lubricants

Article

Kinetic Friction of Sport Fabrics on Snow

Werner Nachbauer [1,2,*], Martin Mössner [2], Sebastian Rohm [2], Kurt Schindelwig [1] and Michael Hasler [2]

[1] Department of Sport Science, University of Innsbruck, 6020 Innsbruck, Austria; kurt.schindelwig@uibk.ac.at
[2] Centre of Technology of Ski and Alpine Sports, University of Innsbruck, 6020 Innsbruck, Austria; martin.moessner@uibk.ac.at (M.M.); sebastian.rohm@uibk.ac.at (S.R.); michael.hasler@uibk.ac.at (M.H.)
* Correspondence: werner.nachbauer@uibk.ac.at; Tel.: +43-512-507-45890; Fax: +43-512-507-45998

Academic Editors: Ille C. Gebeshuber and George van Aken
Received: 28 December 2015; Accepted: 8 March 2016; Published: 14 March 2016

Abstract: After falls, skiers or snowboarders often slide on the slope and may collide with obstacles. Thus, the skier's friction on snow is an important factor to reduce incidence and severity of impact injuries. The purpose of this study was to measure snow friction of different fabrics of ski garments with respect to roughness, speed, and contact pressure. Three types of fabrics were investigated: a commercially available ski overall, a smooth downhill racing suit, and a dimpled downhill racing suit. Friction was measured for fabrics taped on a short ski using a linear tribometer. The fabrics' roughness was determined by focus variation microscopy. Friction coefficients were between 0.19 and 0.48. Roughness, friction coefficient, and friction force were highest for the dimpled race suit. The friction force of the fabrics was higher for the higher contact pressure than for the lower one at all speeds. It was concluded that the main friction mechanism for the fabrics was dry friction. Only the fabric with the roughest surface showed friction coefficients, which were high enough to sufficiently decelerate a sliding skier on beginner and intermediate slopes.

Keywords: kinetic friction; sport fabrics; snow; roughness; speed; contact pressure; safety

---

1. Introduction

In a collision accident, the severity of an injury results from the skier's kinetic energy at the time of impact, injury tolerance of colliding body part, and size of the contact area where the impact energy is distributed, as well as mechanical properties of the collision target (hardness, edges, *etc.*). Protection equipment, such as helmets, back protectors, safety nets and mats, is used to reduce the severity of collision accidents. The severity and number of collision injuries can be lowered by high friction between skier and snow which reduces sliding speed and thus impact energy.

Coulomb friction $F_F = \mu F_N$ as well as the friction laws $F_F = \mu F_N^n$ [1] and $F_F/A = \mu(F_N/A)^n$ [2] were considered for friction of fabrics. F_F, F_N, and A denote the friction force, the normal force, and the contact area, respectively; the friction coefficient μ and the friction exponent n serve as coefficients. Typical values for the friction exponent n are between 0.6 and 1. Sülar *et al.* [3] reported Coulomb friction coefficients between two cotton fabrics ranging from 0.15 to 1.14, depending on wave type and weft setting. Das *et al.* [2] found friction coefficients from 0.93 to 1.62 and friction exponents from 0.68 to 0.84 for friction between two fabrics at contact pressures between 0.3 and 0.5 kPa. They further measured friction coefficients from 0.16 to 0.28 and friction exponents from 0.91 to 0.96 for friction between fabrics and metal. Mostly dry friction of textiles was investigated. For lubricated friction boundary and hydrodynamic lubrication were distinguished [1]. In boundary lubrication a few molecules thick film prevents direct contact between the fibers and the asperities of the solid counterparts. In hydrodynamic lubrication a rather thick lubricating film exists in which the resistance force is given by the viscous flow in the lubricant.

