The Physics of Curling

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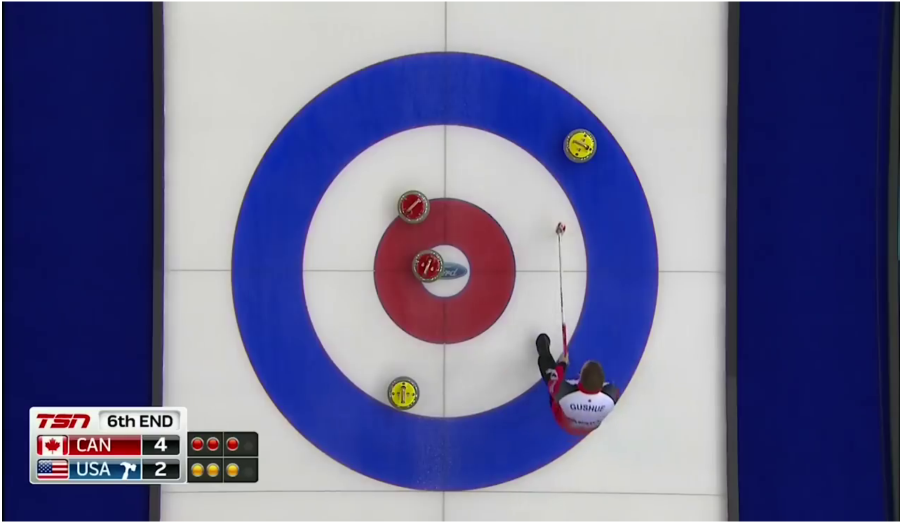
Curling? The sport where they sweep the ice?

Curling: An Introduction



Curling: An Introduction

Curling dates back to 16^{th} century Scotland

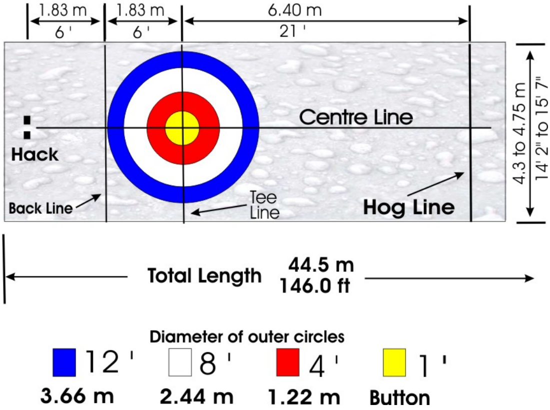
Curling was reintroduced as an Olympic sport in 1998

Since 1998:

Nation	Gold Medals
	5
	2
	1

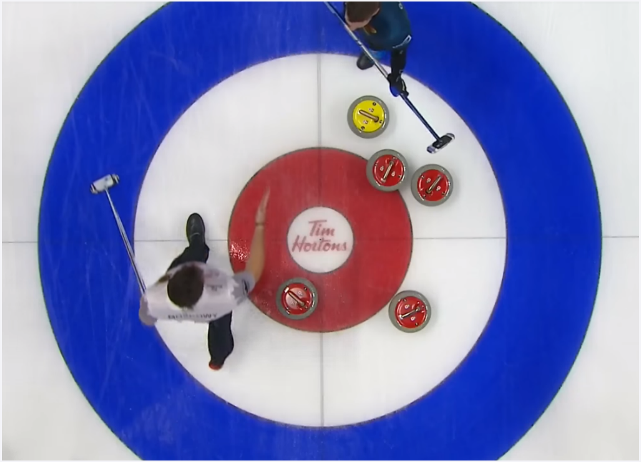
Curling: An Introduction

- The sport is played by two teams of four.
- Each team takes turns sliding stones 130 feet (40 meters) toward a 12 foot (3.6 meter) target called "the house."
- Each team throws eight stones and are trying to get their stones as close to the center of the house this is called "the button."



