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Aerodynamic drag is not the major determinant of performance during giant slalom skiing at the elite level

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This investigation was designed to (a) develop an individualized mechanical model for measuring aerodynamic drag (F_d) while ski racing through multiple gates, (b) estimate energy dissipation (E_d) caused by F_d and compare this to the total energy loss (E_t), and (c) investigate the relative contribution of E_d/E_t to performance during giant slalom skiing (GS). Nine elite skiers were monitored in different positions and with different wind velocities in a wind tunnel, as well as during GS and straight downhill skiing employing a Global Navigation Satellite System. On the basis of the wind tunnel measurements, a linear regression model of drag coefficient multiplied by cross-sectional area as a function of shoulder height was established for each skier ($r > 0.94$, all $P < 0.001$). Skiing velocity, F_d, E_t, and E_d per GS turn were 15–21 m/s, 20–60 N, –11 to –5 kJ, and –2.3 to –0.5 kJ, respectively. E_d/E_t ranged from ~5% to 28% and the relationship between E_t/v_{in} and E_d was $r = -0.12$ (all NS). In conclusion, (a) F_d during alpine skiing was calculated by mechanical modeling, (b) E_d made a relatively small contribution to E_t, and (c) higher relative E_d was correlated to better performance in elite GS skiers, suggesting that reducing ski–snow friction can improve this performance.

In competitive alpine skiing, the final times of elite World Cup skiers often differ by no more than fractions of a second, even though, as we have previously reported, the performance times of the fastest skiers on individual sections of the race can vary by as much as 10% (Supej & Cernigoj, 2006). Thus, on certain sections, there is room for significant improvement, even among elite skiers.

Aerodynamic drag and ski–snow friction are the two mechanical forces that can decrease skiing performance (von Hertzen et al., 1997; Federolf et al., 2008). Several investigations have evaluated the effects of such friction (Colbeck, 1994; Ducret et al., 2005) and of body posture on aerodynamic drag under laboratory conditions (Luethi & Denoth, 1987; Savolainen, 1989; Thompson et al., 2001; Barelle et al., 2004). In a similar manner, the impact of movements by a skier that alter the point at which the ground reaction force is applied on gliding times over straight alpine terrain has been examined (Federolf et al., 2008). However, to our knowledge, the influence of aerodynamic drag and ski–snow friction under conditions similar to those actually encountered during competitive alpine ski racing has not yet been elucidated.

The first of two recent approaches to characterizing differences in energy dissipation during skiing involves quantification of differential specific mechanical energy as the amount of energy dissipated per change in altitude and unit mass (Supej, 2008). The second approach is based on the change in mechanical energy divided by the velocity of entry into the section being investigated (Supej et al., 2011). Although these approaches extend parameters employed previously to provide a more detailed biomechanical evaluation, neither measures the amount of energy dissipated by either aerodynamic drag or ski–snow friction directly.

In principle, if the total energy dissipation is known, determination of the contribution by one of the aforementioned factors would also reveal the significance of the other. Therefore, further characterization of aerodynamic drag in connection with different techniques of alpine ski racing would improve understanding of performance. Unfortunately, current technology does not allow direct measurement of aerodynamic drag under the conditions encountered during competitive alpine skiing and, consequently, reliable estimates of aerodynamic drag on large sections of a ski slope (ranging from

Fig. 1. The standard skiing positions (high, mid and low; top) and a skier standing in a midposition in the wind tunnel with a wind velocity of 60 km/h (bottom).

individual sections containing multiple gates up to an entire course) can be difficult to obtain.

Accordingly, the aims of the present investigation were as follows: (a) to develop a mechanical model for determining the aerodynamic drag of an individual skier passing through multiple gates on an alpine course; (b) to estimate the energy dissipated by aerodynamic drag (E_d) and compare this to the total change in energy (E_t); and (c) more specifically, to characterize the impact of energy dissipation due to aerodynamic drag relative to the total loss of energy (E_d/E_t) on performance during giant slalom skiing (GS).

Materials and methods

Participants

Nine elite male alpine skiers [age: 20 ± 4 years; height: 1.81 ± 0.05 m; body mass: 80.1 ± 7.0 kg; FIS (International Ski Federation) points in connections with competitions in GS: 19.2 ± 10.8 (means ± SD)], all members of the Swedish national ski team, were involved in this investigation. The study was pre-approved by the Regional Ethics Committee, Trondheim, Norway, and all subjects fully informed of its nature prior to providing their written consent to participate.

Experimental setup and data collection

The experiments were conducted both in a wind tunnel (to measure aerodynamic drag associated with different skiing positions and wind velocities) and on a ski slope (where the data from the wind tunnel were used to calculate the energy dissipated by aerodynamic drag under realistic conditions).

In the wind tunnel, the subjects positioned themselves on a force platform in three standard skiing stances (high, mid, low) in wind of three different velocities (40, 60, and 80 km/h) and each skier repeated this procedure five times (Fig. 1, top). The skiers were asked to assume the same three positions as when skiing in full giant slalom equipment. The three positions tested are typically assumed in connection with the dynamic movements of the body during alpine skiing: the high position is often used when transferring weight from one ski to the other; the midposition is approximately what the skier assumes most of the time while turning; and the low position is normally taken by the skier to reduce aerodynamic drag at highest velocities with less intensive turning. These natural and typical skiing positions were assessed by recording two subjects performing giant slalom at several speeds.

