research. Ice hockey offers many of the same challenges as robot soccer: the robot must identify key features in its environment (e.g. puck/ball, goal posts), orient itself within the field of play, and manoeuvre itself into position to pass or shoot on goal. Hockey also requires cooperation with teammates, and presents time-limited opportunities. Unlike soccer, however, these tasks must be executed in a low-friction environment, the speed of the game in terms of player movement is significantly faster, and environmental issues such as temperature may need to be considered. We have already demonstrated that the robot is able to manipulate a small ball or puck in an ice hockey setting [22] by mounting a small hockey stick to the robot's arm. We plan on continuing this research, ideally to the point where international robot ice hockey competitions, similar to current-day robot soccer competitions, are feasible.

In the long term we intend to use our findings to create a large-scale humanoid robot that is capable of actively changing from a walking gait to a skating gait if it enters a low-friction area. This will allow the robot to make optimal use of its environment, crossing slippery surfaces quickly and stably.

References

[1] Federation of International Robot Soccer Associations. Fira hurocup rules 2010. http://fira.net/?mid=HuroSot.

[2] John Anderson, Jacky Baltes, Chi Tai Cheng, Robotics competitions as benchmarks for AI research, The Knowledge Engineering Review 26 (1) (2011) 11–17.

[3] Seung-Joon Yi, Byoung-Tak Zhang, Dennis Hong, Daniel D. Lee, Practical bipedal walking control on uneven terrain using surface learning and push recovery, in: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2011, San Francisco, CA, September 2011, pp. 3963–3968.
[4] Seung-Joon Yi, Boung-Tak Zhang, Daniel D. Lee, Online learning of uneven terrain for bipedal humanoid walking, in: Proceedings of AAAI-10, Atlanta, GA, 2010, pp. 1639–1644.
[5] Min-Yi Chen, Katie Byl, Analysis and control techniques for the compass gait with a torso walking on stochastically rough terrain, in: Proceedings of the 2012 American Control Conference, ACC 2012, Montreal, Canada, 2012, pp. 3451–3458.
[6] Brian Shackel, A biomechanical comparison of starting technique in speed skating and hockey, Master's Thesis, University of Manitoba, Winnipeg, Canada, 2008.
[7] S. Kajita, F. Kanehiro, K. Kaneko, K. Yokoi, H. Hirukawa, The 3D linear inverted pendulum mode: a simple modeling for a biped walking pattern generation, in: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, vol. 1, Maui, HI, 29 October–3 November 2001, pp. 239–246.
[8] T. Sugihara, Y. Nakamura, H. Inoue, Realtime humanoid motion generation through zmp manipulation based on inverted pendulum control, in: Proceedings of the IEEE International Conference on Robotics and Automation, ICRA 2002, vol. 2, Washington, DC, May 2002, pp. 1404–1409.
[9] Jacky Baltes, Patrick Lam, Design of walking gaits for tao-pie-pie, a small humanoid robot, Advanced Robotics 18 (7) (2004) 713–716.
[10] Albertus Hendrawan Adiwahono, Chee-Meng Chew, Weiwei Huang, Van Huan Dau, Humanoid robot push recovery through walking phase modification, in: Proceedings of the IEEE Conference on Robotics, Automation and Mechatronics, RAM 2010, Singapore, June 2010, pp. 569–574.
[11] Sara McGrath, Jacky Baltes, John Anderson, Active balancing using gyroscopes for a small humanoid robot, in: S.C. Mukhopadhyay, G. Sen Gupta (Eds.), Second International Conference on Autonomous Robots and Agents, ICARA, Massey University, 2004, pp. 470–475.
[12] Sachin Chitta, Frederik W. Heger, R. Vijay Kumar, Design and gait control of a rollerblading robot, in: Proceedings of the IEEE International Conference on Robotics and Automation, ICRA'04, vol. 4, New Orleans, LA, April–May 2004, pp. 3944–3949.
[13] Sachin Chitta, R. Vijay Kumar, Dynamics and generation of gaits for a planar rollerblader, in: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2003, vol. 1, Las Vegas, NV, October 2003, pp. 860–865.
[14] Roger Bartlett, Introduction to Sports Biomechanics: Analysing Human Movement Patterns, second ed., Routledge, New York, 2007.
[15] William R. Wilson, Cross section of the blade of an ice skate, http://commons.wikimedia.org/wiki/File:Ice_Skate_Blade_Cross_Section.png.
[16] Barry Publow, Speed on Skates, Human Kinetics, Champaign, IL, 1999.
[17] Thomas Stoggle, Erich Muller, Stefan Lindinger, Double push skating in cross country skiiing. 26 (11) (2008) 1225–1233. September.
[18] Robotis. DARwIn-OP: robotis. http://www.robotis.com/xe/darwin_en.
[19] RoboSavvy. RoboSavvy—experimenting with DARwIn: part 3 joint layout and kinematics. http://robosavvy.com/site/index.php?option=com_content&task=view&id=221.
[20] Kuo-Yang Tu, Wei-Cheng Lee, Analysis and study of human joint torque and motion energy during walking, in: Proceedings of 2009 CACS International Automatic Control Conference, 2009.
[21] Springnote, DARwIn-OP—Springnote Home. http://darwin-op.springnote.com.
[22] Chris Iverach-Brereton, Jacky Baltes, Humanoid robot ice hockey player—YouTube. http://youtu.be/D4xaaJNBhlk.

Chris Iverach-Brereton is a graduate student in Computer Science at the University of Manitoba, currently working in the Autonomous Agents Laboratory under the supervision of Dr. Jacky Baltes. He received his Bachelor's of Computer Science (honours) from the University of Manitoba in 2008. He has represented the university at several humanoid robotics competitions including FIRA HuroCup, RoboCup, and the DARwIn-OP Humanoid Application Challenge.

Jacky Baltes received his Ph.D. in 1996 from the University of Calgary in Artificial Intelligence. From 1996 to 2002, he worked as a senior lecturer for the University of Auckland in Auckland, New Zealand. Since 2002, he has been a professor in the Department of Computer Science at the University of Manitoba in Winnipeg, Manitoba. Prof. Baltes' research interests are intelligent robotics, artificial intelligence, machine learning, and computer vision. Dr. Baltes and his students have competed successfully at various international intelligent robot competitions. Dr. Baltes has also been a vice president of the FIRA robotic soccer association, chair of the HuroCup competition, and a member of the RoboCup executive committee. He is also interested in robotics education and a member of the steering committee of the International Robot Olympiad robot competition for high school students.

John Anderson is a Professor in the Department of Computer Science at the University of Manitoba. He received his Ph.D. from the University of Manitoba in 1995, in the area of artificial intelligence, and founded the Autonomous Agents Laboratory in the Department of Computer Science shortly afterwards. His primary research interests lie in the areas of robotics, multi-agent and multi-robot systems, and include cooperative problem-solving, heterogeneous team formation, social learning, and the application of these to challenging problems such as robotic soccer and urban search and rescue. He is also interested in improving Computer Science education through the use of artificial intelligence and robotics.

Andrew Winton is a graduate student in Computer Science at the University of Manitoba working in the Autonomous Agents Laboratory under the supervision of Dr. Jacky Baltes. He has worked on adult-size and kid-sized humanoid robots, and represented the university at FIRA HuroCup and RoboCup.

Diana Carrier is an undergraduate student in Computer Science at the University of Manitoba. Her research interests include domestic robotics, computer vision and augmented reality. She recently represented the University of Manitoba at FIRA HuroCup 2012 and the DARwIn-OP Humanoid Application Challenge at ICRA 2012.