Curling: An Introduction

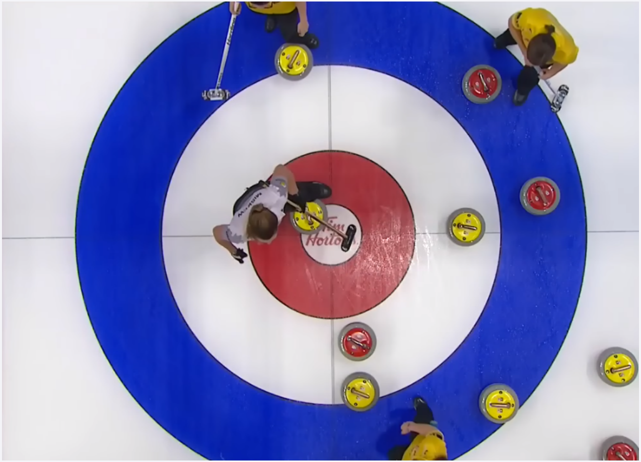
After all 16 stones are thrown the team whose rocks are closest to the button scores a point for each stone closer than their opponent's.



Red scores four points

Curling: An Introduction

After all 16 stones are thrown the team whose rocks are closest to the button scores a point for each stone closer than their opponent's.



Yellow scores one point

Curling: An Introduction

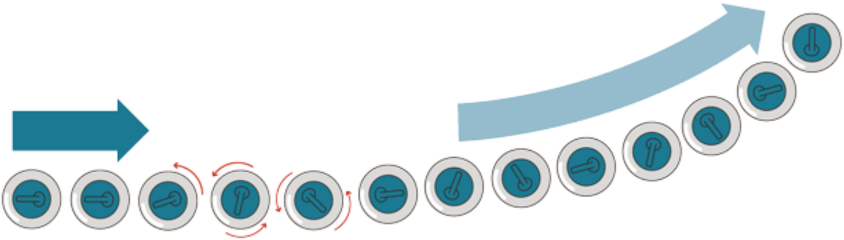
- Curling stones are made of granite and weigh around 40 pounds (18 kg)
- The stones have concave bottoms and actually slide on a small ring

Curling: An Introduction

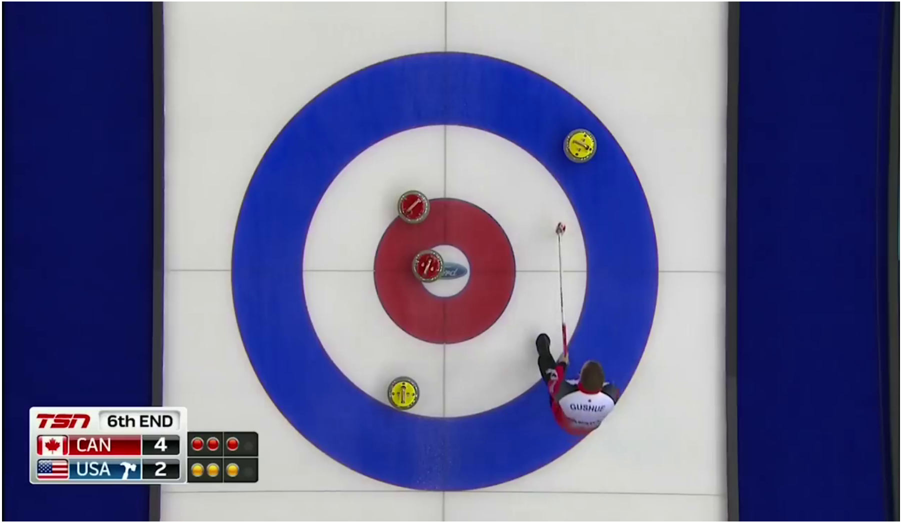
- The surface of the ice is not smooth.
- The ice is prepared with small droplets of water frozen on the surface.
- This is called "the pebble"

Curling: An Introduction

- Curling gets it's name from the fact that the stones travel along curved paths
- This is achieved by releasing the stone with a rotation
- The deep and interesting strategy of the game all comes from the curling of the stones