The order in which each skier assumed the three different test stances in the wind tunnel was randomized. Before this experiment, the skiers were told about the difference between anterior-posterior balance in the wind tunnel and during skiing and they were instructed to try consciously not to adapt their body position to the wind tunnel, but to assume their natural skiing positions, so that the aerodynamic drag measured would be as valid as possible to field conditions. Prior to each individual trial the force transducer was adjusted to zero under windless conditions to compensate for possible forces in the wind direction due to the skier's body weight. The skier was given a sign that indicated the body position to be taken. Measurement began when the force signal had stabilized and the average value during the subsequent 5 s

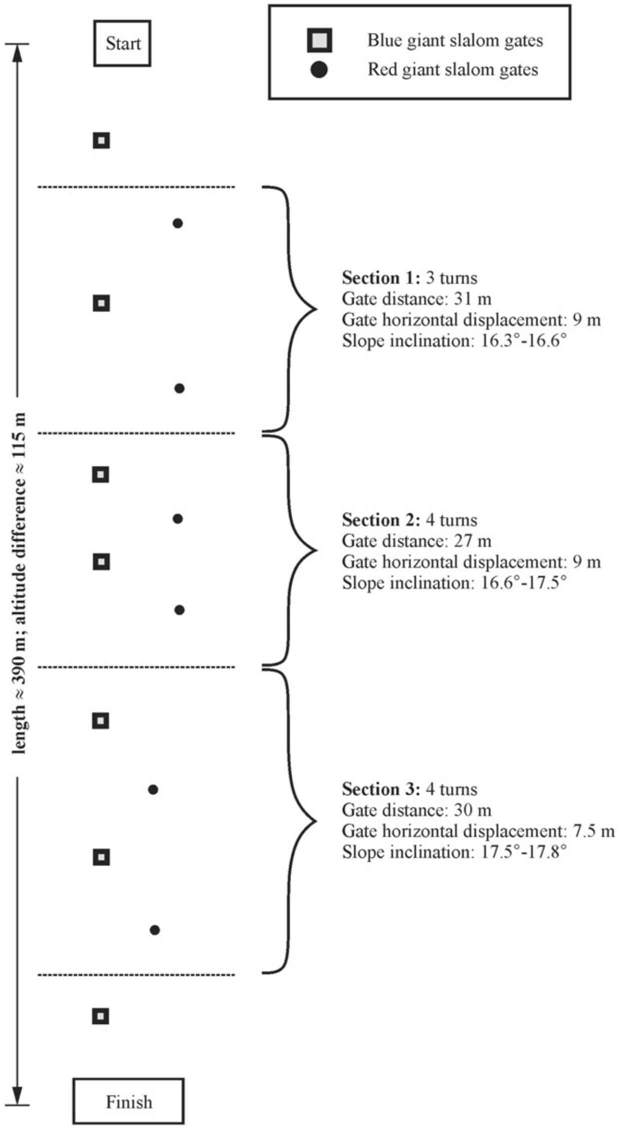

Fig. 2. Schematic illustration of the setup of the giant slalom course, showing the three different sections with different distances and horizontal displacements between the gates.

determined. All wind tunnel measurements were conducted on the same day and the skiing experiment was performed on the following day.

During the four different runs on the ski slope, each skier donned his own GS racing equipment (ski length: 1.92 ± 0.015 m; side cut = 27 m) and was equipped with a high-end (top-quality) Global Navigation Satellite System (GNSS). First, each participant skied through a 13-gate giant slalom course [set up by an experienced coach and containing three different gate distances that enabled predominantly carved turns (Fig. 2)] as fast as possible. Thereafter, the participant skied three runs straight down the fall line* (which was clearly marked) employing the high, mid, or low body positions, respectively, again in randomized order.

All of these measurements were performed under optimal conditions: minimal or no wind; groomed, hard and smooth snow, which in addition was side slipped after each skiing run; an air temperature between −9 and −7 °C; and a clear sky with good visibility. Wind velocity and direction were measured during each run utilizing three WindSonic™ 2-Axis Ultrasonic Anemometers (Gill instruments LtD, Hampshire, UK) located at the start, middle, and end of the course. These anemometers were connected to a base station, where they were monitored continuously by one of the investigators whenever data was being collected. All GS and straight skiing runs were performed within a 30-min period of time with headwind velocities of 0.3 ± 0.2, 0.1 ± 0.1, and 0.0 ± 0.1 at the three locations, respectively; when the wind velocity approached 0.5 m/s, the data were discarded and the trial repeated.

To minimize differences in gliding properties, all skis employed were subjected to the same stone grinding and waxed and tested by a professional ski technician before the measurements and inspected afterwards. For calculation of the parameters of energy dissipation, the mass of each skier wearing racing equipment was measured on an AMTI force plate (Watertown, MA, USA) and body height determined with a calibrated stadiometer (Holtain Ltd, Crosswell, UK).

*The fall line is by definition the negative of the gradient, which points uphill, and is perpendicular to the contour lines.

Instrumentation

A 220-kW centrifugal fan produced wind of speeds up to 30 m/s in the wind tunnel, the test area of which was 12.5 m long, 2.7 m wide, and 1.8 m high (Fig. 1, bottom). The aerodynamic drag was quantified with a Kistler force platform (Model 9286AA, Kistler Instrument Corp., Winterthur, Switzerland) and the skier's shoulder height measured by two-dimensional kinematics using a full high-definition Sony HDR-HC7 camcorder (Sony Corp., Tokyo, Japan) positioned to record in the sagittal plane. Shoulder position and ground level were digitalized using two-dimensional kinematics software (Avi AD Measure v2.4, Intelligent Solutions and Consulting s.p., Kranjska Gora, Slovenia).

The trajectories of the athletes on the ski slope were monitored with a high-end GNSS real-time-kinematics (RTK) system (with 99.99% position reliability according to the manufacturer Leica Geosystems AG, Heerbrugg, Switzerland). For corrections in real time, a rover and a reference station were constructed from identical dual frequency L1/L2, geodetic, GNSS RTK receivers (Leica GX1230GG), Leica survey antennae (GLONASS/GPS AX1202 GG) and Leica Satelline 3AS radio modems. In the RTK mode with a maximal 20 Hz sampling rate, this system measures horizontal and vertical positions with accuracies of 10 mm (millimeters) ± 1 ppm (parts per million) and 20 mm ± 1 ppm, respectively, according to the manufacturer. The GNSS system provides position accuracy for each surveyed position along the trajectory.

