

Manuscript Details

Manuscript number	CRST_2017_198_R1
Title	Measurement of sliding velocity on ice, as a function of temperature, runner load and roughness, in a skeleton push-start facility
Article type	Research Paper

Abstract

– The sliding velocity on ice is proposed as a precise measure for measuring the sliding on ice. A sled was positioned with one runner in a groove and the other on flat ice, and then released to slide 25 meters down an ice track. The sliding velocity was calculated from 20 repeat experiments on runners with a different roughness (polished vs abraded) under different loads (30 kg, 40 kg and 50 kg) and at a range of air temperatures (-15 oC, -10 oC, -2 oC, 0oC and 2 oC). The error in sliding velocity was sufficiently small (0.15%) to clearly show the effect of different parameters, and allowed trends to be identified. Sliding velocity was mostly influenced by a change in temperature, then by a change in load, and then the runner roughness. A maximum speed was recorded at 0 oC, and this is where the roughness and intermediate loads played a larger effect on the sliding velocity. The results are discussed in reference to solid friction, movement over a water film, and the mechanical properties of the ice. Sliding velocity with a controlled release mechanism that removes the influence of the operator is an alternative means to distinguish the effects of different parameters on sliding velocity, instead of measuring the ice friction and making predictions of the acceleration and the resulting sliding velocity.

Keywords	Ice friction; sliding speed; co-efficient of friction; test method; lubrication
Corresponding Author	Karlis Gross
Corresponding Author's Institution	RTU
Order of Authors	Ernest Jansons, Janis Lungevics, Klavs Stiprais, Liene Pluduma, Karlis Gross
Suggested reviewers	Louis Poirier, Roman Boettcher, Anne Kietzig, Francesco Braghin, Sebastian Rohm

Submission Files Included in this PDF

File Name [File Type]

cover letter.docx [Cover Letter]

Atbildes uz recenzentu jautājumiem_v2.docx [Response to Reviewers]

Highlights.docx [Highlights]

Sliding on ice_v3a.docx [Manuscript File]

To view all the submission files, including those not included in the PDF, click on the manuscript title on your EVISE Homepage, then click 'Download zip file'.

Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
Data will be made available on request

1 Measurement of sliding velocity on ice, as a function of temperature, runner 2 load and roughness, in a skeleton push-start facility

3 Ernest Jansons, Janis Lungevics, Klavs Stiprais, Liene Pluduma, Karlis Agris Gross

4 *Abstract*– The sliding velocity on ice, as opposed to coefficient of friction measurements, is proposed to show the effect of
5 experimental conditions on the sliding velocity. A sled was positioned with one runner in a groove and the other on flat ice and then
6 released to slide 25 meters down an ice track. The sliding velocity was calculated from 20 repeat experiments using runners with a
7 different roughness (polished vs abraded) under different loads (30 kg, 40 kg and 50 kg) and at a range of air temperatures (-15 °C, -
8 10 °C, -2 °C, 0 °C and 2 °C). The error in sliding velocity was sufficiently small (0.15%) to clearly show the effect of different
9 parameters, and allowed trends to be identified. Sliding velocity was mostly influenced by a change in temperature, then by a change
10 in load, and then the runner roughness. The highest speed was recorded at 0 °C, when the roughness and intermediate loads played
11 a larger effect on the sliding velocity. The results are discussed in reference to solid friction, movement over a water film, and the
12 mechanical properties of the ice. Measuring the sliding velocity, with a controlled release mechanism on the sled obviates the
13 operated related error, and also provides a good insight on the influence of different conditions, instead of measuring the ice friction
14 and making predictions of the acceleration and the resulting sliding velocity.
15

16 *Keywords* – ice friction, sliding speed, coefficient of friction, test method, lubrication

17 1. INTRODUCTION

18 Communities that experience cold winters have learned to live with ice, but progress in materials science is
19 seeking ways of further improving the slip-resistance and faster movement on ice. These challenges require
20 improved test methods. Small-scale test methods for assessing the ability of objects to slide on ice are available,
21 but there is no adopted test method for larger objects. Large-scale tests are needed to confirm predictions from
22 laboratory studies. Such large-scale tests with heavier objects in field tests are needed for the transportation
23 industry, the sporting industry, and since the wellbeing of citizens is now a higher priority in society, the safety
24 sector. This study will evaluate a new test method for measuring the ability for heavier objects to slide down an
25 angled ice plane.
26

27 For measuring the movement of objects over ice, experiments should be designed to directly measure the
28 velocity of an object as it moves over ice, as opposed to calculating the resistance to motion. Measuring ice-friction
29 has been the accepted norm for two reasons; scientists resorted to established test methods from the field of
30 tribology to measure the coefficient of friction (de Koning et al., 1992; Lozowski et al., 2014; Scherge et al., 2013;
31 Spagni et al., 2016), and the research community was accustomed to “ice-friction” as an indirect measure when
32 discussing the ease-of-sliding. The velocity of a freely moving object is determined not only by ice-friction, but
33 also other factors such as air-drag (Poirier et al., 2011). As a result, a more accurate test will need to consider
34 factors that alter the air-drag as well as the friction on ice. Direct velocity measurements on a freely moving object
35 will then allow the consideration of all factors contributing to faster movement over snow and ice.