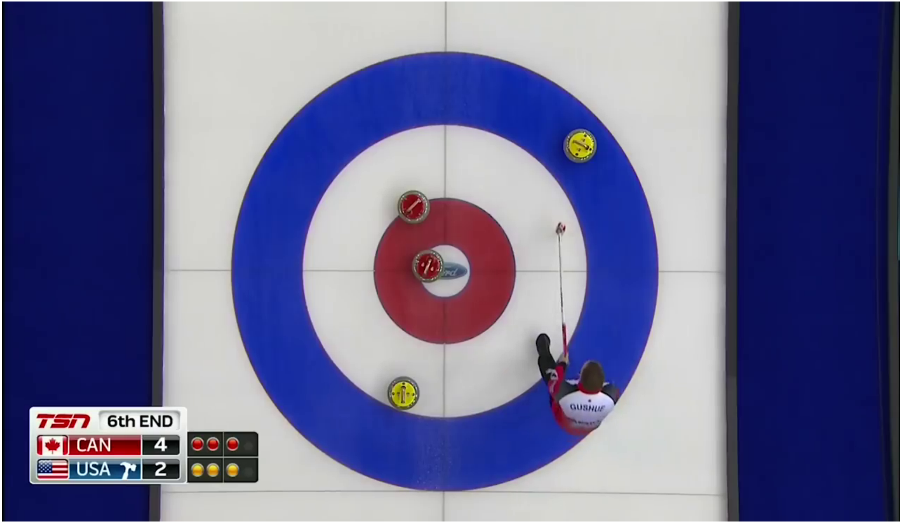
Curling: An Introduction



Curling: An Introduction

- The sweeping heats the ice in front of the stone
- This reduces the friction on the stone
- This causes the stone to travel farther and straighter

Curling: An Introduction



The Unintuitive Physics of the Curling Stone

Take for example a upside down glass rotating and sliding across a table. The glass deflects in the opposite direction than a curling stone! So we need a model of the curling stone that:

- Deflects in the same direction of rotation.
- Deflects about 1 meter when slowly rotating.

Mark Shegelski's Model

The motion of a curling rock

Mark R.A. Shegelski, Ross Niebergall, and Mark A. Walton

The motion of a curling rock: Analytical approach

Mark R.A. Shegelski

Received May 05, 2000. Accepted August 24, 2000. Published on the NRC Research Press Web site on September 20, 2000.

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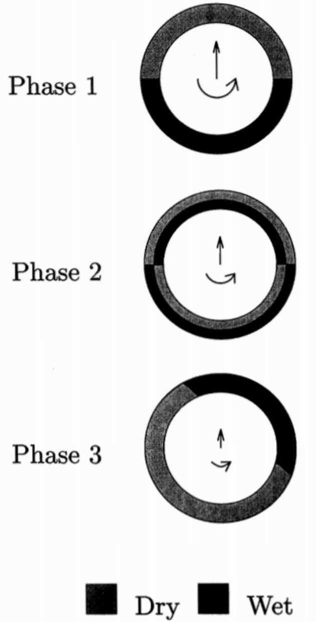
Can. J. Phys. **78**: 857–864 (2000)

Asymmetric Friction Due to Liquid Thin Film

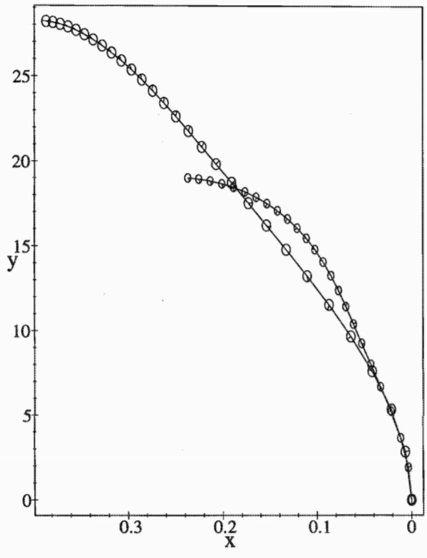
- Phase 1: The leading semicircle experiences dry friction
- Phase 2: The rock slows distributing the areas of wet and dry friction
- Phase 3: The rock moves slowly enough to drag liquid film from the back to the front creating a front back frictional asymmetry

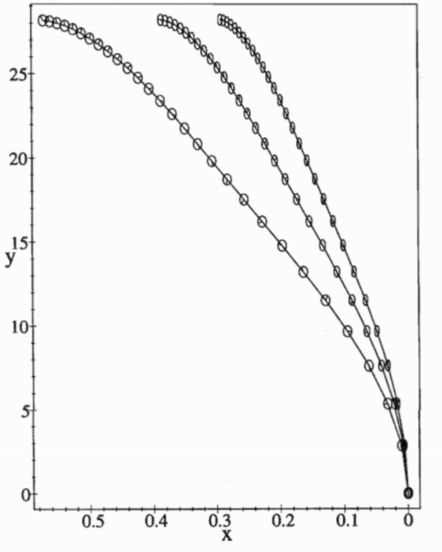
Dry friction: $\Delta F^d = \mu M g \left(\frac{\Delta\theta}{2\pi}\right)$ Wet Friction: $\Delta F^w = k[u(\theta)]^2$