During data collection, the reference station stood on a fixed tripod less than 250 m from all of the points surveyed in order to transmit real-time corrections. To monitor trajectories, the rover's receiver, modem, and antenna were placed in a small backpack worn by the athlete, with the antenna carefully positioned at the level of the upper thoracic spine (T2-T4). None of the subjects complained about discomfort and/or disturbance due to this equipment (which measured 21.2 × 16.6 × 7.9 cm and weighed 1.64 kg). It was assumed that the initial position of the GNSS antenna relative to the body did not change substantially during the skiing runs due to the attachment protocol of the antenna and backpack.

For surveying gate positions and the configuration of the terrain, the antenna was attached to a 2-m high-carbon geodetic pole with an inclinometer (Leica Geosystems AG, Heerbrugg, Switzerland). To measure a sufficient number of points on the slope, the fall line and each gate were swept left to right several times with this setup. A local geodetic coordinate system was used; an elevation cutoff angle of 15° was set for all measurements, which were planned on the basis of a satellite availability prediction performed with Leica Geo Office Combined software (Leica Geosystems AG, Heerbrugg, Switzerland) for optimal accuracy (Parkinson & Spilker, 1996).

To assist processing and analyses, all ski runs were also recorded in their entirety with two full high-definition Sony HDR-HC7 camcorders. In the case of the three straight downhill runs, one of these camcorders monitored two-dimensional kinematic skiing performance in the sagittal plan. The four points digitalized were the tip and tail end of the ski, the skier's shoulder and the heights of the antennae.

Calculations

Energy dissipation due to aerodynamic drag during giant slalom turns was calculated as follows:

Step 1

Using the wind velocity in the wind tunnel (V), the aerodynamic drag (F_d), air density (ρ), and Rayleigh's drag equation ($F_d = \text{CdS}\cdot\rho\cdot V^2/2$), the product of the skier's cross-sectional area and the coefficient of aerodynamic drag (CdS) was calculated ($\text{CdS} = 2\cdot F_d/(\rho\cdot V^2)$) for each test (five tests in each of the three positions at three different wind velocities for each of the nine skiers).

Step 2

The relationship between the shoulder height (l_s) in the wind tunnel (measured by two-dimensional kinematics) and the CdS for each skier was found to be linear, allowing construction of a linear function $\text{CdS} = f(l_s)$ for each individual athlete.

Step 3

In order to employ the relationship derived in step 2 during skiing, a linear transformation between the shoulder (l_s) and antenna heights (l_a) was constructed utilizing two-dimensional kinematic data recoded during the straight skiing runs. In the same manner as in step 2, a linear function $l_s = h(l_a)$ was derived for each skier.

Step 4

In order to obtain CdS during skiing after performing steps 1–3, the distance between the skis and the shoulders (l_s) in connection with each point of observation must be known. Firstly, on the basis of the GNSS data, the trajectories of the skis and of the centre of mass (COM) of the skier were calculated. Because these trajectories cannot be obtained directly by GNSS, an approximation was made by assuming that the skier behaves like an inverted pendulum (Morawski, 1973; Supej et al., 2008), that is dynamically balanced at any given time. Initially, an approximate position of the bottom of this inverted pendulum x_b was obtained by assuming that the measured position x_m was actually the COM of this pendulum. This inverted pendulum is illustrated in Fig. 3, where θ was the angle of inclination between the pendulum and the ground in the radial direction of the turn, ω the angular turning velocity of the skier around the normal vector of the slope, r the turning radius of the COM, g the gravitational constant, and l_{COM} and l_a the distances from the ground to the COM and to the GNSS antenna, respectively. The following balance equation for force torque describes this inverted pendulum when the skier's mass m and the length l_{COM} have been eliminated:

$$0 = \ddot{\theta} - \cos(\theta)\cdot g + \sin(\theta)\cdot\omega\times r \quad [1]$$

Employing the angular acceleration $\ddot{\theta}$ from the previous frame of measurement, θ in the subsequent frame was estimated from this equation. As mentioned above, r was initially calculated assuming

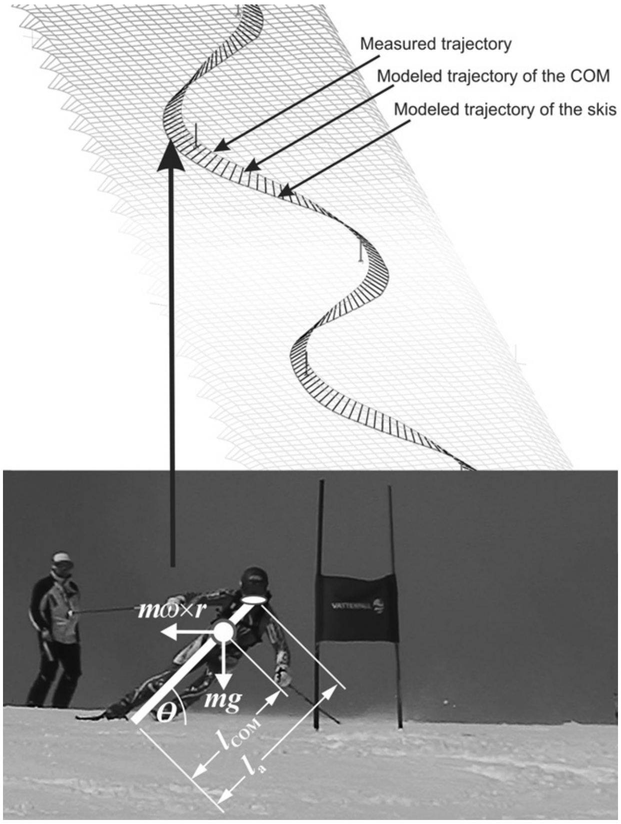

Fig. 3. Three-dimensional representation of the measured antenna trajectory and the modeled trajectories of the COM and skis (top). The inverted pendulum model (bottom), where m is the mass of the skier, r the turning radius of the COM, θ is the angle of inclination between the pendulum and the ground in the radial direction of the turn, ω the angular turning velocity of the skier around the normal vector of the slope, g the gravitational constant, and l_{COM} and l_a the distances between the ground to the COM and to the GNSS antenna, respectively.