36 Measurement of the sliding velocity down an angled plane needs to be improved. This approach is more
37 practically relevant than measurements of ice-friction (Baurle et al., 2007; Maeno et al., 2003; Spagni et al., 2016),
38 and the resistance to movement by rheometers (Hainzmaier, 2005; Kietzig et al., 2009). The validity of the
39 coefficient of friction (CoF) tests in a circular path is under question due to the changing ice conditions, as ice
40 transforms into water (Spagni et al., 2016). Large errors in the small CoF further make it difficult to discern
41 changes from a change in sliding conditions. Controlled sliding velocity measurements down an angled plane have

42 been previously conducted in a laboratory, (Jansons et al., 2016), so further development needs to scale up the tests
 43 to include larger objects such as sleds used in the sporting industry.

44 Sliding velocity needs to be measured on large freely-moving objects with heavier loads, sliding for longer
 45 sliding distances. Table 1 compares previously conducted tests showing sliding distances were at least 24 m. All
 46 tests used freely moving objects except for one study on a linear tribometer that tested lighter loads (Rohm et al.,
 47 2015); higher loads change the interaction with ice and are needed to replicate life-like situations. This study
 48 showed two factors that influence sliding on compacted snow – wet friction, and adhesion on ice by the film of
 49 water that is more prevalent on warmer ice (Rohm et al., 2015). The CoF could did not clearly show factors that
 50 most influenced the ease-of-sliding, supporting once again the need to consider movement down an angled ice
 51 plane as a new test method.

52 All large-scale tests have involved a human factor, and so are not reproducible. Sliding with skates on ice is
 53 affected by the individual performance of the skater (Colbeck et al., 1998; de Koning et al., 1992). Studies on the
 54 bobsled were initiated by a manual push-start (Poirier et al., 2011a). The results were dependent on the athlete’s
 55 daily and hourly performance. A reliable field test requires the absence of human intervention, allowing an object
 56 to initiate sliding and then slide freely for the entire distance. This study will show that sliding down an angled ice
 57 plane without a push-start provides a test method with less error to show the influence from test conditions. The
 58 maximum speed will be similar to previous tests (shown in Table 1). The objective of this study is to establish a
 59 reliable field test method to investigate the influence of different loads, different runner surface conditions and
 60 temperature on the sliding velocity.

Table 1
 Previous tests on the ease-of-sliding over ice showing test conditions and the outcome.

Researchers	Frozen surface	Sliding distance (m)	Sliding object	Max weight (kg)	Max speed (m/s)	Outcome
Colbeck et al., 1997	Ice -10 °C Skating rink	-	Person on skates	-	-	Measured increase in temperature of ice and skate from frictional heating.
Koning et al., 1992	Ice -11°C to -2 °C Skating rink	100	Person on skates	73	11	CoF 0.004-0.006 (~20% error).
Poirier et al., 2011	Ice -4 °C to -2 °C Hockey field	30	Frame supporting four bobsleigh runners	193	10	CoF lower than previously thought to be 0.004.
Rohm et al., 2015	Snow -12 °C to -3 °C Laboratory	24	Linear tribometer controlled metal ski	15	12	CoF is higher for smoother surfaces, and at higher temperatures. CoF varies from 0.08 to 0.30

63
 64

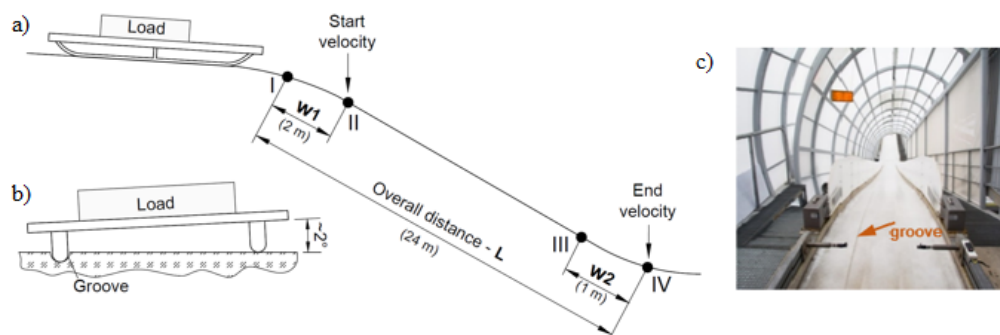
2. MATERIALS AND METHODS

2.1. PREPARATION OF THE ICE TRACK

65 A 24 m long ice-track at a bobsled push training facility in Sigulda was used for determining the sliding
 66 velocity down an angled plane. The 1st set of sensors at w_1 measured the start velocity and the 2nd set of sensors at
 67 w_2 provided the end velocity, Fig 1a. To ensure the same sliding distance for every run, one of the runners
 68 followed a groove made in the ice. As a result, the runner in the groove has a larger contact area with the ice than
 69 the second runner that slid on flat ice, Fig 1b. The sliding velocity represented the combined effect one runner in
 70

71 the groove and other runner on flat ice. There was no way of differentiating the sliding velocity of the runner in the
72 groove from the sliding velocity of the runner on the flat ice.
73 The ice was prepared for a more uniform surface. Five test runs over the ice removed any loose surface crystals
74 and annealed the ice. An interval of several minutes between each run was sufficient for the possible thin surface
75 water layer to crystallize into a dense layer before the next run.