Can. J. Phys. Vol. 74, 1996



Front Back Frictional Asymmetry





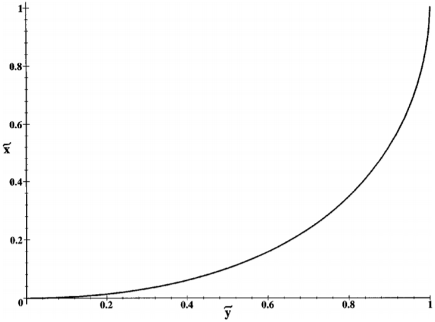
Can. J. Phys. Vol. 74, 1996

Front Back Frictional Asymmetry

The model was simplified using the assumption that the coefficient of kinetic friction felt by the running band of the stone went by

$$\mu(\theta) = \mu_0(1 - f_0 \sin\theta)$$

The resulting force and dynamics give the desired deflection seen by curling stones



Can. J. Phys. Vol. 78, 2000

Mark Denny's Model

Curling rock dynamics

Mark Denny

Curling rock dynamics: Towards a realistic model

Mark Denny

Received July 7, 1997. Accepted January 19,1998.

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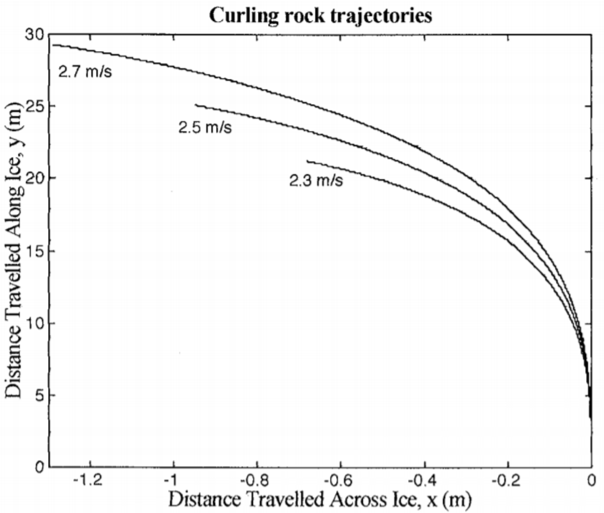
Can. J. Phys. **76**: 295–304 (1998)

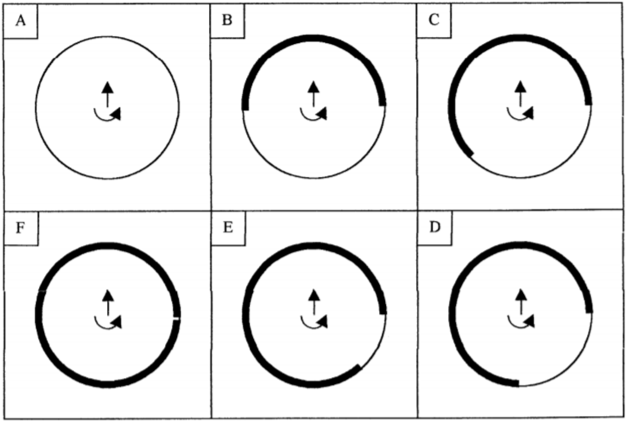
Left Right Frictional Asymmetry

Denny showed that with a left right asymmetric μ_k independent of velocity the desired curl path can be achieved



Snowplow Model

Denny proposed that as the stone rotates it picks up pieces of ice thereby reducing the fiction of the running band resulting in an asymmetric friction



Can. J. Phys. Vol. 80, 2002

Criticism of Shegelski's Model

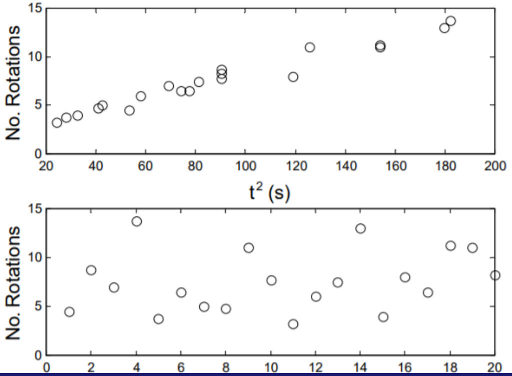
DISCUSSION / DISCUSSION

Comment on "The motion of a curling rock"[1]

