Frictional heat generated by sweeping in curling and its effect on ice friction

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Abstract: In the sport of curling, players sweep the ice in the front of curling stones to increase the distance that the projectiles slide. Their vigorous sweeping raises the surface temperature of the ice, thereby reducing its coefficient of friction. The change in ice temperature is dependent on the velocity that curlers sweep the ice, the downward force they apply, and the pattern that is swept. The forces and velocities applied by Olympic level curlers were recorded with an instrumented brush. Laboratory-based rubbing experiments were conducted to determine the temperature rise in ice from sweeping. A numerical model was developed on the basis of the recorded sweeping profiles and laboratory-based rubbing experiments. The model was used to compare the thermal effects of two popular sweeping styles and shows that a conventional low attack angle style is the most efficient.

Keywords: thermomechanical modelling, curling, sports engineering, frictional heating, equipment design

1 INTRODUCTION

The distance and trajectory that stones slide over ice in the Olympic sport of curling are modified by athletes who sweep vigorously in front of their stones. The act of sweeping raises the surface temperature of the ice, which reduces its coefficient of friction, resulting in metre-scale variations in the distances the stone travels. Curling is unique among target-based sports to allow ‘in-flight’ correction of the projectile’s trajectory. The ability to significantly modify a stone’s path combined with the skill to correctly judge how best to make such a correction is the key component in the sport [**1**].

The change in temperature and related variation in the coefficient of friction of ice [**2**, **3**] are dependent on the velocity that curlers sweep, the downward force they apply, and the pattern that is swept. Sweeping is a highly physical component of the sport. The effectiveness of the curler’s sweeping action tends to deteriorate over the course of a match as players become fatigued, leading to a reduction in the frequency of their stroke rate [**4**]. It is therefore essential that the most efficient methods for sweeping ice be identified.

A three-dimensional thermomechanical numerical model has been developed to identify the most efficient sweeping style. The forces and velocities applied by an Olympic level male curler were measured using an instrumented brush, known as a sweep ergometer [**4**], to provide the numerical model with realistic brush head dynamics. A laboratory-based rubbing apparatus was designed and built to measure the thermal change in ice from sweeping and results were used to calibrate the numerical model. The model is used to compare the thermal response in ice of two commonly used sweeping styles and their effects on the trajectory of curling stones.

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2 ICE FRICTION AND CURLING

In curling, two teams of four players alternately slide 19 kg granite stones across 28 m of ice to a target area known as the house. The ice is not flat but covered by fine droplets of water that freeze to form millimetre scale protrusions known as pebbles. Teams score points by having the stone(s) closest to the centre of the house, once both teams have delivered all eight of their stones. Once a stone has been released, players are allowed to sweep in front of the stone to modify its trajectory. It is a sport that combines skill, strength, and a very high level of strategy.

Ice friction is the central process in the sport of curling. Ice is commonly regarded as an extremely slippery material because it has a coefficient of friction an order of magnitude lower than other crystalline solids. Friction on ice depends on a number of parameters including the velocity, thermal properties, and surface roughness of the sliding object and on the morphology and temperature of the ice.

The mechanisms that operate when a material slides across ice are complex. Several interdependent mechanisms have been identified, although different mechanisms tend to dominate under different conditions. At velocities greater than $\sim$0.01 m/s and temperatures above $-10\,^{\circ}$C, frictional heating is sufficiently high to melt the ice surface and provides a lubricating film of liquid water [**2**, **5–7**]. At velocities less than $\sim$0.01 m/s, frictional heating is not sufficiently high to lubricate the ice–slider interface and frictional sliding proceeds via the deformation of asperities and surface fractures [**8–11**]. Thus at low sliding velocity, the coefficient of friction is controlled by the creep rate of ice [**8**], adhesion by sintering leading to asperity growth [**9**, **12**] or a combination of both processes [**13**].

Lubricated sliding due to frictional heating is the dominant friction mechanism for most of the velocity and temperature ranges in curling and other winter sports involving sliding on ice or snow. The thickness and behaviour of the fluid films that form at the sliding interface control the friction of curling stones on ice. For a given load, the frictional heating and the thickness of the fluid film increase with velocity, resulting in a non-linear reduction of friction with velocity ($\mu \propto v^{-1/2}$) [**2**, **14**]. It is this inverse and non-linear relationship that is responsible for the curved trajectory of curling stones [**1**, **15**].