77



78

79 **Fig. 1.** The angle ice plane showing a) the positioning of the sensors at the start (w_1) and the end (w_2) of the 24 m sliding track, b) the
80 placement of the runner in a groove for reproducible testing and c) a view of the enclosed ice track.

81

82 Ice was formed in different layers on the track primarily by cooling the base of the inclined plane and
83 secondarily by the air temperature. Tepid water was sprayed to build up the ice thickness and to fill pores and
84 cracks in the previous layer. Once the desired thickness was achieved, the ice was planned and a groove with
85 diameter of 20 mm placed in the ice to guide the runner of the sled. The bobsled push-start training facility was
86 used from late autumn until early spring when the air temperature was between $-20\text{ }^\circ\text{C}$ and $+5\text{ }^\circ\text{C}$.

87 An enclosed ice track provided good test conditions for repeatability. Ice conditions were stable between test
88 runs and any outside wind did not interfere with the sliding measurements. Changes in the air temperature and air
89 humidity only occurred from day-to-day variations in the outside climate conditions, Fig 1c. Experiments were
90 conducted in the evening, after sunset, when the sun could not influence the quality of the ice. The temperature and
91 humidity were measured 5 cm above the ice at the start with a P330 Temp instrument (Dostmann electronic,
92 Germany). The air temperature deviated less than $1\text{ }^\circ\text{C}$ during the course of the experiments. Where the air
93 temperature is positive, a film of water can be expected, but the actual ice temperature was maintained by the
94 cooling system under the ice track.

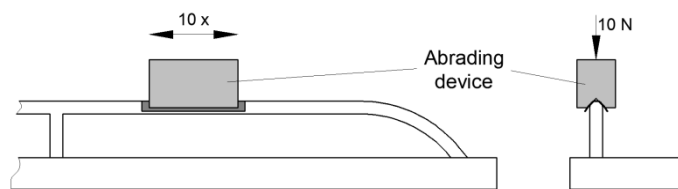
95 The angled ice plane with a groove for guiding the sled, conditioning of the ice, relatively constant environment
96 conditions, and an accurate timing system collectively gave a good reproducibility for measuring the sliding time
97 and velocity.

98 2.2. PREPARATION OF THE RUNNERS

99 A sled was chosen with two runners to provide a setup allowing conditions – runner roughness and sled weight
100 – to be varied over a wide range. The 1000 mm long runners with a diameter of 16 mm fit into the 20 mm diameter
101 U-shaped groove made in the ice. The runners were not curved in the middle. Runners were made from an
102 International Bobsleigh and Skeleton Federation (IBSF) standardized austenite structure stainless steel (Fe-62%,
103 Ni-16%, Cr-14%, Mo-4,5%; Co-1,4%, Mn-1,25%, Cu-0,8%) shaped according to the requirements of a standard

104 skeleton runner (“International Skeleton Rules,” 2016) . It was bent up at the front. The 10 kg weight (12 cm wide,
105 24 cm long and 6 cm high) and the 20 kg weight (24 cm wide, 31 cm long and 11 cm high) were placed in the
106 centre of the skeleton. It was noted that the location of the additional load may significantly affect the sliding
107 velocity, and so the weights were positioned with great care.

108 The runners were abraded with 3000 grade sand paper for 10 times back and forth along the runner under a 10
109 N load. The abrading block prepared the sides of the runner so the runner in the ice groove would have the same
110 roughness at all points of contact with the ice, Fig. 2. This gave a roughness S_a of ~ 0.22 . A new piece of sand paper
111 was chosen every time the runner was abraded. When a rougher surface was required, a 600 grade sand paper was
112 chosen, giving a roughness S_a of ~ 0.14 . Any loose particles remaining on the runner surface were removed with a
113 tissue soaked in ethanol. Since the preparation took place at the push-start facility, the runner temperature was
114 maintained the same, and gloves were used during the abrasion to prevent the heat transfer during handling. The
115 skeleton was placed on the ice 5 minutes after surface modification of the runner, and several runs made to
116 equilibrate the temperature.



117
118 **Fig. 2.** Sled runner preparation.

119

120 2.3. MEASUREMENT OF THE SLIDING VELOCITY

121 The sled was placed in the starting position, secured by inelastic rope, and then released by removing a lock-
122 pin, allowing the sled to freely slide down the ice track. This approach ensured test runs without influence from the
123 operator. One runner was placed in a groove so that the sled always moved down the same path. Optical sensors
124 clocked the time for calculating the sliding speed. The temperature and humidity were the only two parameters that
125 could not be controlled; suitable evenings after sunset were chosen for conducting the tests. At least 20 runs were
126 conducted at each test condition for repeatability.

127 Any liquid that may have formed on the ice surface from ice-friction between the runner and ice would have
128 resolidified after retrieving the skeleton that stopped about 75 m from the start position. The sled was returned to
129 the start position by pulling the sled with a rope up the ice track while maintaining contact with the ice.

130 The runners were abraded with 3000 grade sand paper to prepare a polished set of runners, and then with 600
131 grade sandpaper for preparing a scratched surface. The surface roughness, S_a , (instead of a linear roughness, R_a)
132 was reported since it is a more accurate measure of the surface (Jansons et al., 2016). Previous reports have
133 measured the roughness optically with a focus variation microscope (Rohm et al., 2015), but we used a contact
134 profilometer, a Form Talysurf Intra 50 (Taylor Hobson, UK).