Little is known about friction of ski garments on snow. vonAllmen [4] proposed to measure friction of a sliding skier on a slope with spring gauges in the three positions: "sideway boot-pull", "front arm-pull", and "back arm-pull". Without reference, vonAllmen and Glenne [5] reported friction coefficients of 0.25, 0.33, and 0.50 for "wet look garments", "nylon garments", and "coarse wear", respectively. Prokop [6] investigated the sliding distance and sliding time on ice for fabrics glued to the running surface of ice stocks (mass 5 kg) and measured an approximately three times larger sliding distance for PVC than for fabrics with spikes. In a similar sliding experiment, Prokop [6] studied real persons (mass 90 kg) wearing PVC or garments with spikes. The sliding distance was 93 and 4.6 m, the sliding duration 16.6 and 3.0 s, and, consequently, the mean speed 5.6 and 1.5 m/s. Nachbaur [7] determined friction coefficients of 0.40 for a ski overall and 0.38 for a downhill racing suit of a skier with ski boots (mass 80 kg) sliding down a racing slope. The acceleration of the skier's center of mass was determined from video data and then the coefficient of friction was calculated from the equation of motion. In a recent study, Belloni *et al.* [8] presented a novel tribometer for the measurement of friction of fabrics on ice but did not yet publish any data.

In simulation studies, vonAllmen and Glenne [5] and Brown *et al.* [9] determined the skier's trajectory after loss of control. The authors calculated the final speed after a given distance of sliding as function of initial speed, hill steepness, and friction coefficient. Depending on the ratio of hill steepness versus friction coefficient, the sliding skier slowed down, kept its speed, or even speeded up. It was concluded that the injury risk is increased for low friction garments when sliding on snow.

Various friction measurements indicate a dependency of the friction force on type and roughness of fabrics (e.g., [2,3,10]). Speed and contact pressure affect friction of skis on snow [11–14]. Preliminary results suggest also for fabrics on snow a speed and contact pressure effect [10]. The purpose of this study was to demonstrate a novel approach to study snow friction of different fabrics used for ski garments with respect to fabric roughness, speed, and contact pressure.

2. Method

2.1. Fabrics

Three types of fabrics were tested: a fabric of a commercially available ski overall, of a smooth racing suit (Speed V AP50, Plastotex S.R.L., Italy), and of a dimpled racing suit (Corsair V AP50, Plastotex S.R.L, Italy). The ski overall was intended for recreational skiing, the smooth racing suit for downhill racing, and the dimpled racing suit for competitive skicross or snowboarding. The surface fabric of the ski overall was made of a single layer of woven polyester with a plane 1 × 1 weave pattern. The two racing suits were made of laminated fabrics with knitted inner and outer layers of polyester and elastane and a membrane of polyurethane.

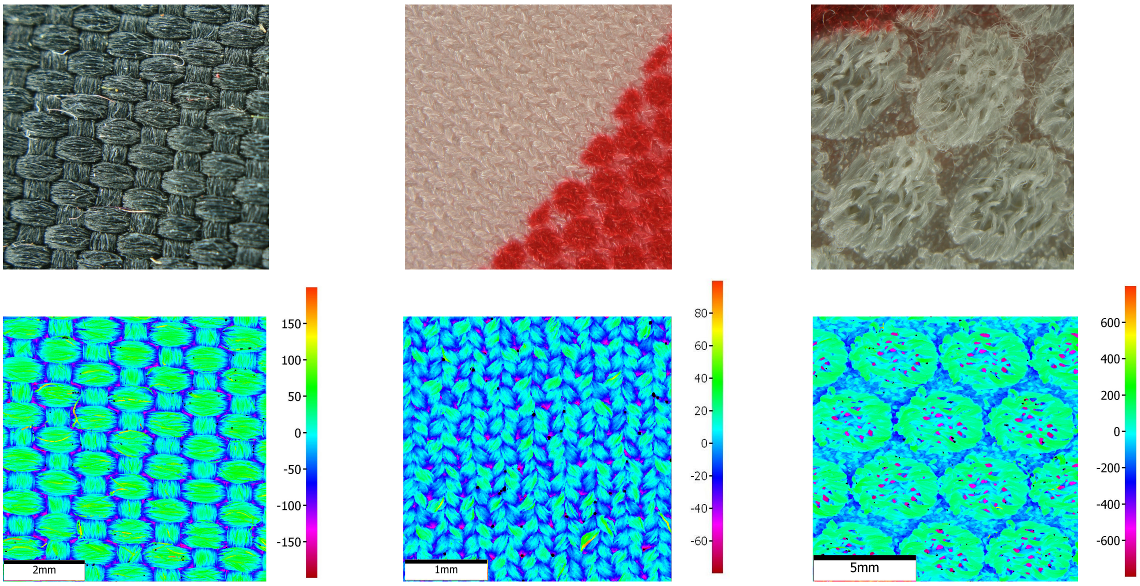
Figure 1 shows pictures and focus variation microscope images (Infinite Focus G4, Alicona, Austria) of the tested fabrics. The focus variation microscope images were taken to determine the roughness of the fabric's surfaces [15,16]. The images show the fabric's surface heights $z(x, y)$ in false colors. To separate the surface's waviness and roughness, the height data were filtered using a Gaussian filter. From the height data, the surface roughness parameters Sa and $S10z$ were calculated [17]. Sa is the mean of the absolute heights:

$$Sa = \frac{1}{A} \iint_A |z(x, y)| \, dxdy$$

$S10z$ is the difference of the mean value of the 5 highest peaks ($S5p = \frac{1}{5} \sum_{i=1}^{5} p_i$) and the mean value of the 5 lowest pits ($S5v = \frac{1}{5} \sum_{i=1}^{5} v_i$) of the height data:

$$S10z = S5p - S5v$$

The surface roughness increased from the smooth racing suit to the ski overall and the dimpled racing suit; values are presented in Table 1.



(**a**) (**b**) (**c**)

Figure 1. Pictures (upper row) and focus variation microscope images (lower row) of the tested fabrics: ski overall (**a**), smooth racing suit (**b**), and dimpled racing suit (**c**). In the lower row the height of the surface's roughness is given in µm. The horizontal scale is displayed in the lower left corner of each frame.

Table 1. Roughness parameters Sa and $S10z$ of the tested fabrics.

	Sa (µm)	$S10z$ (µm)
ski overall	35	398
smooth racing suit	11	185
dimpled racing suit	101	1539

2.2. Friction Measurements

The linear tribometer (Figure 2a) of the Centre of Technology of Ski and Alpine Sports of the University of Innsbruck was used to determine the friction between fabrics and snow [14]. Fabrics were attached with double sided tapes to a short ski with a length of 0.47 m (Figure 2b). The ski was mounted to the guided carriage of the tribometer. The carriage was pulled via a fiber cable by a high torque electric motor. After acceleration, the ski moved over a distance of about 18 m at a constant speed during which the friction force between carriage and probe was measured. A normal force of 117 and 255 N was applied to the probes via two spring-loaded vertical bars. The ski's contact area was 275 cm^2 resulting in contact pressures of 4.3 and 9.3 kPa. The probes were measured at speeds of 4.9, 9.7, and 14.6 m/s.

The tribometer was located in an air-cooled chamber. Snow produced by a snow lance was sieved and then placed in the trough. The snow was pressed and leveled out with a broad steel blade to get a uniform surface. The width of the trough of 0.8 m allowed testing on multiple fresh tracks. Prior to the friction measurements a snow temperature of –4.3 °C, a snow density of 400 kg/m^3, and grain sizes of approximately 250 µm were measured. All measurements were performed on the same snow.

Figure 2. The linear tribometer (**a**) and the ski (**b**) on which the fabrics were taped.

Series of 10 consecutive runs were recorded for each probe in the same track. Each series was started in a new track. Since the consecutive runs altered the snow during the series, only the first run was analyzed. The friction coefficient was calculated by $\mu = F_F/F_N$ with F_F the friction force and F_N the normal force.

3. Results

The measured friction coefficients ranged between 0.19 and 0.48 (Table 2). The smooth racing suit and the ski overall showed about the same values while the ones of the dimpled racing suit were clearly higher. The friction coefficient tended to increase with increasing roughness of the fabrics especially at the higher contact pressure (Figure 3). The friction force of the fabrics was higher at the higher contact pressure at all speeds. Interestingly, the friction coefficients were lower at the higher contact pressure (Figure 4). At the lower contact pressure the friction coefficients decreased with increasing speed while it was almost constant at the higher contact pressure (Table 2).

Table 2. Measured friction coefficients of the tested fabrics at different speeds (v) and contact pressures (p). Sa is the mean surface roughness of the fabrics.