Friction on ice is strongly dependent on temperature. As the bulk temperature of ice approaches its melting point, less thermal energy is required to melt its surface. Thus, for a given load and velocity, more lubricating melt is produced at higher bulk temperature T. Given the temperature of the film is constantly at the melting point of ice (0 °C) [**2**], the viscosity of the water film is also constant so that μ varies inversely with T. The presence and the thickness of the fluid film are also dependent on the thermal properties of the slider. As the thermal diffusivity of the slider increases, more frictional heat is transported away from the sliding interface and is not available for ice melting, so the thickness of the fluid film is reduced and friction increased [**3**]. The thermal history of both the slider and the ice is important. The longer that a sliding event occurs the more heat is accumulated by the system. In the case of sweeping on ice, the thermal history can be complex and strongly affect the coefficient of friction.

Friction is dependent on the surface roughness of both the ice and the slider. A proportion of the lubricating fluid penetrates into the ‘valleys’ between surface asperities, thereby reducing the effective thickness of the fluid film. As the sum surface roughness of the ice and its counter-facing surface increases, the effective thickness of the fluid film reduces and μ increases.

When curlers sweep in front of the sliding curling stones, they reduce the coefficient of friction for granite sliding on ice so that the stone decelerates less rapidly and can slide several metres further. Sweeping reduces μ by polishing the ice and raising its temperature. The running surfaces on the curling stones can be roughened to increase the amount that the stones curl. The roughness of the stone’s running surface ($\gg$10 μm) is several orders of magnitude larger than that of the ice (except in extreme conditions when the ice is covered in frost). The change in the surface roughness of relatively smooth Olympic standard ice by polishing is negligible relative to the magnitude of the surface roughness of the counter-facing curling stone. Polishing, therefore, has little effect on μ. Raising the temperature of the ice by frictional heating via sweeping has the greatest effect on μ and is the focus of the following study.

3 MEASURING SWEEPING DYNAMICS

3.1 Monitoring an Olympic curler

A sweep ergometer has been developed to perform the first quantitative analysis of sweeping dynamics [**4**]. The sweep ergometer is a curling brush equipped with a series of strain gauges and a tri-axial accelerometer that measures the forces and velocity applied by curlers [**4**]. A typical sweeping profile of an Olympic level male curler is shown in Fig. 1. Elite curlers sweep with a frequency of $\sim$4.5 Hz with a peak velocity of $\sim$2.5 m/s and a peak downward force of $\sim$450 N (Figs 1(a) and (b)). Given that the ergometer brush head dimensions are 0.21 m × 0.08 m, the peak downward pressure is $\sim$25 kPa.

The peak velocity achieved by each curler is generally close to the centre of their stroke (Fig. 1(c)).

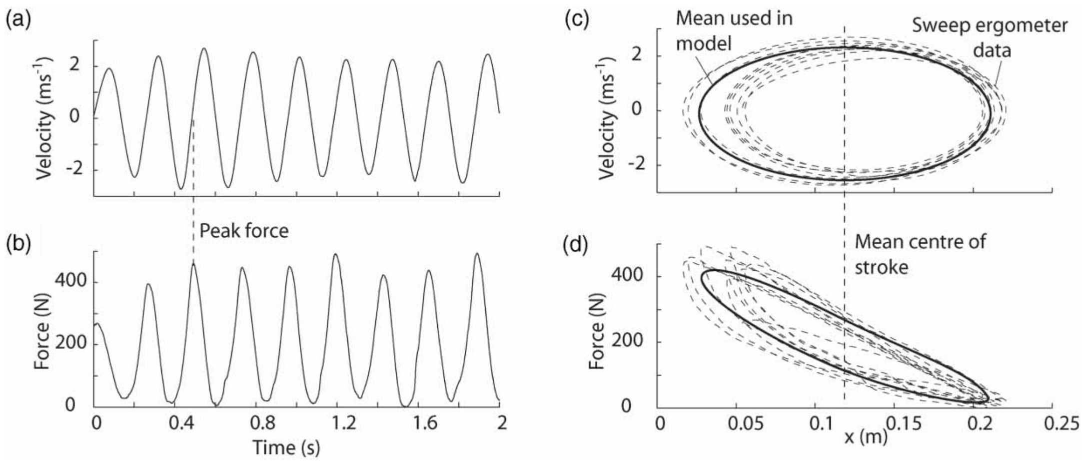

Fig. 1 Velocity and force recorded from an Olympic level male curler with the sweep ergometer. (a) Horizontal velocity–time history and (b) vertical force–time history. Peak velocity and force do not coincide. (c) Variation of velocity with position for a curler whose centre of mass is close to the origin. (d) Variation of vertical force with position. Solid line shows the mean used in the numerical model (Fig. 4)

The peak downward force does not coincide with the peak velocity (Figs 1(a) and (b)), but occurs at the point in the stroke where the brush head is closest to the player's feet (Fig. 1(d)). When the brush head is closest to the player, the horizontal moment arm from the curler's centre of mass is reduced to a minimum, increasing the vertical force exerted on the brush head.