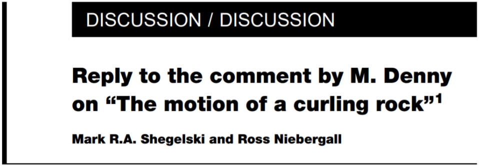
Mark Denny

M. Denny's comment brings up two criticisms Shegelski's Model

- The number of rotations N is independent of total travel time t_0
- The dependence of deflection distance on initial angular velocity does not agree with



Response by Shegelski



DISCUSSION / DISCUSSION

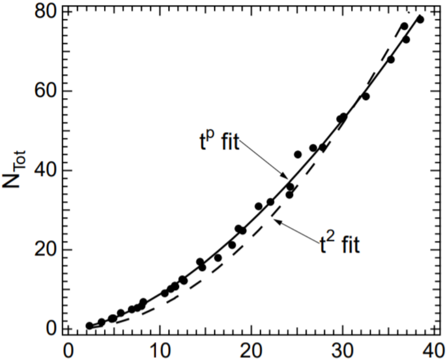
Reply to the comment by M. Denny on "The motion of a curling rock"[1]

Mark R.A. Shegelski and Ross Niebergall

Shegelski preformed his own experiment determining the relationship between rotations N_{Tot} and total time t_{Tot}. He fits his data to

$$N_{Tot} = m(t_{Tot})^p$$

to find that $p = 1.637 \pm 0.024$ which implies wet friction.



A. Raymond Penner's Model

The physics of sliding cylinders and curling rocks

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(Received 2 February 2000; accepted 7 June 2000)

The lateral deflection of a rotating cylindrical shell sliding on one of its ends is considered and both theoretical and experimental results are presented. The coefficient of kinetic friction between a curling rock and an ice surface is then derived and compared with experiment. Current models of the motion of a curling rock are discussed and an alternate hypothesis is presented.
[DOI: 10.1119/1.1309519]

A. Raymond Penner's Model

A. R. Penner showed that if the frictional energy is conducted into the ice the resulting coefficient of friction goes by

$$\mu_k \propto v^{-1/2}$$

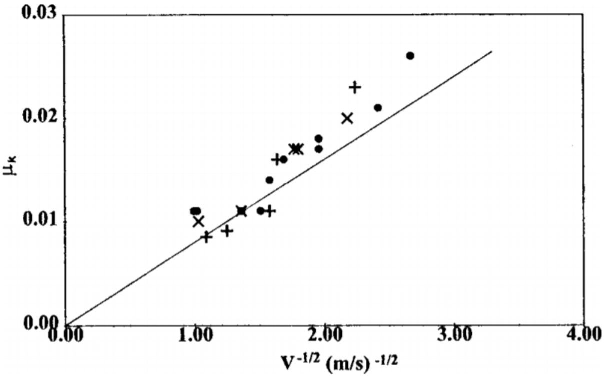
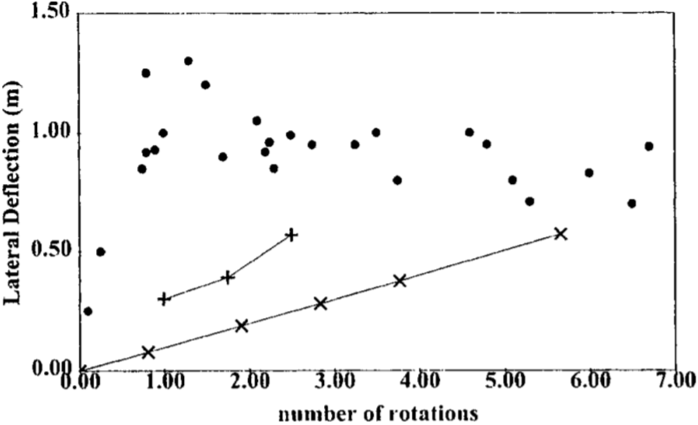


Fig. 9. The dependence of the coefficient of kinetic friction on velocity; (●) experimental values for a curling rock, (×) experimental values for the full curling rock model, (+) experimental values for the half curling rock model, (—) theoretical values as per Eq. (17).