		$p = 4.3$ kPa		
		$v = 4.9$ m/s	**$v = 9.7$ m/s**	**$v = 14.6$ m/s**
smooth racing suit	($S_a = 11$ µm)	0.44	0.33	0.27
ski overall	($S_a = 35$ µm)	0.41	0.31	0.28
dimpled racing suit	($S_a = 101$ µm)	0.48	0.48	0.44
		$p = 9.3$ kPa		
		$v = 4.9$ m/s	$v = 9.7$ m/s	$v = 14.6$ m/s
smooth racing suit	($S_a = 11$ µm)	0.23	0.19	0.23
ski overall	($S_a = 35$ µm)	0.25	0.26	0.28
dimpled racing suit	($S_a = 101$ µm)	0.31	0.35	0.35

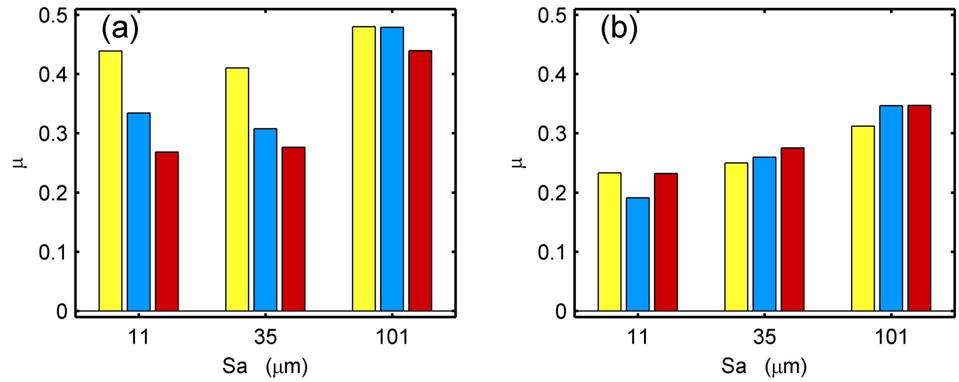


Figure 3. Coefficient of friction (μ) versus mean surface roughness (*Sa*) at contact pressures of 4.3 kPa (**a**) and 9.3 kPa (**b**) and at speeds of 4.9 m/s (yellow bar), 9.7 m/s (blue bar), and 14.6 m/s (red bar).

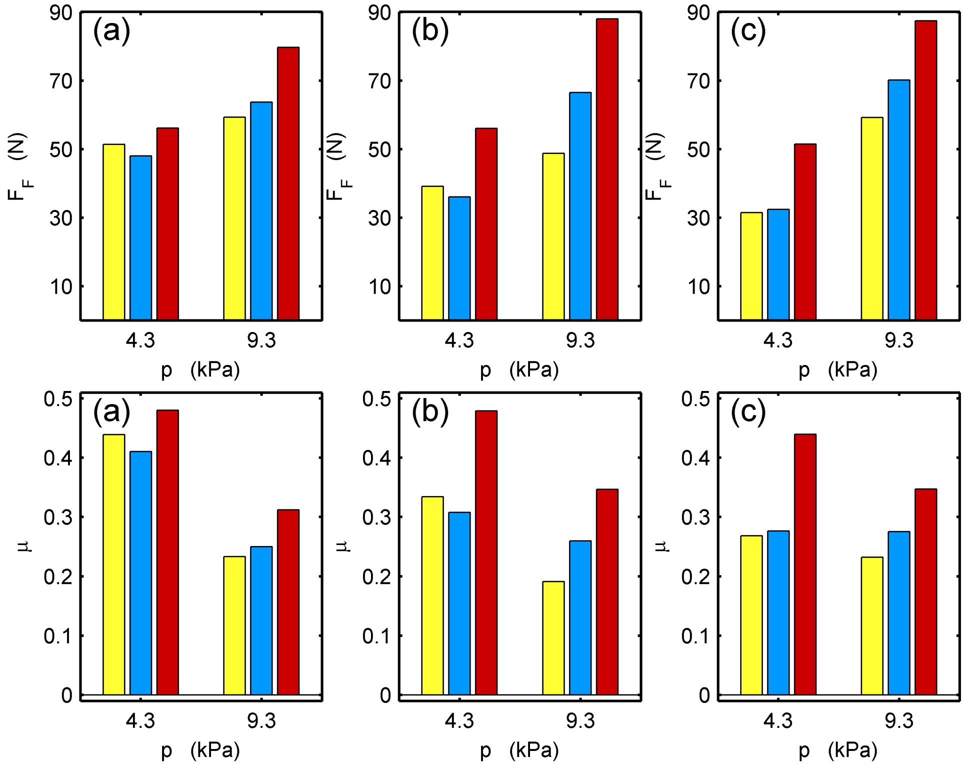


Figure 4. Friction force (F_F) and coefficient of friction (μ) versus contact pressure (p) for the smooth racing suit (yellow bar), ski overall (blue bar), and dimpled racing suit (red bar) at speeds of 4.9 m/s (**a**), 9.7 m/s (**b**), and 14.6 m/s (**c**).