3.2 Measuring the temperature change produced by sweeping

A laboratory-based assembly was built to measure the temperature increase in ice due to rubbing with a standard nylon curling brush (Fig. 2) and the resulting data were used to calibrate the numerical model. The rig oscillates a nylon brush head under constant load across flat ice with an array of thermocouples embedded 2 mm below its surface. A motor-driven crank system was used to replicate the sinusoidal velocity pattern employed by curlers (Fig. 1). A 0.37 kW AC induction motor controlled with a PowerFlex700 AC inverter drive was used to power the system via a 3.33:1 gearing ratio. The crank reciprocates the body of the rig along two fixed running bars (Fig. 2) in the horizontal plane with PVC bushes to ensure smooth running. The vertical load applied by curlers fluctuates as a function of the position in its stroke (Fig. 1(d)). However, a constant load was used on the rig to keep the mechanism as simple as possible. A range of loads were applied by placing known masses on the mass cradle attached to a

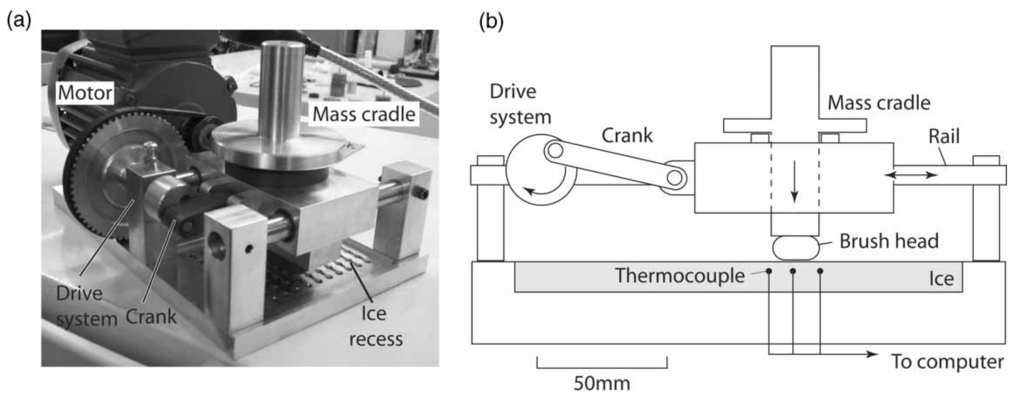

Fig. 2 Laboratory-based sweeping rig. (a) Photograph from an oblique viewpoint. Circular holes in the recess are positions where thermocouples were fixed. (b) Schematic representation of the mechanical system

vertical sliding shaft with the brush head attached to its base (Fig. 2).

Brush heads were reduced to a 1:10 scale so that the force per unit area applied by curlers could be reproduced. The distance swept was likewise scaled from the curlers' average of 0.20 m (Fig. 1(c)) to 20 mm. The reduction in the distance sweep means that less work is done at the sliding interface, so less heat is produced. However, determining the effect of sweeping patterns on surface temperature was a prime goal, so the rig was designed such that the successive stokes overlapped with the same frequency as those in the sport (full-scale). The base of the assembly contained a 120 × 120 mm, 5 mm deep recess containing ice (Fig. 2). At the base of the recess, a series of 5 mm diameter holes were drilled to contain thermocouples (type K). A 50 kΩ sliding potentiometer was used to determine the distance between the ice surface and the position of the thermocouples and to record any change due to the wear of the ice surface. The signals from the thermocouples and potentiometer were then amplified and data logged using an external computer with LabView software at a rate of 100 Hz.

Figure 3 shows the change in the temperature of ice measured 2 mm below the ice surface for different sweeping frequencies and applied pressures. Each experiment began with a 10 s ramping period over which time rotational velocity of the drive system accelerated from 0 until the brush head attained the frequencies shown in Fig. 3. The greatest temperature increase in the ice is produced by a low-pressure–high-velocity (frequency) style (Fig. 3(a)). This suggests that curlers should sacrifice the amount of downward pressure they apply for greater brush head velocity.