Am. J. Phys. Vol. 69, No. 3, March 2001

A. Raymond Penner's Model



Am. J. Phys. Vol. 69, No. 3, March 2001

Harald Nyberg Model

The asymmetrical friction mechanism that puts the curl in the curling stone

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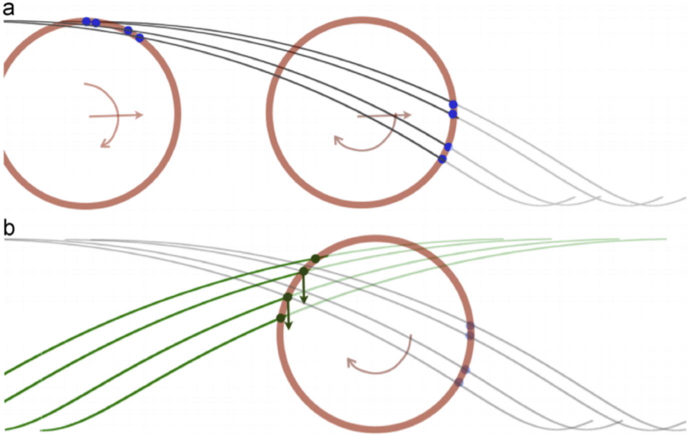
A B S T R A C T

Curling is an Olympic winter sport in which two teams slide stones across a sheet of ice towards a target area, some 28 m away from the release line. The sport has its name from the fact that the trajectory of a rotating stone becomes slightly curled, a fact used to reach open spots or take out opponent stones behind hindering "guarding" stones, etc. By slowly turning the stone clockwise when it is released, it will curl to the right, and vice versa. The resulting sideward deviation is typically slightly more than a metre. This intriguing tribological phenomenon has so far lacked a satisfactory explanation, although many attempts have been presented. In many of them, the curling motion has been attributed to an asymmetrical distribution of the friction force acting on the sliding stone, such that the friction on the rear of the stone (as seen in the direction of motion) is higher than that on the front. In a recent paper, we could show that no such redistribution of the friction, no matter how extreme, can explain the magnitude of the observed motion of a real curling stone. The present work presents an alternative asymmetrical mechanism that actually is strong enough to account for the observed motion. Further, in contrast to previous models, it satisfies other observed phenomena, including the independence of rotational speed of the stone and the strong dependence of the roughness of the stone. The model is backed up by experimental evidence and is based on the specific tribological conditions presented by the contact between a scratched curling stone and a pebbled ice sheet.

Harald Nyberg Model

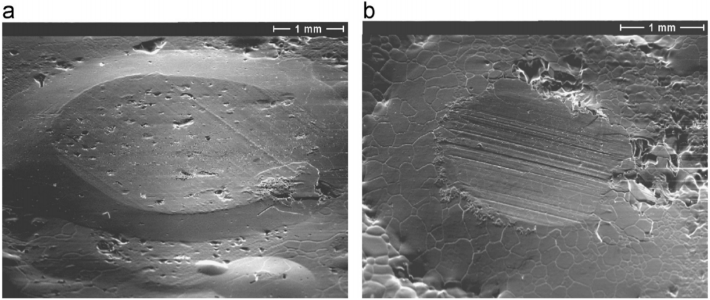
Nyberg proposed that the asymmetric friction is a result of the curling stone scratching the ice.



Wear 301 (2013) 583-589

Harald Nyberg Model

Nyberg observed scratches on the pebble after a single stone has passed. As well as a change in coefficient of friction by manually scratching the ice.



Wear 301 (2013) 583-589

Shegelski Comments on the Harald Nyberg Model

Comment on the asymmetrical friction mechanism that puts the curl in the curling stone

CrossMark

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A R T I C L E I N F O

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A B S T R A C T

Features of a proposal to address the curl of curling rocks, based on scratches made by a curling rock, are shown to be in contradiction with observed motions of curling rocks. Examples are as follows. Scratches are not required for curling. No comparisons are made with experimental results. The proposal predicts serpentine paths of curling rocks, which are not observed. The proposal predicts that a second rock moving behind a first rock will curl less than the first rock, which is contradicted by observations. The proposal has no quantitative results: there are no equations for the curl distance as a function of time, the distance travelled down the ice, the speed of the rock, the angular speed, or the trajectory of the rock.