4. Discussion

4.1. Measurement Values

The friction coefficients of 0.19–0.48 for the tested fabrics corresponded well to published values of fabrics on snow [5,7]. The low friction coefficients below 0.1 [14, Table 1] of polyethylene ski bases on snow were explained by a lubricating water film due to frictional heating [18,19]. Das *et al.* [2] reported friction coefficients between 0.16 and 0.28 for friction of fabrics on metal. We obtained the same or even higher values and since these values were clearly above the ones for skis on snow, it is likely that the main friction mechanism for the fabrics was dry friction.

Dry friction includes adhesion as well as elastic and plastic deformation. For smooth sliding surfaces adhesion dominates [20]. If both surfaces have similar roughness, friction is governed by asperity interlocking [21]. The number and deepness of the overlapping connections depend on the geometry of the two surfaces. The interlocking is most pronounced for two surfaces with similar roughness. The grain size of the snow was 250 µm, from which we estimated a mean snow roughness of 125 µm. The dimpled fabric possessed with Sa = 101 µm a similar roughness while the two other fabrics had a considerably lower roughness. As a consequence interlocking and thus the friction force increased from smooth to rough fabrics.

The friction force of the fabrics was higher for the higher contact pressure than for the lower one at all speeds. At the higher contact pressure more asperities are in contact and interlocking is more pronounced and thus the friction force increases. However, the friction coefficients were lower at the higher contact pressure. Das *et al.* [2] explained lower values of the friction coefficient with higher regularity of the surface of the fabric with increasing contact pressure.

The friction coefficients decreased with increasing speed at the lower contact pressure. This may be due to boundary lubrication [1] caused by partial wetting of the fabric's yarns due to frictional heating. Hydrodynamic lubrication [1] as cause is very unlikely since a water film thickness at least in the size of the roughness of the fabric would be required. In such a water film the viscous friction would increase with increasing speed. Additionally, viscous friction would be smaller than the measured one.

4.2. Safety Issue

In the following the effect of the friction coefficient on the sliding distance of a fallen skier is assessed. In recreational skiing, a mean speed of 12 and a maximum speed of 26 m/s were measured with radar guns [22]. A skier (mass 95 kg) lying with his back on the snow surface (contact area 0.5 m^2) has a contact pressure of 1.9 kPa. In a sitting position (contact area 0.12 m^2) the contact pressure is 7.8 kPa. Let m be the mass and v the speed of the skier, α the angle of the slope, ρ the air density, and $C_d A$ the drag area of the skier. A sliding skier is accelerated by the downhill force ($F_W = mg\sin\alpha$) and decelerated by drag ($F_D = \frac{1}{2}\rho C_d A v^2$) and snow friction ($F_F = \mu mg\cos\alpha$). Assuming a drag area of 0.5 m^2 for a sitting position and a friction coefficient of 0.3 a skier with a mass of 95 kg sliding at a speed of 12 m/s on an inclined slope of 15° has F_W = 241 N, F_D = 43 N, and F_F = 270 N. Because the drag force is small with respect to the friction force, drag is neglected at speeds lower 12 m/s. The acceleration (a) of a sliding skier is then given by $a = g\cos\alpha(\tan\alpha - \mu)$. A sliding skier decelerates, when the garment's friction coefficient is larger than the tangent of the hill angle. To sufficiently decelerate, the friction coefficient should be considerably larger then the tangent of the hill angle. The sliding time, until a sliding skier stops, is given by $t_s = -v_0/a$ and the sliding distance by $s_s = -v_0^2/2a$. For friction coefficients of 0.3, 0.4, and 0.5 sliding times of 39.5, 9.6, and 5.5 s and sliding distances of 237, 58, and 33 m, respectively, were calculated. According to the standard ON S 4611 [23], ski slopes are divided into blue (beginner), red (intermediate), and black (sophisticated) slopes depending on the maximum steepness of the hill in longitudinal or transverse direction. Steepness of a blue slope is less than 25% (14.0°), of a red slope less than 40% (21.8°), and of a black slope greater equal 40% (21.8°). To obtain a reasonable sliding distance of about 40 m the friction coefficient has to be 0.1–0.2 higher than the tangent of the hill angle. In our measurements we obtained friction coefficients between 0.19 and 0.48. Therefore, the friction of the tested fabrics decelerates sliding skiers by an appropriate extent on beginner and intermediate slopes. Sophisticated slopes require friction coefficients of 0.5 or higher for acceptable sliding distances. Such high values were only exceptionally measured, e.g., for the dimpled racing suit at the low contact pressure. Manufactures of ski garments could improve safety in skiing by paying attention to the friction properties of the processed fabrics. It has to be stated, that the friction of a fabric on snow gives only a lower bound for the friction of sliding skiers. Additional sources of friction are the textile processing of the ski garments (openings, shutters, seams. . .), the ski equipment (skis, boots. . .), and the motion of the skier.