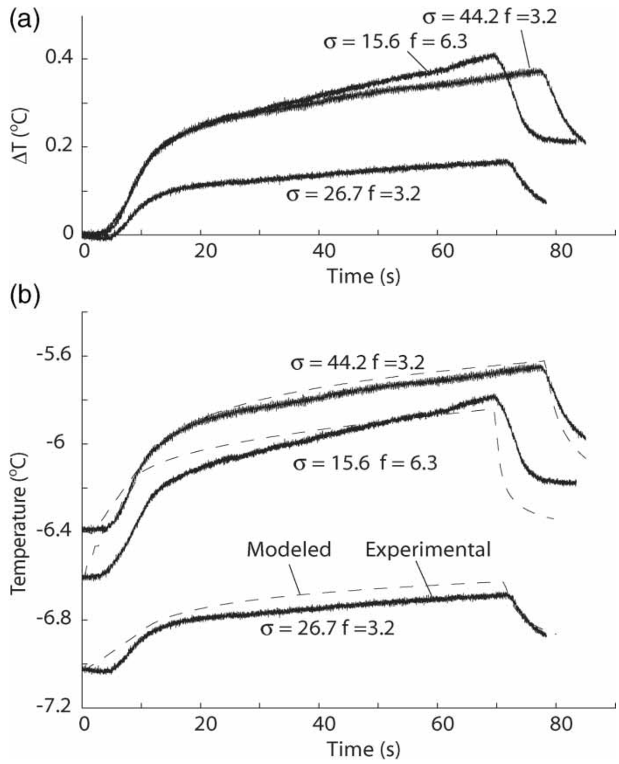

Fig. 3 Thermal profiles measured 2 mm below the surface of the ice, using a laboratory-based sweeping rig. (a) Comparison of temperature change for experiments with frequency $f = 3.2$ Hz and load per unit area $\sigma = 44.2$ kPa; $f = 3.2$ Hz, $\sigma = 26.7$ kPa; and $f = 6.3$ Hz, $\sigma = 15.6$ kPa. The high-frequency–low-pressure experiment produced the greatest thermal increase. (b) Comparison of experimental data and results of calibrated model

4 MODELLING THE THERMAL RESPONSE TO SWEEPING

4.1 Thermomechanical model

A three-dimensional thermal model has been developed to determine which sweeping styles and patterns produce the greatest temperature increase in the surface temperature of ice. The model determines the heat produced by rubbing at the interface between the brush head and the ice and solves thermal conduction equations to determine how the ice temperature varies both temporally and spatially.

The model employs two three-dimensional cubic meshes that are configured to represent the brush head and ice. The ice surface lies in the x–y plane (at $z = 0$) of a right-hand Cartesian coordinate system, where y is parallel to the sliding direction of the curling stone and z is vertical. The mesh representing the brush head is based at $z = 0$ and can have any position and orientation in the x–y plane so long as it lies within the outer boundary of the ice mesh. In the x and y directions, the mesh elements have equal side lengths $\Delta x = \Delta y = 0.1$ mm. Most heat flow occurs in the z-direction, so elements have shorter side lengths in this direction ($\Delta z = 0.01$ mm). The mesh representing the brush is configured to represent the brush head of the sweep ergometer, which has side lengths of 0.21 and 0.08 m. Elements in the ice and brush meshes are assigned the appropriate physical and thermal properties (Table 1). The ice and brush are assumed to be initially in thermal equilibrium at −5 °C and a numerical time step of $\Delta t = 0.001$ s was used. The frictional heat Q generated by rubbing is equivalent to the work done over a finite time Δt

$$Q = Fv\Delta t \tag{1}$$

Table 1 Values of thermal and physical properties used in the numerical model

		Ice	Nylon
Thermal conductivity	k (W/mK)	2.2	0.35
Density	ρ(kg/m^3)	927	900
Specific heat	c (J/kg K)	2090	2000
Thermal diffusivity	κ(m^2/s)	1.14×10^{-6}	1.95×10^{-7}

where v is the sliding velocity and F is the friction. Equation (1) is discretized by rewriting it as the heat per area of each element in the surface of the mesh, which allows the incorporation of μ and the load per unit area σ

$$\frac{Q}{\Delta x \Delta y} = \mu\sigma v\Delta t \tag{2}$$

Both the ice and the nylon absorb heat and increase in temperature. Heat is partitioned between each material on the basis of their relative thermal conductivity k to maintain thermal equilibrium. The model determines which elements in the ice surface are in contact with elements in the surface of the nylon brush head and their temperature increases according to

$$\Delta T = \frac{Q}{c\rho\Delta x\Delta y\Delta z} \tag{3}$$

where c and ρ are the specific heat and density of the relevant material. Heat then conducts through each material according to the three-dimensional thermal conduction equation