that the position measured was actually the COM of this pendulum, so that the value obtained for θ was only an approximation. This approximation allowed, in turn, a more accurate approximation of r using the relationship $r \leftarrow r + \cos(\theta)\cdot(l_s - l_{COM})$, where $l_s = h(l_a)$ derived in step 2. As demonstrated in a previous study (Supej, 2008), the relative distance between the COM and the skis (l_{COM}) is linearly proportional to the relative shoulder height (l_s) ($l_{COM} = q(l_s)$). Therefore, the values for the inverted pendulum had to be recalculated utilizing this new estimation of COM. This entire procedure based on eqn. [1] was repeated until both r and θ converged. The value for θ thus obtained was then utilized to calculate the new vector x_b and the angular acceleration $\ddot{\theta}$, which were applied to the subsequent time frame.

Prior to these calculations, the raw trajectory provided by the GNSS was filtered through the Rauch-Tung-Striebel algorithm (Rauch et al., 1965), which involves two unscented Kalman filters running forward and backward in time and achieves fixed-interval offline smoothing of the estimated signals. At the same time, the turning radii r and the corresponding angular velocity of the skier ω were calculated. The accuracies of the trajectory points indicated by the GNSS were employed to set the lowest frequency of the filter, assuming that each smoothed point does not move further than the accuracy with which its position has been obtained. This calculation and filtering procedure were found to provide an appropriate estimate of the position of the skis x_b and of

COM, using only the kinematic measurements made by the GNSS antenna (see Fig. 3). Finally, the distance between the position of the skis and the shoulders was calculated (l_s).

Step 5

The time differential for the angle at which the pendulum moved in the somatic coordinate system (step 4) allowed estimation of the rate at which the COM was turning. By determining the points at which this differential parameter crossed the *x* and *y* axis, the times and, consequently, the positions at the beginning and end of the turns could be obtained, positions that are analogous to the definitions of the beginning and end of the turn employed previously (Supej et al., 2003; Reid et al., 2009).

Step 6

The distance between the skis and the antenna for all skiing runs was calculated using their trajectories obtained with the inverted pendulum model (step 4). In combination with the linear models (steps 2–3), this distance provided CdS values for each point of observation.

Step 7

Aerodynamic drag (F_d) during skiing was calculated by entering the CdS values (step 6) and COM velocity (step 4) into Lord Rayleigh's equation. The energy dissipation (E_d) caused by aerodynamic drag was subsequently obtained as the numerical integral of F_d with respect to the distance moved. Using the positions at the beginning and end of the turn (step 5), E_d was calculated for each turn in the giant slalom runs.

Step 8

For each turn in the giant slalom runs the alteration in the potential and kinetic energy of the COM (E_t) were calculated, along with the ratio E_d/E_t. The mass employed in this equation was the sum of the masses of the skier's body and his racing equipment.

In order to simulate the characteristics and position of the skier's body during each turn, an average CdS (avgCdS) value per turn was calculated. Prediction of turn performance was based on a sectional energy parameter developed especially for this purpose, that is, E_t divided by the velocity of entry into the turn (E_t/v_{in}; Supej, et al., 2011). In addition, turning times (using step 5), together with the average turn velocity and trajectory length of the COM were calculated.

For purposes of validation, the force of friction between the skis and the snow (F_f; defined here as the total friction, including nonoptimal guiding of the skis (Ducret et al., 2005) and the coefficient of friction (c_f) were calculated for the straight skiing runs. The same approach presented in steps 1–7 was then applied to calculate F_d and the acceleration of the COM. Using Newton's second law and the forces acting on the skier (F_d, the force of gravity and the ground reaction force), F_f and c_f could be calculated. The inclination of the slope required for these calculations was obtained from the three-dimensional terrain mesh and the skiers' positions.

To evaluate the influence of GNSS accuracy on the models and calculations employed, white noise of the same amplitude as this experimentally determined accuracy was added to the giant slalom data. Thereafter, the velocity of the COM and the distance between the skis and the shoulders were recalculated as described in steps 4 and 6.

Statistical analyses

A Kolmogorov–Smirnov test (KS-test) and Shapiro–Wilks' *W*-test (*W*-test) were applied to confirm normal distribution of the data obtained. Scatter plots, error bar plots, and linear regression functions were utilized to look for relationships between the various parameters and Pearson product-moment correlation coefficients together with the associated *P*-values used as indications of the strengths of relationships observed. The data are expressed as means ± standard deviations (mean ± SD) and *P*-values <0.05 considered to be statistically significant.

Results

First, the CdS and shoulder height obtained from the wind tunnel experiments with each skier demonstrated a highly significant linear relationship, with correlation coefficients (r) ranging from 0.938 to 0.991 ($P < 0.001$). Secondly, in the case of the straight downhill runs, antenna and shoulder heights also exhibited an extremely strong linear relationship ($r = 0.992$, $P < 0.001$). These findings were subsequently employed in our mechanical model, as explained in the Materials and methods.