135 Experiments were conducted on six different days. The days were chosen so as to provide an ice temperature
136 close to $-15\text{ }^\circ\text{C}$, $-10\text{ }^\circ\text{C}$, slightly below the melting temperature, and slightly above the melting temperature, Table
137 2. The error shown for each test point was from sliding tests made on one day. If a similar temperature was
138 obtained on another day, the results were not combined since it was not possible to get the same temperature and

139 the same humidity. Reproducibility of the results was determined by two tests conducted at an ice temperature of
 140 about 0 °C, as well as to confirm the unexpected behavior at this temperature.

142 **Table 2**
 143 Experimental settings

	Temperature experiment	Load experiment
Air temperature (Relative humidity)	-14 (RH 75%) -10 (RH 44%) -0.5 (RH 91%) +0.5 (RH 80%) +3 (RH 84%)	-10 (RH 44%) +0.5 (RH 91%) +2.5 (RH 84%)
Sandpaper grade	3000, 600	3000, 600
Load, (± 0.1 kg)	30	30; 40; 50

144 * Error in the temperature is ± 1 °C; air humidity $\pm 1\%$

145
 146 The effect of air drag was determined by including a box (28 cm wide, 35 cm long and 18 cm high) with a lid
 147 on top of the skeleton during the sliding experiment. The skeleton was slid down the ice track with the different
 148 loads in the box or just on the skeleton. A box ensured the same geometry for each loading condition, and so
 149 sliding experiments gave an indication of the air drag. The air drag experiment was only conducted on one day.

150
 151 The load has been given for each experiment instead of the pressure. The pressure was different for each runner depending
 152 on the contact area in the groove and the flat ice. One runner was positioned in the groove and so had a larger contact area than
 153 the other runner that placed on flat ice.

155 3. RESULTS AND DISCUSSION

156 Before initiating the investigation, the repeatability of velocity measurements was determined on the first day of
 157 testing. The small 0.15% error, measured from 30 runs, is significantly smaller than the error stated in previous
 158 investigations. Compared to the 2.5% to 4% error reported by Hainzlmaier (Hainzlmaier, 2005), the 2.2% error
 159 from the linear tribometer by Hasler et al. (Hasler et al., 2016), and the 1% error from the bobsleigh push start
 160 facility reported by Poirer et al (Poirer et al. 2011), the error in this work is at least 7 times smaller. The larger error
 161 was attributed to the human error arising from the athletes; this study did not involve the human factor and so will
 162 show a smaller error from many repeat experiments. The greater sensitivity provided suitable conditions to
 163 determine the effect of experimental parameters on the sliding speed.

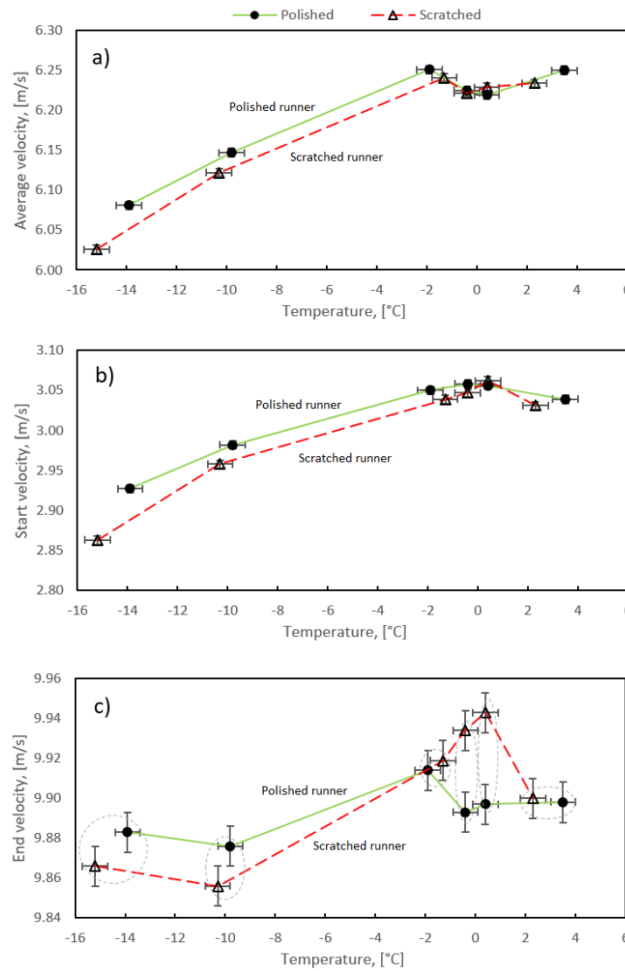
164 Another advantage of this study was the measurement of velocity at different points: the start (2 m from the
 165 start), the end (24 m from the start), as well as the average velocity. The influence of the test conditions could then
 166 be tested at different distances after the start. Results will be discussed for the average velocity, the start velocity
 167 and lastly, the end velocity.

168 3.1. INFLUENCE OF TEMPERATURE ON THE SLIDING VELOCITY

169 The average sliding velocity was faster for polished surfaces, and increases with temperature. This observation
 170 is consistent with previous observations (Kietzig et al. 2010). A 0.2 m/s improvement (3% increase) in the average
 171 sliding velocity occurs after an increase in air temperature from -15 °C to 0 °C, Fig 3a. Changing the temperature,
 172 however, is not a practical solution. A change in the sliding velocity is better achieved by altering the surface

173 roughness. Polished metal surfaces showed a markedly faster sliding velocity, especially at colder temperatures.
 174 Rougher surfaces had a lower sliding velocity. The sliding velocity for rougher runners was 1%, 0.4% and 0.16%
 175 slower at -15 °C, -10 °C and a 0 °C, respectively.