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \kappa\left(\frac{\partial^2 T}{\partial x^2}\frac{\partial^2 T}{\partial y^2}\frac{\partial^2 T}{\partial z^2}\right) \tag{4}$$

where κ is the thermal diffusivity of the relevant material. Heat conduction also occurs across the sliding interface. For simplicity, it is assumed that the counter-facing surfaces are in perfect thermal contact, no thermal energy is lost to the surrounding air, and energy lost to overcome the latent heat of fusion is negligible.

The velocity dependence of μ for a non-melting body sliding on ice has the form [**2**]

$$\mu = a + bv^{-1/2} \tag{5}$$

where a is a dimensionless parameter and b is a parameter with the dimensions m$^{1/2}$s$^{-1/2}$. The numerical model was calibrated by modifying these parameters and comparing the results to the change in ice temperature that was measured experimentally using the laboratory-based sweeping rig (Fig. 3). The model used a 10 s ramping period over which time the frequency of the brush head was increased from zero to its eventual running frequency. The ramping period was incorporated so that the model most accurately replicated the experimental methods used to measure the change in temperature. It was found that the model reproduced the experimental results best when a friction law with $a = 0.13$ and $b = 0.5$ m$^{1/2}$s$^{-1/2}$ was used. The comparison of experimental and model changes in temperature 2 mm below the ice surface for different frequencies and applied pressures are shown in Fig. 3(b).

5 THERMAL EFFECTS OF SWEEPING

5.1 Thermal footprint produced by sweeping in curling

The calibrated numerical model is used to determine the optimal pattern for sweeping the ice. To satisfactorily compare the sweeping patterns, the force–velocity history needs to be more consistent than that of an actual player. A synthetic velocity–force history based on mean sweep ergometer results was used (Figs 1(c) and (d)). At each numerical time step, the synthetic velocity and vertical forces are substituted into equation (2), the heat of friction calculated, and allowed to conduct through the system (equations (3) and (4)). The heat generation and flow calculations combined with those related to the motion of the brush produce a thermal footprint on the ice with each brush stroke. The surface temperature here refers to the mean temperature in the upper 0.1 mm of the ice.

Conventionally, curlers sweep across the path of the approaching curling stone with a low attack angle with respect to the x-axis. This conventional style of sweeping leaves a sinusoidal thermal footprint as the curler brushes back and forth in front of the stone while progressively moving along the ice in front of the sliding stone (y-direction). There is an asymmetry in the downward force with respect to position in each stroke (Fig. 1(b)). When curlers use a conventional style, this asymmetry results in higher surface temperatures on the side of the stone that the curler is sweeping from. Figure 4(a) shows the results for a male player standing on the left side of the curling stone and sweeping with a low attack angle style. The greatest heat is generated as the players begin to sweep away from themselves (Fig. 4(a), frame 2). Highest temperatures occur where successive strokes overlap each other, where temperature increases of 2.0 °C are produced.

A popular variation from the conventional sweeping style is when curlers place their feet behind the