Average velocities, times, and trajectory lengths for each turn on the giant slalom course are presented in Fig. 4. The average velocity ranged from approximately 15–21 m/s, being higher in section 3 (turns 8–11) and slightly lower in sections 1 and 2 (turns 1–7). The most prolonged turns (approximately 1.9 s) occurred in section 1, with markedly shorter turns (approximately 1.6 s) in the other two sections. The longest turn trajectories (as much as approximately 33 m) were observed in

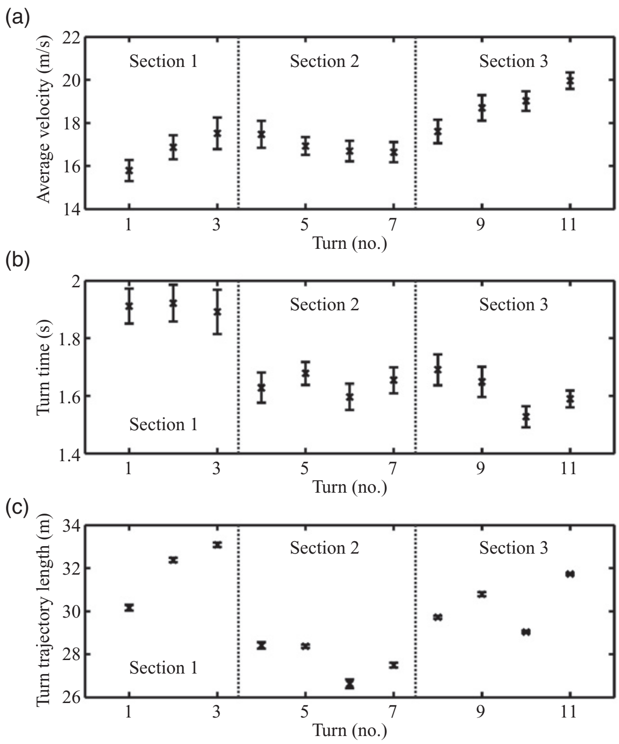

Fig. 4. Average turn velocities (a), turn times (b) and lengths of the turn trajectories (c) for all skiers combined. For each parameter at each gate, the average value is depicted with a cross and the standard deviation with error bars.

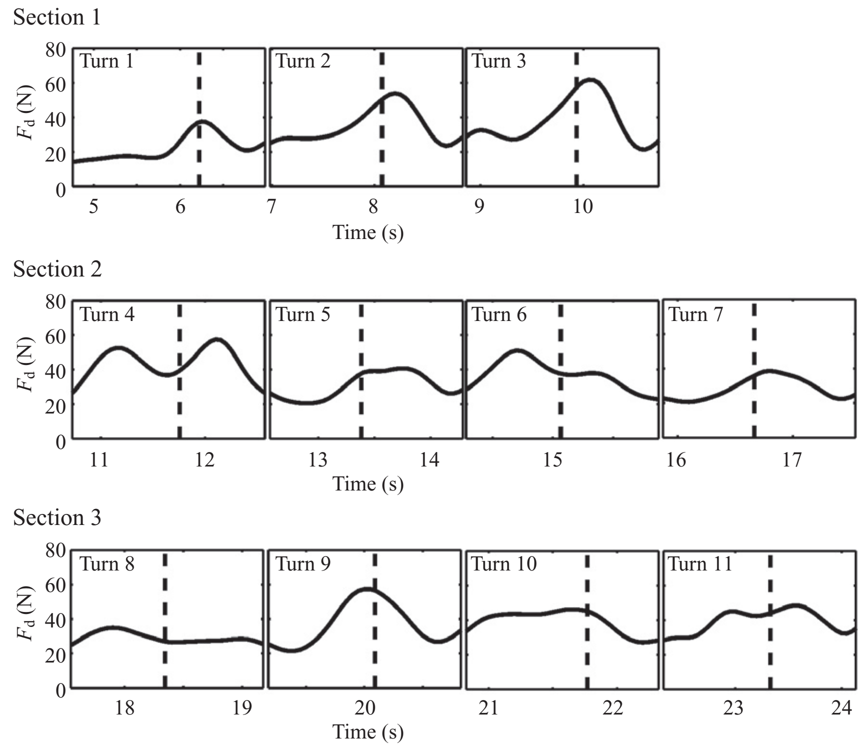

Fig. 5. Aerodynamic drag (F_d) associated with each individual turn in connection with a representative run by one skier. The individual gates in the three different sections of the course are shown, with the broken vertical lines marking the skier's passage through the gate.

section 1 and the shortest (approximately 27 m) in section 2, with intermediate lengths (approximately 30.5 m) in section 3. The standard deviations were large for the average velocities and turning times and small for the average trajectory lengths.

The aerodynamic drag, associated with all 11 turns performed by one representative skier, is presented in Fig. 5(a). The F_d values for all of the skiers ranged from approximately 20–60 N, and were observed to increase during the first three turns. For most of the turns, F_d was minimal when the skier was transferring his weight and maximal at one or two points in the vicinity of the starting gate. The average F_d for all skiers at each gate, documented in Fig. 6(a), exhibited a large standard deviation for most of the turns, being smallest in connection with turns 1, 2, and 6 and highest for turns 9–11 (section 3).

The relative energy dissipation caused by aerodynamic drag (E_d/E_t) ranged from approximately 0.05 to 0.28, with an average for most turns of around 0.15 (Fig. 6(b)). The highest E_d/E_t was observed in the last turn of section 3 and the lowest in turn 6 (section 2), again with relatively large standard deviations. The total energy dissipation per turn (E_t) ranged from −5.0 to −10.5 kJ, with energy dissipation due to aerodynamic drag (E_d) ranging between −0.5 and −2.3 kJ and no apparent visual relationship between these two parameters for any of the turns (Fig. 6(c)).

The correlation coefficients obtained from comparison of the parameters examined, along with the associated *P*-values are presented in Table 1. In general, most of the statistically significant correlations were associated with section 1, the last turn of section 2, and section 3. Significant negative or positive correlations between E_d and E_t were associated with only one and two turns, respectively. Furthermore, only in the case of turn 2 was there a strong correlation between E_t/v_{in} and E_d, as well as between E_t/v_{in} and avgCdS.