176 Just like the average sliding velocity, the start sliding velocity increased with temperature. Again, smoother
 177 surfaces slid faster than scratched surfaces, especially at colder temperatures, Fig 3b. The start sliding velocity was
 178 2.39%, 0.67% and 0.33% slower on scratched surfaces at -15 °C, -10 °C and 0 °C, respectively. The difference in
 179 sliding velocity was more significant at -15 °C, clearly indicating that smoother surfaces provided a faster start
 180 sliding velocity.



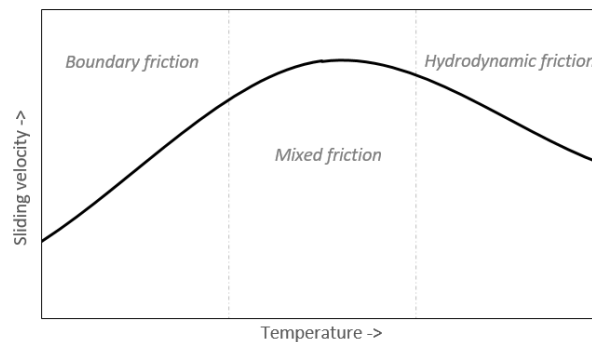
182
 183 **Fig. 3.** (a) The sliding velocity for polished and rough runners over a temperature range of -15 °C to +2 °C shown as a) the average velocity,
 184 b) the start velocity and c) the final velocity. Solid green curve show trends for the rough runner, dotted circles group together experiments
 185 from the same day.

186 The difference in end sliding velocity across the -15 °C to 2 °C temperature range was small. For smoother
 187 surfaces, there is possibly a slightly higher speed at -2 °C, however, the 0.04 m/s difference is small and it remains
 188 inconclusive, Fig 3c. Rougher surfaces had a clear difference in sliding velocity, showing a 0.1 m/s difference
 189 across the range of temperatures; the velocity was lowest at the coldest temperature, increased at -2 °C, showed a
 190 maximum at 0 °C, followed then by a decrease in sliding velocity. This peak at 0 °C for the rougher surface,
 191 supported by measurements on two separate days, has previously not been noted. This observation could be
 192 attributed to more detailed results; small temperature intervals between -2 °C and +2 °C, and the small error in
 193 sliding velocity.

194 It is expected that rougher surfaces slide more slowly from a higher coefficient of friction. Previous work
 195 showed that rougher surfaces slid more slowly (Braghin et al., 2011). The rougher surfaces slid more slowly at

196 colder temperatures, Fig 3c. At slower speeds of about 3 m/s, a clear difference was maintained in the sliding
197 velocity between rough and polished runners at all temperatures, but the difference was no longer present at higher
198 speeds of about 10 m/s, between -2 °C and 2 °C.

199 These results will be interpreted using a previously established model made on the coefficient of friction at
200 different temperatures. Given that a lower coefficient of friction leads to greater acceleration and an accompanying
201 faster sliding, the trend will be redrawn for sliding velocity versus temperature, to aid the discussion of results.
202 Sliding is slowest at colder temperatures, then increases with temperature until a maximum is reached, and finally
203 decreases, Fig 4. A lower speed at colder conditions has been previously attributed to dry friction between the
204 asperities on the ice and the runner (Kietzig et al.). An increase in temperature supposedly introduces a thin liquid
205 layer leading to a decrease in friction, and consequently a higher velocity. At still higher temperatures, the liquid
206 films builds up to a thickness where viscous drag of the water layer slows the movement over ice.



207
208 **Fig. 4.** The sliding velocity predicted at different temperatures (based on the liquid film arising from coefficient of friction experiments
209 (Bhushan, 2013); (Colbeck, 1992); (Kietzig et al., 2010).

210
211 A more detailed discussion needs to focus on the both surfaces and their mechanical properties.

212 Close to the ice-water phase transition (Poirier et al., 2011), ice is likely to see a change in mechanical
213 properties, that could change the deformation of ice, the friction and the resulting ice surface characteristics. Ice
214 should be easier to deform, and so any loose debris could be compacted into a smooth surface. The reason for the
215 increased sliding velocity close to 0 °C requires further investigation. The effect of a more easily altered ice surface
216 and the introduction of water need to be differentiated to see how each influence the changes of the interface and
217 the effect on sliding speed.

218 Further work could consider the topography on the metal surface before sliding, at the initial stage of sliding,
219 and after sliding the entire length. Features of interest may be the metal pile-up or raised metal burrs resulting from
220 scratching, the changes in the metal surface during sliding and the influence of the changing surface on the sliding
221 velocity. The change in the surface could also be investigated to see whether it is related to changes in sliding
222 velocity on ice.