4.3. Limitations

The presented study provides a limited set of data regarding fabrics and snow types. A manifold of fabrics are used in the fabrication of ski garments. Each fabric may have its specific frictional characteristics. Only one kind of snow was used. Density, hardness, temperature, or surface roughness vary on slopes and affect friction. The different fabrics were characterized by the fabric's mean and maximum surface roughness. Although these surface roughness parameters showed a high effect, fabric parameters such as yarn orientation or yarn material likely affect snow friction, too. The measured friction coefficients are mean values over the measurement distance of the tribometer. Already along this distance of 18 m fabrics were altered by entrained snow grains as observed after the measurements. The sliding length of a skier can be considerably longer in which the contacting fabric may be further altered causing a change in snow friction.

5. Conclusions

A novel measurement procedure to measure kinetic friction of fabrics of ski garments was presented. Friction coefficients between 0.19 and 0.48 were obtained for three different fabrics at different speeds and contact pressures. It was concluded that the main friction mechanism for the measured fabrics was dry friction. Snow friction increased from smooth to rough surfaces. This effect was explained by more asperities in contact and increased asperity interlocking between fabric and snow grains for increased roughness. Only the fabric with the roughest surface showed friction coefficients, which were high enough to sufficiently decelerate a sliding skier on beginner and intermediate slopes. Therefore, manufactures of ski garments could improve safety in skiing by paying attention to the friction properties of the processed fabrics.

Acknowledgments: The study was supported by the project "Competence Centre Sports Textiles", which is funded by the Standortagentur Tirol (Austria) and region Vorarlberg (Austria).

Author Contributions: All authors were involved in the design and planning of the study as well in the preparation and correction of the manuscript.

Conflicts of Interest: The authors declare that there is no conflict of interest.

References

1. Gupta, B. *Friction in Textile Materials*; Woodhead Publishing: Cambridge, UK, 2008.
2. Das, A.; Kothari, V.; Vandana, N. A study on frictional characteristics of woven fabrics. *Autex Res. J.* **2005**, *5*, 133–140.
3. Sülar, V.; Öner, E.; Okur, A. Roughness and frictional properties of cotton and polyester woven fabrics. *Indian J. Fibre Text.* **2013**, *38*, 349–356.
4. vonAllmen, B. *Sliding Control of Ski Garments*; Skiing Safety II; Figueras, J., Nelson, R., Morehouse, C., Eds.; University Park Press: Baltimore, MD, USA, 1978; pp. 185–192.
5. vonAllmen, B.; Glenne, B. *Skiing Accident Dynamics*; Skiing Safety II; Figueras, J., Nelson, R., Morehouse, C., Eds.; University Park Press: Baltimore, MD, USA, 1978; pp. 199–208.
6. Prokop, L. Untersuchungen mit rutschfester Skibekleidung (Investigations with anti-slip ski garments). In *Zur Biomechanik des Schilaufs (On Biomechanics of Skiing)*; Fetz, F., Ed.; Inn Verlag: Innsbruck, Austria, 1977; pp. 37–45.
7. Nachbaur, H. *Reibungskoeffizienten von Skibekleidung (Friction Coefficients of Ski Garments)*; Internal Report; Department of Sport Science, University of Innsbruck: Innsbruck, Austria, 1994.
8. Belloni, E.; Milani, D.; Braghin, F. An innovative tribometer for measurements between sport fabrics and ice. In Proceedings of the 33rd IMAC, A Conference and Exposition on Structural Dynamics, Orlando, FL, USA, 2–5 February 2015; Sensors and Instrumentation; Sit, E.W., Ed.; Springer: New York, NY, USA, 2015; Volume 5, pp. 37–44.