Shegelski has two main complaints of the scratch model:

- The model predicts oscillations in the path and this is not observed behavior
- Even with a polished running surface that does not scratch the ice a curved path is observed

Numerical Calculations of Asymmetrical Friction

ORIGINAL PAPER

Calculated Trajectories of Curling Stones Sliding Under Asymmetrical Friction: Validation of Published Models

Harald Nyberg · Sture Hogmark · Staffan Jacobson

Received: 4 December 2012 / Accepted: 30 March 2013 / Published online: 9 April 2013

Numerical Calculations of Asymmetrical Friction

Nyberg created a numerical simulation with the ability vary asymmetrical friction in a rotating cylinder. The resulting deflections are well short of observed curling stone deflections even in extreme cases.

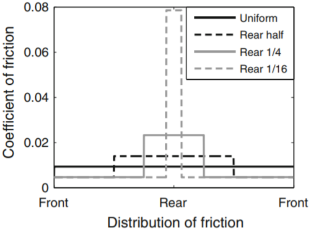

Fig. 4 Distributions of coefficient of friction along the running band, used in the calculations in Fig. 5. The normal force is assumed to be evenly distributed over the running band

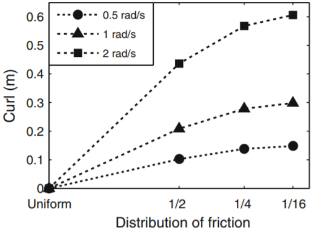

Fig. 5 Calculated curl for different rotational velocities and the four friction distributions illustrated in Fig. 4. The rotational velocities correspond to roughly 1.5, 3 and 6 revolutions of the stone

Further Precision Measurements

Measurements show as rotational speed increases deflection decreases.

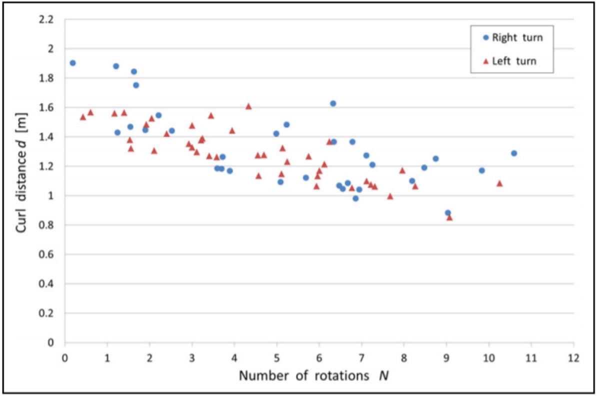

Figure 7. Relationship between curl distance *d* and number of rotations *N*. Directions of rotation are shown by different signs.

Hattori et al. (2016)

Pivot-Slide Model

1305

NRC Research Press

ARTICLE

Pivot–slide model of the motion of a curling rock

Mark R.A. Shegelski and Edward Lozowski

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Contents lists available at ScienceDirect

Cold Regions Science and Technology

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

First principles pivot-slide model of the motion of a curling rock: Qualitative and quantitative predictions

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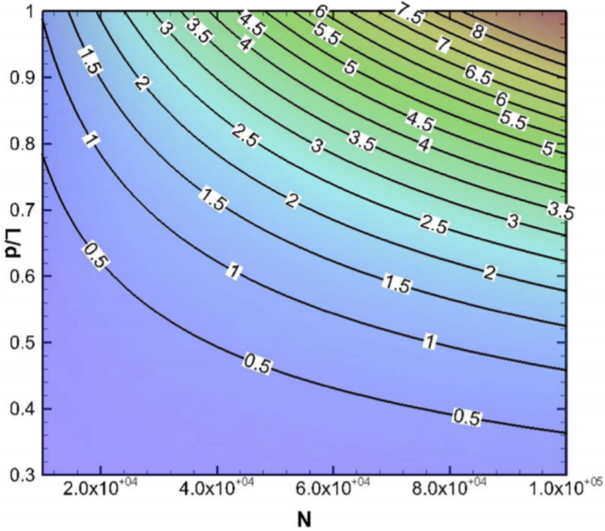
[b] *Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada*

Check for updates

Pivot-Slide Model

The pivot-slide model proposes that the curl results from an adhesion of the running band with the pebbled ice. The major advantage of this model is that the deflection distance is weakly dependent on the angular velocity.



The Olympic Curling Competition Starts February 14

PyeongChang 2018