In the case of turns 7–9, equally large or even larger correlation coefficients were observed for avgV vs avgCdS (positive correlation) and time vs avgCdS (negative correlation). In connection with all turns in sections 1 and 3, either a tendency towards a significant correlation or large-to-very-large *r* values were observed for time vs E_d (positive correlations), time vs E_d/E_t (negative correlations), avgV vs E_d (negative correlations), and avgV vs E_d/E_t (positive correlations). When all turns were analysed together, the only highly significant correlations obtained were between E_t/v_{in} and E_d/E_t, avgV and E_d, and avgV and E_d/E_t.

The force of friction (F_f) and coefficient of friction (c_f) on the straight downhill runs were calculated for each skier and one example (also including F_d, the dynamic component of gravity, the product of the skier's mass times acceleration, as well as the velocity of the COM) is illustrated in Fig. 7. The c_f (Fig. 7(b)) and F_f (Fig. 7(a)) values were relatively stable, with minor fluctuations associated with acceleration. Even at the highest velocities (approximately 22 m/s) and the highest F_d (approximately 180 N), the F_f value tended

Table 1. Correlation coefficients between different mechanical parameters for each individual giant slalom turn and for all turns combined

Turn no. and section	E_d vs E_t	E_t/v_{in} vs E_d	E_t/v_{in} vs E_d/E_t	E_t/v_{in} vs avgCdS	Time vs E_d	Time vs E_d/E_t	Time vs avgCdS	avgV vs E_d	avgV vs E_d/E_t	avgV vs avgCdS
1 – sec. 1	–0.12	–0.33	0.80**	0.08	0.66#	–0.80**	–0.41	–0.63#	0.82**	0.37
2 – sec. 1	–0.82**	–0.76*	0.80**	0.75*	0.68*	–0.69*	–0.50	–0.71*	0.71*	0.52
3 – sec. 1	–0.06	–0.38	0.76*	0.37	0.71*	–0.61#	–0.47	–0.70*	0.63#	0.46
4 – sec. 2	0.51	–0.04	0.37	0.10	0.56	–0.50	–0.31	–0.58	0.48	0.32
5 – sec. 2	0.78*	0.45	0.28	–0.48	0.58	–0.58	–0.33	–0.57	0.59#	0.31
6 – sec. 2	0.27	–0.30	0.44	0.32	0.42	–0.46	–0.29	–0.58	0.60#	0.43
7 – sec. 2	0.32	–0.12	0.66#	0.22	0.80**	–0.54	–0.68*	–0.82**	0.56	0.71*
8 – sec. 3	0.19	–0.30	0.68*	0.19	0.81**	–0.87**	–0.71*	–0.82**	0.88**	0.72*
9 – sec. 3	0.19	–0.57	0.80**	0.52	0.78*	–0.80**	–0.62#	–0.76*	0.80**	0.59#
10 – sec. 3	0.88**	0.48	–0.41	–0.47	0.65#	–0.60#	–0.55	–0.68*	0.63#	0.58
11 – sec. 3	0.51	–0.07	0.49	0.03	0.63#	–0.65#	–0.51	–0.66#	0.66#	0.54
All turns	0.32*	–0.12	0.57**	–0.09	0.29*	–0.20*	–0.16	–0.67**	0.62**	0.19#

*$P < 0.05$; **$P < 0.01$; #A tendency toward significance, that is, $P < 0.1$.

sec., section on the giant slalom course; E_d, energy dissipation caused by air drag; E_t, total energy dissipation; E_t/v_{in}, total energy dissipation divided by velocity of entry into the turn; time, turning time; avgCdS, average coefficient of air drag multiplied by cross sectional area; avgV, average velocity of the skiers.

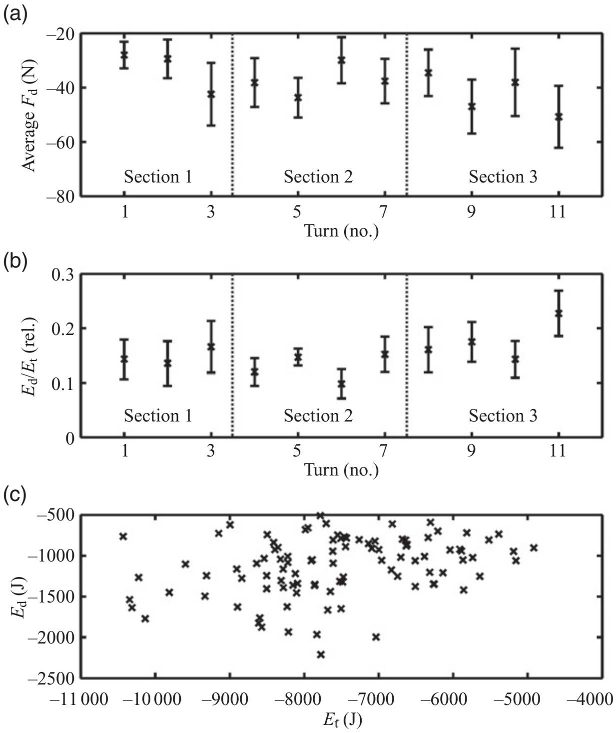

Fig. 6. Average aerodynamic drag (F_d) (a) and the relative energy dissipation caused by aerodynamic drag (E_d/E_t) (b) in connection with each individual turn for all skiers combined. Diagram c shows energy dissipation caused by aerodynamic drag with respect to the total energy dissipation per turn. The average values for diagrams a and b are depicted with crosses and the standard deviations with error bars.