223 The humidity showed signs that could have influenced the sliding velocity. Previous work has shown a lower
224 coefficient of friction after increases in the humidity from 0% to 50% (Calabrese et al., 1980). An increase in
225 sliding speed at -15 °C could be attributed to the higher 75% humidity compared to the sliding speed at -10 °C and
226 44% humidity. Given a constant humidity, it is expected to see a clearer trend in sliding velocity with temperature.
227 A higher humidity may support faster sliding at colder temperatures by creating a thin water layer, but this effect
228 needs to be determined by measuring the sliding velocity at a selected temperature and different levels of humidity.

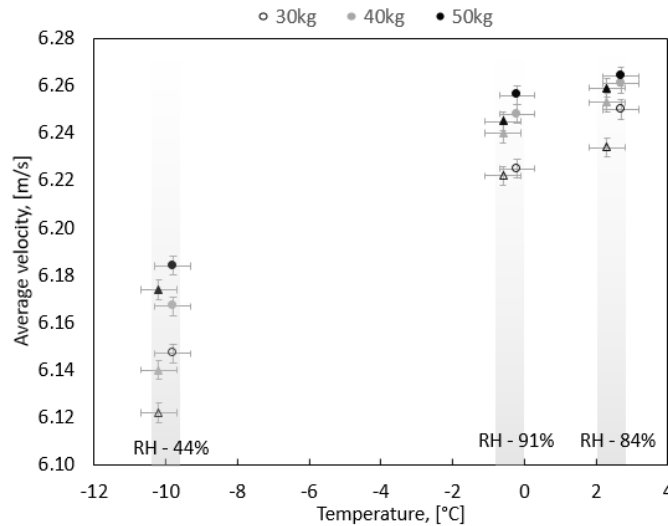
229

230 **3.2. Influence of load on sliding speed for scratched and polished runners**

231 The effect of pressure was studied by placing a 10 kg or a 20 kg weight on the sled with polished or scratched
232 runners. The sliding velocity for the scratched runner is displaced to the left (illustrated with a triangle), but the
233 polished runner displaced to the right of the test temperature (illustrated with a circle), allowing an easier
234 comparison for the scratched and polished runners, Fig 5. The percentage increase in sliding velocity from the
235 addition of a 10 kg and 20 kg load is shown in Table 3.

236 The average sliding speed increased with temperature, as previously reported, and does so for the different
237 loads. This is to be expected since assuming a negligible change in the friction, a heavier load will provide a
238 greater acceleration and a resulting higher speed. In all cases, the polished runner slid faster than the roughened
239 runner, Fig 3. A 30% increase in load (from 30 kg to 40 kg) gave ~ 0.3% increase in the sliding speed, Table 3. A
240 60% increase in load (from 30 kg to 50 kg) approximately doubled the increase in the speed, but this was only
241 noted at -10 °C for both scratched and polished surfaces.

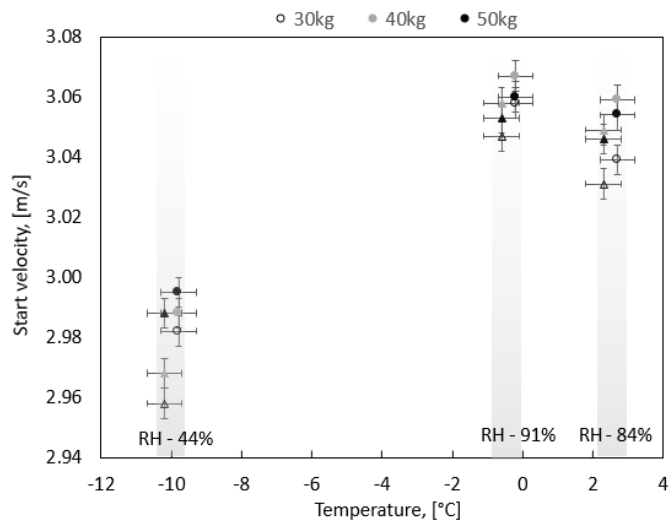
242



243 **Fig. 5.** Influence of load on the average sliding velocity showing faster sliding under greater loads and at warmer temperatures. (Δ) –
244 scratched, (O) – polished surface. Experiments at one temperature were conducted on the same day.
245
246

247 The influence of air drag on the sliding velocity was assessed by adding a box with the different loads. The air
248 drag by the box (26 cm wide, 35 cm long and 18 cm high) was greatest for the lightest skeleton (weighing 30 kg)
249 giving a 0.8% slower average speed. Adding the 10 kg load and the 20 kg load into the box showed a 0.4% and a
250 0.3% decrease in the average sliding speed, respectively. The air drag from the box was greater than the loads since
251 the box was 18 cm high, but the 10 kg load was 6 cm high and the 20 kg load was 11cm high, but this shows that if
252 the air drag was constant for all the different loads, then the percentage increase from loading the skeleton would
253 have a larger difference than that show in Table 3.

254 The start speed was faster with higher loads at -10 °C, but this trend was not found at -0.5 °C and 2.5 °C. The 40
255 kg sled showed the highest sliding velocity. According to Hainzmaier, there is an optimum load that will lower the
256 coefficient of friction (Hainzmaier, 2005). Based on the finding here, the selected runners used on the ice at the
257 Sigulda push-start facility will perform the best under a load of 40 kg at -0.5 °C and 2.5 °C.