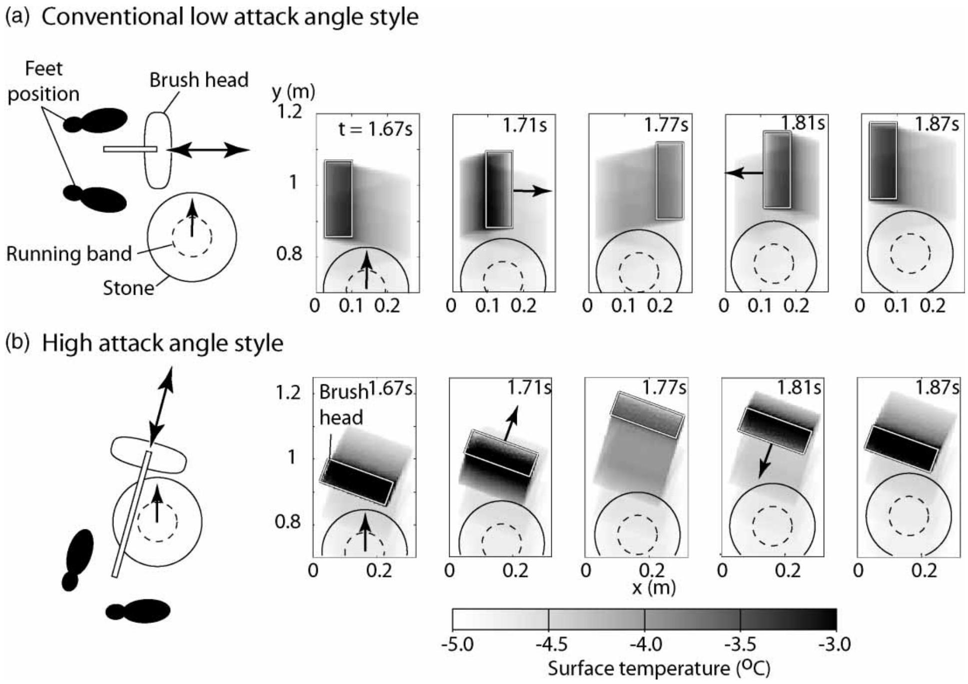

Fig. 4 Thermal footprint produced by two popular sweeping styles with schematic representation of feet and brush position. The surface temperature is taken as the mean temperature in the upper 0.1 mm of the ice. (a) A conventional low attack angle with frames showing modelled ice surface temperature for one complete sweeping cycle and (b) a high attack angle style of sweeping. Each successive stroke overlaps the previous one, thus producing elevated ice surface temperatures

stone and sweep over it with a high attack angle with respect to the x-axis (Fig. 4(b)). A significant advantage of this style is that the brush tends to sweep over the same piece of ice several times adding heat each time resulting in surface temperatures $\sim$0.4 °C higher than for an equivalent force–velocity profile with a conventional sweeping style (Figs 4(b) and 5(a)). The maximum heat generation also occurs closest to the player's feet and lies in a band directly in front of the stone. The thermal footprint is, therefore, less asymmetric than a conventional sweeping style (Fig. 4(b)).

5.2 Efficiency of sweeping pattern

The purpose of sweeping is to raise the temperature of the ice that comes in contact with the running surface of the curling stone. Once sweeping of a section of ice has ceased, it rapidly cools towards the bulk temperature of the ice rink (-5 °C). It is, therefore, vital that the ice surface is heated as close to the approaching stone as possible. Figure 5 shows the surface temperature profile in ice after 3 s sweeping before a stone with a velocity of 0.5 m/s and the relative position of the trailing curling stone. The geometry of the stone is such that the running surface lies 50 mm from the outside of the stone (Fig. 5). There is, therefore, a period of time before the running surface reaches a section of swept ice (i.e. 0.1 s in the case of a stone moving at 0.5 m/s).

The maximum temperature rises occur where successive strokes overlap. Overlapping strokes, when a conventional style is used, tend to form triangular areas with high temperatures close to the approaching stone (at 1.5 m, Fig. 5(a)). High attack angled strokes tend to overlap in the centre of the stroke some distance from the stone (Fig. 5(b)). The ice, therefore, has longer time to cool before the stone arrives and the ice temperature in contact with the stone is $\sim$0.2 °C lower than when a conventional style is used.

5.3 Additional distance stones travel due to sweeping

The deceleration of curling stones is dependent on the coefficient of friction between ice and granite, which varies with the velocity of the stone v_s and the temperature of the ice according to [**14**]

$$\mu = C\frac{(T_m - T)}{\sqrt{v_s}}, \quad C = \frac{2\,k}{\sigma\sqrt{\pi\kappa l_c}} \tag{6}$$