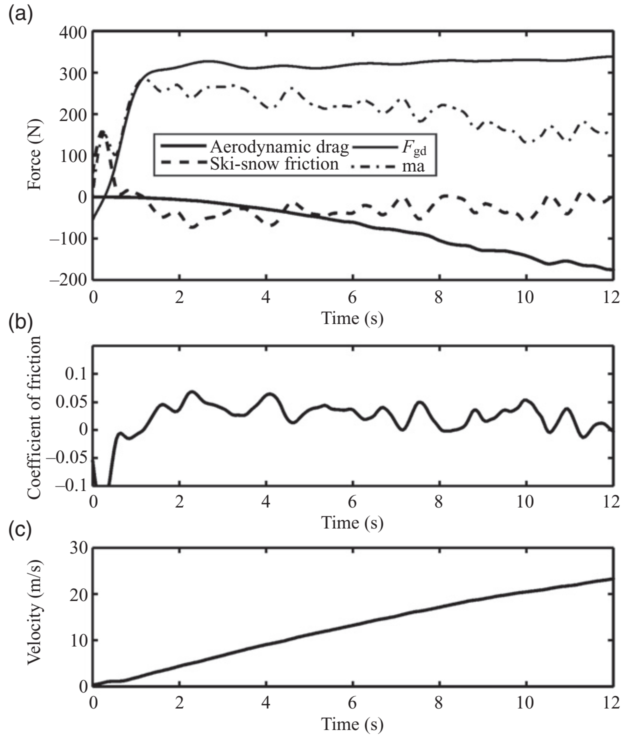

Fig. 7. (a) Aerodynamic drag, ski–snow friction, the dynamic component of gravity (F_{gd}), and the product of the skier's mass times acceleration of the COM (ma) for an individual skier during a straight downhill run in the midposition. (b) illustrates the corresponding coefficient of friction and (c) the velocity of the COM. Note that the behavior during the first second in (a) and (b) is different because the skier started on a flat surface with a slight push-off.

not to vary by more than 15 N, or approximately 8% (an example of this tendency is shown in Fig. 7). The c_f values obtained ranged between 0 and 0.07. Furthermore, simulation of GNSS accuracy by adding white noise of the same amplitude as this measured accuracy to the trajectory determined altered the modeled COM velocity at each point of observation by less than 0.001 m/s and the distance between the shoulders and skis by less than 0.01 m. The position errors in the latitude, longitude, and height during the GS runs indicated by the GNSS system were 5.8 ± 1 mm, 4.5 ± 0.7 mm, and 12.9 ± 2 mm, respectively. Furthermore, 95% of the GNSS data obtained were associated with corresponding position errors of less than 7.8, 5.7, and 17 mm.

Discussion

The major findings of the present investigation were the following: (a) the influence of aerodynamic drag on performance in connection with alpine skiing can be determined by employing a combination of mechanical modeling and experimental measurements; (b) the energy dissipated by aerodynamic drag is a relatively small portion of the total energy lost per turn; and (c) a more pronounced contribution of aerodynamic drag to the total energy dissipation was correlated to better performance by our elite skiers, indicating that reduction of ski–snow friction exerts a more pronounced impact on performance.

Evaluation of the model developed here for estimation of the aerodynamic drag associated with skiing

We validated our present procedure for evaluating aerodynamic drag (F_d) using two different approaches. First, addition of white noise to the data obtained revealed that potential inaccuracies in the measurements made by the GNSS system had a negligible effect on the velocity of the COM and the calculated position of the skier's body, two key parameters involved in the estimation of F_d (see the Materials and methods). Furthermore, calculation of the friction and coefficient of friction associated with the straight downhill runs indicated that these parameters were relatively independent of velocity.

Our model was based on accurate wind tunnel measurements and the correlation between the CdS and shoulder position was extremely strong. However, the positions of the skier's body while actually skiing are not necessarily the same as the positions he assumed in the wind tunnel, which could introduce differences in aerodynamic drag (Barelle et al., 2004). This explains why the friction force decreased slightly with increasing velocity in connection with some of the straight downhill runs (one example is shown in Fig. 7). Accordingly, the accuracy of the estimated F_d would be approximately 8% (an error of 15 N in a total value of 180 N). This accuracy also includes error that may possibly have been introduced by any alteration in the position of the GNSS antenna relative to the skier's body during skiing (which was assumed not to have changed). It can be estimated that a 2-cm movement of the antenna would lead to a 1–2% error in the values obtained employing our model of aerodynamic drag.

Furthermore, the movement of the different parts of the skier's body relative to one another is greater in connection with GS than during straight downhill skiing, which potentially introduces an additional dynamic error that was not unaccounted for here. For example, during rotation around its longitudinal axis, different parts of the body have different relative velocities that change in time. As far as we know, it is not possible to evaluate this dynamic factor when making field measurements. However, it seems likely that for an average turn, a large portion of this unknown error approaches zero since the skier assumes a similar position at the beginning of each turn and even after sudden movements of body parts (e.g., of the arms) end up in the same relative positions rapidly at similar velocities of the COM.

Despite the minor nature of this potential absolute error in F_d, the relative error was not unimportant and therefore the correlations observed here between performance and energy dissipation due to aerodynamic drag should be interpreted with some caution. However, to our knowledge, no presently available technologies allow direct and accurate determination of F_d during skiing. An alternative approach would be to obtain a more accurate estimation of COM and/or body position employing either a three-dimensional camcorder (e.g., Nachbauer et al., 1996) or inertial sensor (Brodie et al., 2008; Krüger & Edelmann-Nusser, 2010; Supej, 2010). In any case, an experimental mechanical model of aerodynamic drag in relationship to the skier's position should be developed and applied. All approaches have their limitations and it is not clear which would be most useful in connection with outdoor racing conditions ranging from sections including several gates to an entire course.

Finally, the fluctuations in the friction and coefficient of friction associated with the straight downhill tests were caused mainly by inaccuracies in the second derivative, that is, acceleration of the COM. This inability of our present procedure to provide a reliable force of friction during turning, when acceleration is part of the equation, constitutes an important limitation that should be addressed in future studies. However, the acceleration of the COM, which was used for estimating the friction, was not included in our present calculation of the aerodynamic drag and energy parameters.