9. Brown, C.; Hoffman, A.; Heinzmann, R. Skier trajectories after loss of control. In Proceedings of the ASTM STP 1266 Skiing Trauma and Safety; Mote, C.; Johnson, R., Hauser, W., Schaff, P., Eds.; American Society for Testing and Materials: Philadelphia, PA, USA, 1996; Volume 10, pp. 186–195.
10. Hasler, M.; Schindelwig, K.; Nachbauer, W. *Friction Coefficient of Fabrics on Snow*; Book of Abstracts of the 21st Internetional Congress on Ski Trauma and Skiing Safety; San Vito di Cadore—Cortina d'Ampezzo, IT; Petrone, N., Marcolin, G., Eds.; International Society for Skiing Safety: Aviemore, Scotland, 2015; p. 68.
11. Colbeck, S. *A Review of the Processes That Control Snow Friction*; Technical Report 92-2; Cold Regions Research and Engineering Laboratory: Hanover, NH, USA, 1992.
12. Bäurle, L.; Szabó, D.; Fauve, M.; Rhyner, H.; Spencer, N. Sliding friction of polyethylene on ice: Tribometer measurements. *Tribol. Lett.* **2006**, *24*, 77–84.
13. Linnamo, V.; Ohtonen, O.; Rapp, W.; Lemmettylä, T.; Göpfert, C.; Komi, P.; Ishikawa, M.; Holmberg, H.; Vähäsöyrinki, P.; Mikkola, J.; et al. Sports technology, science and coaching. In Proceedings of the 2nd Internetional Congress on Science and Nordic Skiing, Vuokatti, Finland, 28–31 May 2012; pp. 28–31.
14. Nachbauer, W.; Kaps, P.; Hasler, M.; Mössner, M. Friction between ski and snow. In *The Engineering Approach to Winter Sports*; Braghin, F., Cheli, F., Maldifassi, S., Melzi, S., Sabbioni, E., Eds.; Springer: New York, NY, USA, 2016; pp. 17–32.
15. Rohm, S.; Hasler, M.; Knoflach, C.; van Putten, J.; Unterberger, S.; Schindelwig, K.; Lackner, R.; Nachbauer, W. Friction between steel and snow in dependence of the steel roughness. *Tribol. Lett.* **2015**, *59:27*, doi:10.1007/s11249-015-0554-x.
16. Nwaogu, U.; Tiedje, N.; Hansen, H. A non-contact 3D model to characterize the surface roughness of castings. *J. Mater. Process. Technol.* **2013**, *213*, 59–68.
17. Leach, R. *Characterization of Areal Surface Texture*; Springer: New York, NY, USA, 2013.
18. Bowden, F.; Hughes, T. The mechanism of sliding on ice and snow. *Proc. R. Soc. Lond.* **1939**, *A172*, 280–298.
19. Ambach, W.; Mayr, B. Ski gliding and water film. *Cold Reg. Sci. Technol.* **1981**, *5*, 59–65.
20. Nosonovsky, M.; Bhushan, B., Mechanisms of dry friction, their scaling and linear properties. In *Multiscale Dissipative Mechanisms and Hierarchical Surfaces*; Nosonovsky, M., Bhushan, B., Eds.; Springer: Berlin, Germany, 2008; pp. 27–45.
21. Holmberg, K.; Matthews, A. *Coatings Tribology: Properties, Mechanisms, Techniques and Applications in Surface Engineering*; Elsevier: Amsterdam, The Netherlands, 2009.
22. Ruedl, G.; Sommersacher, R.; Woldrich, T.; Kopp, M.; Nachbauer, W.; Burtscher, M. Durchschnittsgeschwindigkeit von Wintersportlern in Abhängigkeit verschiedener Einflussfaktoren (Mean speed of winter sport participants depending on various factors). *Sportverletz Sportsc* **2010**, *24*, 150–153.
23. Austrian Standards Institute (ON). *Skipisten—Klassifizierung und Grundlegende Schilder (Ski Runs—Classification and Basic Sings)*; Austrian Standards Institute (ON): Vienna, Austria, 2003.