When Knees Become Ankles

Nils Smit-Anseeuw[1], Ramanarayan Vasudevan[2], and C. David Remy[3]
[1]University of Michigan, [2]University of Michigan, [3]University of Michigan
nilssmit@umich.edu

Summary
In this work, we investigate the energetic impact of knee direction on the walking robot RAM*one*. Energetically optimal gaits were found for a range of velocities with knees pointed forward and with knees pointed backwards, and the results were compared. We found that for walking gaits, the knee direction had little impact on the results, while for running gaits, a backwards knee resulted in a significant energetic improvement. These results align with the observation that for bipedal mammals and birds, the most distal link of the legs tends to point forwards.

Introduction
Five link robots with rolling feet have often served as a popular test platform for dynamic walking in robots. Examples include Rabbit [1], Mabel [2], ERNIE [7], and Phides [5]. In each of the above cases, the robots all walk as a human would, with knees pointed forward. However, it is worth considering whether it would instead be better for these robots to walk with the mid-leg joint inverted, like the ankles of an ostrich.

The question of the optimal knee direction for five link walkers has been addressed previously for conceptual robot models [3]. In that paper, the authors looked at a large array of randomly generated five link walkers with both forward and backward knees, and investigated optimal running gaits. It was concluded that for a large percentage of robots, a reversed knee is energetically optimal.

In this paper, we look at a realistic model of our specific robot hardware, and determine the efficiency across speed for knee forwards and backwards configurations across running and walking gaits. We include series elasticity in the joints as well as realistic actuator models, aspects that were absent from [3].

Methods
The robot is modelled as a five link floating base kinematic chain with rolling contacts at each foot. This chain is actuated by four realistic DC motor models, one in each hip and knee. Between each joint and motor is an elastic element in series.

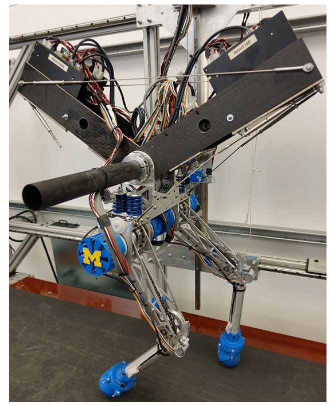

Figure 1: This work investigates the difference between forward and backwards gait on the robot RAM*one*. It was built at the University of Michigan as a testbed for studying efficient gait. The robot is based on the Scarl*ETH* leg design [4], and is mounted on a two dimensional gantry which restricts its motion to the sagittal plane.

We use the multiple shooting package MUSCOD to find periodic trajectories that minimize electrical cost of transport across a range of speeds, for both forward and backward knees.

See [6] for a more detailed description of the optimization and model used.

Results
The results of the optimization are given in Figure 2. We see that for walking gaits, the cost of transport is independent of knee direction, while for running gaits, the backward knee result is significantly more efficient.

The correspondence between the two knee orientations in walking is expected, as we have seen previously that the optimal walking gait for this model keeps the knees nearly straight [6], in which case the two models are identical.

The discrepancy in cost for the forward gait is more surprising. It must be noted that the running results for the forward knee case are preliminary, as there are some indications that they have not reached a global minimum.

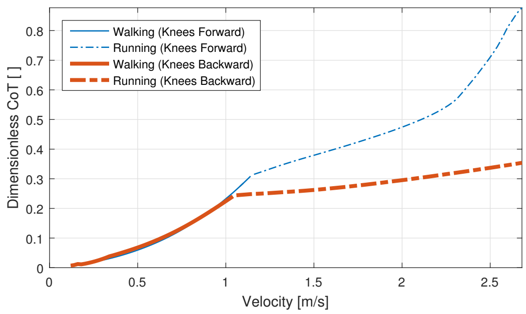

Figure 2: Energetic cost of transport across a range of speeds for both forward knee and backward knee walking. We see that the walking cost of transport coincides between the two cases, while the backwards knee running gait is significantly more efficient than the forward knee gait.

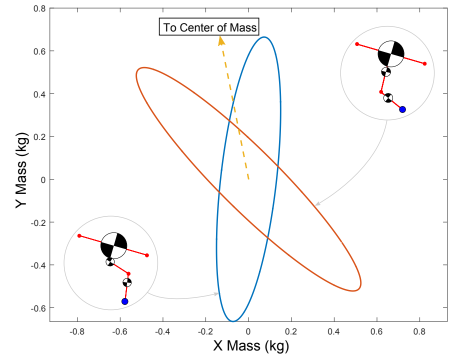

Figure 3: Contact space mass ellipse for a likely contact configuration in knee forward and knee backward cases. We see a larger apparent mass in the direction of the center of mass in the knee forward case. Since it is desirable for the contact impulse to lie in this direction, this points to a larger collision loss with the knee forward.

In order to explain the differences in economy between forward and backward knees, we first need to look at what distinguishes these two cases. One important difference is the mass and stiffness properties seen by the contact point. These are found by using the contact Jacobians to project the mass and stiffness matrices of the robot into the contact space.

The contact space mass matrix is important, as it determines the loss associated with a given impact direction. Assuming the impact is directed towards the center of mass, we would expect to see a larger impact loss for knees bent forwards.

The contact space stiffness matrix also plays an important role in the energetics of gait. Since we have different stiffness at knee and hip, there is a shift in the stiff and soft directions of this matrix. However, determining the exact energetic consequences of this shift requires a more detailed investigation.

The preliminary results of our work seem to agree with the leg morphology seen in mammals and birds, in which the most distal link hinges forward. In this sense, our results suggest that the "knees" of the robot should be treated as ankles.

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