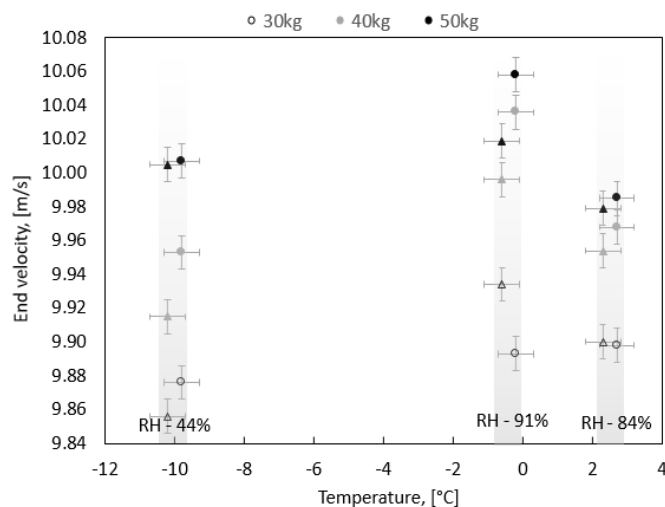


258
259
260
261

Fig. 6. Influence of the load on the start sliding velocity showing a general faster sliding with temperature, but an unexpected faster sliding at 0 °C for scratched surfaces. Experiments at one temperature were conducted on the same day.

262
263
264
265
266

The greatest increase in sliding velocity from loading occurred at higher speeds, at ~ 10 m/s. A 1.5% improvement in sliding velocity was noted for scratched surfaces, but a 1.3% improvement for polished surfaces, Fig 7. It would be interesting to learn how further increases in load influence the velocity. Given the opinion of Braghin et al. (Braghin et al., 2016) on the greatest effect from load, one would expect further increases in velocity from greater loading.



267
268
269
270

Fig. 7. Influence of load on the end sliding velocity for the scratched (Δ) and the polished (O) surfaces. Experiments at one temperature were conducted on the same day.

271
272
273
274
275
276
277
278
279

The results from this work do not give an explanation for the higher velocity, but point to the conditions that produce a greater velocity. Studies previously conducted on the coefficient of friction could be related to the acceleration to explain a higher or lower velocity. Direct measurement of velocity cannot explain the mechanics of motion. The greater measurement accuracy associated with the sliding velocity can quickly show which factors give a faster velocity. The sliding velocity can then be used as the first assessment, to identify which parameters need to be assessed in more detailed tests that may involve determining the coefficient of friction.

280
281

Table 3.
Percentage increase in velocity from loading scratched and polished runners at different temperatures.

Velocity	Surface condition	Conditions		% increase in velocity		
		Temperature (°C)	Humidity (%)	30 kg	Load 40 kg	50 kg
Average	Polished	-10	44	0	0.33	0.60
		-0.5	91	0	0.37	0.50
		2.5	84	0	0.18	0.22
	Scratched	-10	44	0	0.29	0.85
		-0.5	91	0	0.29	0.37
		2.5	84	0	0.37	0.50
Start	Polished	-10	44	0	0.20	0.44
		-0.5	91	0	0.29	0.29
		2.5	84	0	0.49	0.66
	Scratched	-10	44	0	0.34	1.01
		-0.5	91	0	0.36	0.20
		2.5	84	0	0.59	0.49
End	Polished	-10	44	0	0.78	1.33
		-0.5	91	0	1.45	1.67
		2.5	84	0	0.71	0.88
	Scratched	-10	44	0	0.60	1.51
		-0.5	91	0	0.62	0.86
		2.5	84	0	0.55	0.80

282

283 Previous investigations on the coefficient of friction found a minimum at about -5 °C, and little variation in the
284 results (Kietzig et al. 2010). This work found a maximum sliding velocity at an air temperature of 0 °C, and clearly
285 showed smaller sliding velocities at different temperatures. Consequently, the measurement of sliding velocity
286 provides more discernable results to show the influence from temperature, load and surface roughness.

287 The greatest influence on sliding speed came from the temperature, followed by load and finally by the runner
288 roughness. The roughness used in this work was smoother than the surface roughness investigated by Rohm et al.
289 The consideration of surface roughness should not only provide a quantitative measure of the unevenness of the
290 surface, but also identify the geometry of irregularities on the surface. This will give a more detailed enquiry and
291 reveal the most important features that influence sliding speed.

292 Further work can address the influence greater loads and relative humidity on the sliding velocity. For studies on
293 the load, there may be a further influence from the positioning of the load on the sled. The challenge is to separate
294 the effect of relative humidity and temperature on the sliding velocity on ice. We have suggested that an increase in
295 humidity will contribute to faster sliding.

296 The Sigulda bobsled push-start facility with an angled ice plane provides the possibility to measure the effect of
297 different experimental parameters on the sliding velocity. The linear tribometer in a previous study was not able to
298 show the influence of temperature and load due to similar coefficient of friction values (Rohm et al. 2015), but the
299 sliding speed used here clearly showed the influence of all investigated parameters.

300 4. CONCLUSIONS

301 The measurement of sliding velocity provides has a small error and was able to show the influence of
302 temperature, load and runner roughness on the sliding velocity. Sliding velocity measurements at the Sigulda push-
303 start facility were reproducible and precise.

304 The sliding velocity increased the most from an increase in temperature up to 0 °C, less by runner load and the
305 least by runner roughness, for sliding speeds up to 10 m/s. A maximum sliding velocity occurred between -2 °C
306 and +2 °C. Loading increased the sliding velocity, but appeared to be higher at an intermediate load when the

307 temperature was close to 0 °C. A smoother runner surface increased the sliding velocity in all cases except for a
308 lower load at about 0 °C.