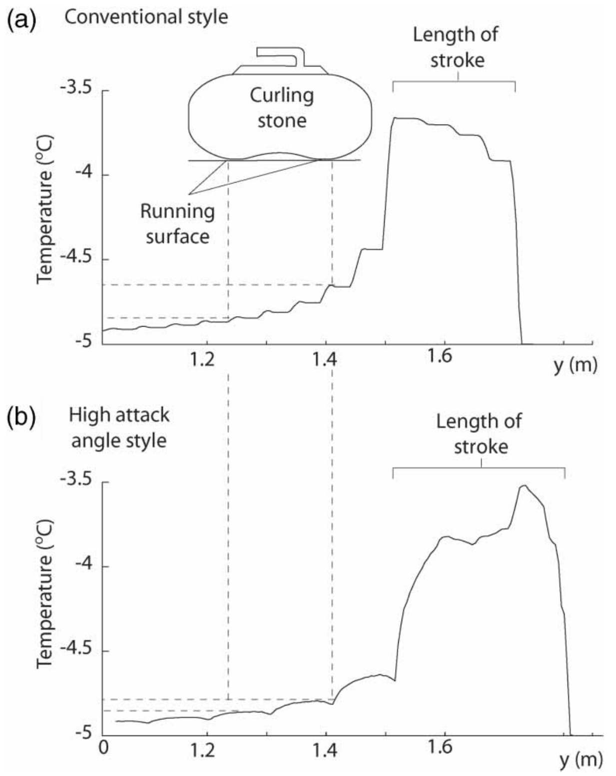

Fig. 5 Surface temperature profile taken parallel to the y-axis through the centre of the stroke after sweeping for 3 s in front of a stone moving at 0.5 m/s. The relative position of the curling stone and its running surface are also shown. (a) A conventional sweeping pattern has its thermal maximum close to the stone. (b) The high attack angle style has a higher thermal maximum, but it occurs well ahead of the stone so that much of the heat has dissipated before the stone arrives

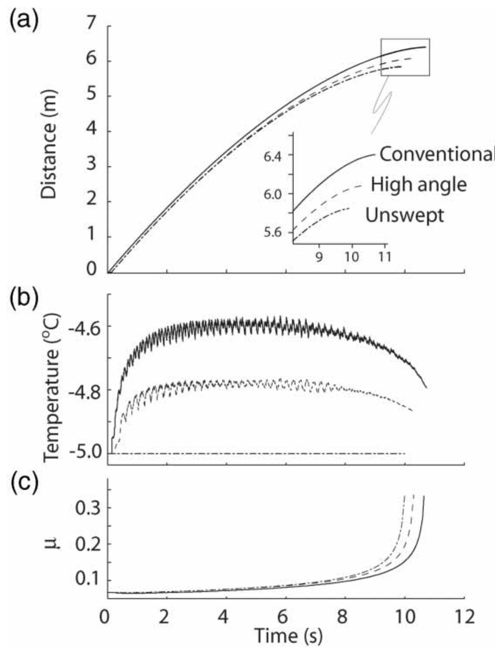

Fig. 6 Comparison of the effects of using different sweeping styles compared with not sweeping at all. (a) The distance a stone travels if sweeping begins when its velocity is 1.0 m/s. A conventional style results in the stone sliding 0.55 m further than an unswept stone, whereas a high attack angle style slides only 0.15 m further. (b) The temperature of the ice that is in contact with the running surface of the curling stone. The conventional style results in ice $\sim$0.2 °C hotter than a high attack angle style. (c) The coefficient between ice and the granite curling stone. The higher ice temperature for the conventional style (Fig. 5(b)) reduces μ, thus allowing the stone to slide further

where T_m is the melting point of ice (0 °C) and l_c is the length of contact, which for ice pebbles in contact with the curling stone's running surface is on average 11 mm. Equation (6) best replicates the motion of a curling stone on -5 °C ice when $C = 0.0134$. Given that the thermal properties of the granite curling stone are $k = 2.1$ W/mK and $\kappa = 3.29 \times 10^{-6}$ m^2/s, the load per unit area must be 2.1 MPa. This is consistent with the sum surface area of approximately 25 pebbles with circular contact areas of 2 mm diameter, supporting the 18.6 kg stone.

Equation (6) was used to estimate the length added to the distance travelled by curling stones due to different sweeping styles (Fig. 6(a)). At each numerical time step, the temperature of the ice in contact with the curling stone's running surface was substituted for T in equation (6) and v_s reduced by $\mu\Delta t$. Commonly, the last third of a stone's journey has its path swept. Figure 6 shows how sweeping, using different sweeping styles, increases the length that a stone slides. A stone with an initial velocity of 1.0 m/s will slide for 5.84 m. The model predicts that sweeping in front of the stone, using a high attack angle style makes the stone slide 6.08 m and a conventional style makes it slide 6.40 m.

The use of a conventional sweeping style resulted in the stone sliding 0.32 m further than the use of a high attack angle style. The large overlap of successive strokes when using the high attack angle style produces higher surface ice temperatures than the conventional style (Fig. 5). However, the maximum temperature tends to be located far from the stone so that much of the heat has dissipated before the arrival of the stone's running surface (Fig. 5). The running surface, therefore, comes in contact with ice that is $\sim$0.2 °C warmer when a conventional style is used (Fig. 6(b)), resulting in lower μ between ice and granite (Fig. 6(c)) and in less deceleration.

6 DISCUSSION

6.1 Assumptions and simplifications that affect the results

A potentially important factor not included in the numerical model is the effect of millimetre-scaled pebbles on the curling ice surface. The model assumed that the curling brush–ice interface is in perfect thermal contact. This is most likely not the case, as the valleys between pebbles may not come in contact with the overlying nylon brush head and therefore not be heated directly by frictional heat generated by sliding or by conduction of heat from the warmer brush head. The load per unit area is also likely to be higher, as only the sum area of the tops of the pebbles supports the downward pressure applied by the curler. The heat of friction calculated in equation (2) is therefore likely to be higher and results in localized surface temperature maxima associated with the high points of pebbles.

6.2 Effects on the stone trajectory

The different thermal patterns associated with the different sweeping styles can be exploited to control the lateral deflection of curling stones. The curved trajectory of rotating curling stones increases with the ratio between rotational velocity ω and translational velocity v_s [**16**]. The asymmetric heating pattern produced by the conventional style can be used to apply a torque on the trailing stone, thereby varying the ratio ω/v_s and the stone's curvature. Consider a counter-clockwise rotating stone with a player sweeping from the left (Fig. 4(a)). The ice temperature is greatest on the left side of the stone so that μ is lower relative to the right side. This produces a clockwise torque that reduces ω/v_s and reduces the curvature of the trajectory.

The high angle sweeping style produces a much less asymmetric thermal pattern and therefore does not affect the ratio ω/v_s. Curlers may view this as an advantage, because the high angle style will produce more consistent trajectories. The lack of asymmetry means that the trajectory will be the same and is not dependent either on who sweeps before the stone or what the players fatigue levels are. Players can also change the curvature of the stone by subtly changing their attack angle.

6.3 Designing better brush heads

The frictional heat produced by rubbing with a curling brush is dependent on the characteristics of the brush head itself. The geometry of the brush head is important, as this controls the surface area in contact with the ice. As the surface area is reduced, the force per unit area is increased as is the amount of frictional heat produced (equation (2)). However, the greatest temperature increase in the ice occurs where successive strokes overlap each other (Fig. 4) and a small brush head would reduce the area of overlapping strokes. Ideally, a large brush head would be used with a dimpled surface to reduce the real area of contact.

The thermal diffusivity of the brush head material is important. The brush head accumulates frictional heat and becomes progressively hotter. A large component of the temperature rise in the ice is due to the conduction of heat from the relatively hot brush into previously unswept ice. As thermal diffusivity of the brush head material is reduced, less heat conducts away from the brush head surface, and the amount of heat that conducts across the interface into the ice increases.

Maximizing the coefficient of friction between the brush head material and ice (equation (5)) can also increase the frictional heat produced by rubbing. Some care must be taken here as one of the few brush design laws, that is strictly enforced by the sports-governing bodies, is that the brush head must not damage the ice. If μ is very great, then the ice will wear at a noticeably higher rate and the brush design will be barred.

7 CONCLUSION

A numerical model was developed that determines the amount of heat produced by sweeping with a standard curling brush and solves thermal conduction equations to determine the thermal history of the ice related to sweeping with a curling brush. Typical forces and velocities were applied to the model on the basis of measurements recorded with a sweep ergometer. The numerical model was calibrated using laboratory-based experimental results that measured the temperature change 2 mm below the surface of ice being rubbed by a nylon brush head with velocities and pressures akin to those in the sport of curling. Laboratory measurements indicated that sweeping is most effective when downward pressure is sacrificed for greater head speed. The numerical model shows that the greatest increase in the surface temperature of the ice is achieved using a high attack angle style of sweeping, as successive strokes tend to overlap, resulting in localized maxima in temperature. However, these thermal maxima tend to occur some distance from the trailing curling stone and will have dissipated before the arrival of the stone's running surface. Conversely, a conventional low attack angle style raises the ice temperature less, but the thermal maxima are located closer to the stone's running surface and, therefore, have a greater effect on reducing the coefficient of friction between ice and the granite curling stone.

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APPENDIX

Notation

C	specific heat capacity
f	sweeping frequency
F	friction force
K	thermal conductivity
l_c	length of contact
Q	heat
t	time
T	temperature
T_m	melting point
v	velocity of brush
v_s	velocity of stone
x,y,z	Cartesian coordinates
$\Delta x,\Delta y,\Delta z$	mesh element side lengths
Δt	numerical time step
κ	thermal diffusivity
μ	coefficient of friction
ρ	density
σ	load per unit area
ω	rotational velocity