309 Acknowledgements

310 The investigators are grateful for the use of the bobsled push-start facility in Sigulda. This investigation was
311 completed as part of the requirement for the IMATEH funding program in Latvia, titled “Innovative Materials and
312 Smart Technologies for Environmental Safety”. This document was prepared during a secondment and so
313 acknowledgement of support is extended to IRSES Project nr. 612691 “Refined Step”.

314 References

- 315 Baurle, L., Kaempfer, T.U., Szabo, D., Spencer, N.D., 2007. Sliding friction of polyethylene on snow and ice: Contact area and modeling.
316 *Cold Reg. Sci. Technol.* 47, 276–289. doi:10.1016/j.coldregions.2006.10.005
- 317 Bhushan, B., 2013. Introduction to tribology.
- 318 Braghin, F., Belloni, E., Melzi, S., Sabbioni, E., Cheli, F., 2016. Friction Between Runner and Ice, in: *The Engineering Approach to Winter*
319 *Sports*. Springer New York, New York, NY, pp. 33–51. doi:10.1007/978-1-4939-3020-3_3
- 320 Braghin, F., Cheli, F., Donzelli, M., Melzi, S., Sabbioni, E., 2011. Multi-body model of a bobsleigh: comparison with experimental data.
321 *Multibody Syst. Dyn.* 25, 185–201. doi:10.1007/s11044-010-9218-7
- 322 Calabrese, S.J., Buxton, R., Marsh, G., 1980. FRICTIONAL CHARACTERISTICS OF MATERIALS SLIDING AGAINST ICE. *Lubr.*
323 *Eng.* 36.
- 324 Colbeck, 1992. *A Review of the Processes That Control Snow Friction*. Hanover, N.H.: U.S. Army Corps of Engineers, Cold Regions
325 Research & Engineering Laboratory.
- 326 Colbeck, S.C., Najarian, L., Smith, H.B., 1998. Sliding temperatures of ice skates. <http://jobs.aapt.org/>. doi:10.1119/1.18576
- 327 de Koning, J.J., de Groot, G., van Ingen Schenau, G.J., 1992. Ice friction during speed skating. *J. Biomech.* 25, 565–71.
- 328 Hainzmaier, C., 2005. A new tribologically optimized bobsleigh runner. Munich.
- 329 Hasler, M., Schindelwig, K., Mayr, B., Knoflach, C., Rohm, S., van Putten, J., Nachbauer, W., 2016. A Novel Ski–Snow Tribometer and its
330 Precision. *Tribol. Lett.* 63, 33. doi:10.1007/s11249-016-0719-2
- 331 International Skeleton Rules, 2016.
- 332 Jansons, E., Lungevics, J., Gross, K.A., 2016. Surface roughness measure that best correlates to ease of sliding, in: *Engineering for Rural*
333 *Development*.
- 334 Kietzig, A.M., Hatzikiriakos, S.G., Englezos, P., 2010. Physics of ice friction. *J. Appl. Phys.* 107, 81101. doi:10.1063/1.3340792
- 335 Kietzig, A.M., Hatzikiriakos, S.G., Englezos, P., 2009. Ice friction: The effects of surface roughness, structure, and hydrophobicity. *J. Appl.*
336 *Phys.* 106, 24303. doi:10.1063/1.3173346
- 337 Lozowski, E., Szilder, K., Poirier, L., 2014. A bobsleigh ice friction model. *Int. J. Offshore Polar Eng.* 24, 52–60.
- 338 Maeno, N., Arakawa, M., Yasutome, A., Mizukami, N., Kanazawa, S., 2003. Ice-ice friction measurements, and water lubrication and
339 adhesion-shear mechanisms. *Can. J. Phys.* 81, 241–249. doi:10.1139/p03-023
- 340 Poirier, L., Lozowski, E.P., Maw, S., Stefanyshyn, D.J., Thompson, R.I., 2011a. Experimental analysis of ice friction in the sport of
341 bobsleigh. *Sport. Eng.* 14, 67–72. doi:10.1007/s12283-011-0077-0
- 342 Poirier, L., Lozowski, E.P., Thompson, R.I., 2011b. Ice hardness in winter sports. *Cold Reg. Sci. Technol.* 67, 129–134.
343 doi:10.1016/j.coldregions.2011.02.005
- 344 Rohm, S., Hasler, M., Knoflach, C., van Putten, J., Unterberger, S.H., Schindelwig, K., Lackner, R., Nachbauer, W., 2015. Friction Between
345 Steel and Snow in Dependence of the Steel Roughness. *Tribol. Lett.* 59, 27. doi:10.1007/s11249-015-0554-x
- 346 Scherge, M., Bottcher, R., Richter, M., Gurgel, U., 2013. High-Speed Ice Friction Experiments under Lab Conditions: On the Influence of
347 Speed and Normal Force. *ISRN Tribol.* 2013, 1–6. doi:10.5402/2013/703202
- 348 Spagni, A., Berardo, A., Marchetto, D., Gualtieri, E., Pugno, N.M., Valeri, S., 2016. Friction of rough surfaces on ice: Experiments and
349 modeling. *Wear* 368–369, 258–266. doi:10.1016/j.wear.2016.10.001