In addition, the positive F_d values observed at the beginning of the straight downhill runs were caused by the skier pushing the ski poles against the snow and are thus artifacts of our modeling. This push-off is necessitated by the ground reaction force and, therefore, the friction between the snow and the skier (ski poles). Furthermore, it can be expected that measurements of velocities close to zero will involve some error, but such velocities only occur at the very beginning of a giant slalom skiing run.

To estimate the aerodynamic drag associated with skiing, we employed the dynamic force torque equilibrium of the inverted pendulum and iterative optimization. Alternatively, this estimation could be achieved by minimization of the cost function $f = (x_p - x_m)^2$, where x_m denotes the measured position of the top of the inverted pendulum; $x_p = F(x_b)$ is the predicted position of the pendulum as a function of the position of the base x_b (which is constrained so as to lie on the terrain); and $F(.)$ denotes the set of dynamic equations that describe the inverted pendulum. Unfortunately, such optimization of our data frequently produced unstable values, so that iterative computation of the quasi-static force equilibrium was more reliable in the present case.

Aerodynamic drag during skiing

Analysis of the skiers' velocities and turning times revealed that the arrangement of the gates and, probably, small changes in slope inclination as well exerted an important influence on skiing (Fig. 4). Furthermore, in section 1, that is, the start of the giant slalom course, the velocity increased, as expected, for each successive turn. Turns made at higher velocities generally demonstrated larger values of F_d (Figs 4(a) and 6(a)), although there were exceptions to this rule (e.g., turn 10 in comparison to turns 9 and 11). This particular exception can be explained by the fact that different body positions are associated with different amounts of aerodynamic drag (Barelle et al., 2004). Determination of F_d during turns (Fig. 5) revealed variations in drag (with either one or two maxima), which can be explained primarily by the use of single and double flexion-extension racing techniques (Supej et al., 2002, 2004), rather than by changes in skiing velocity alone.

Despite the pronounced differences in the skiers' velocities and turning times, the differences in the lengths of their turn trajectories were quite small. This indicates that the procedure used here to define the beginning and end of each turn was appropriate. On the other hand, the lengths of turn trajectories in the three different sections of the course varied greatly. Surprisingly, despite the small differences between the individual skiers, there were also considerable differences between turns in the same section of this course, which reflect both tactical considerations concerning where to start and end the turn, as well as deviations in the setting of the gates.

Our present observations reveal that regardless of the course setting and velocity, the relative contribution of aerodynamic drag to energy loss per turn was approximately 15% (Fig. 6(b)–(c)), suggesting that most of this energy loss can be attributed to ski–snow friction, including nonoptimal guiding of the skis. The values of F_f associated with the straight downhill runs (Fig. 7) should not be confused with the magnitude of F_f during turning, which, according to our present findings, should on the average have been approximately 300 N (or almost sevenfold more than F_d) and exhibited maximal values probably at least twice as high. The conclusion that most of the energy loss can be attributed to F_f receives further support from the correlations between the mechanical parameters observed here (see Table 1). When all turns were analysed together, energy dissipation due to aerodynamic drag (E_d) was poorly correlated to the total energy dissipation (E_t) and, in addition, for most individual turns, this correlation was insignificant. Further support for our conclusion is provided by (a) the lack of correlations between E_d and E_t/v_{in}, since E_t/v_{in} has been shown to be a relevant and decisive measure of sectional performance (Supej et al., 2011); (b) the observation that during turns the average cross-sectional area multiplied by the coefficient of aerodynamic drag (avgCdS) was only infrequently correlated to E_t/v_{in}; and (c) a significant correlation between avgCdS and average turn velocity and turning time in the case of only two turns.

Another indicator that aerodynamic drag is not a decisive factor in connection with giant slalom ski racing are the large negative correlations observed here between the average turn velocity and the E_d, in combination with large positive correlations between the average velocity and relative energy dissipation from aerodynamic drag (E_d/E_t) per turn. As expected, higher velocity was associated with higher F_d. On the other hand, the large positive correlations between E_t/v_{in} and E_d/E_t, as well as the large negative correlations between time and E_d/E_t demonstrated that the better the performance, the larger the portion of total energy dissipation due to aerodynamic drag. Our interpretation of these data is that improving performance involves reducing energy dissipation from sources other than aerodynamic drag, that is, decreasing energy loss due to ski–snow friction.

The observations made on section 2 (where the distance between gates was shorter and/or the angle between gates sharper) deserve special notice. Except in the case of the last turn in this section, which appears to be tactically related to the beginning of section 3, neither E_d nor E_d/E_t demonstrated any significant correlation to any of the parameters documented in Table 1. This finding indicates that on such tighter sections of a course, where more skidding occurs, energy dissipation due to aerodynamic drag is even less important.

In summary, we have developed here an individualized mechanical model for estimating aerodynamic drag during alpine skiing and evaluated the influence of energy dissipation caused by such drag on performance during giant slalom skiing through a series of gates. On the basis of our present findings, we conclude that only a relatively small amount of total energy dissipation in this context is caused by aerodynamic drag, implying that most energy loss is due to ski–snow fiction (which includes guiding of the skis). This investigation provides the basis for future attempts to determine which skiing technique might result in optimal performance sections of a course where the velocity is higher.

Perspectives

For sports in which aerodynamic drag and friction are two major causes of energy dissipation, it is necessary to understand their relative contribution. Our present approach allows estimation of aerodynamic drag during alpine skiing over an entire course, rather than under laboratory conditions. Our findings indicate that giant slalom skiers should focus primarily on optimizing their technique to improve the guiding of their skis (i.e., to reduce ski–snow friction), rather than attempting to reduce aerodynamic drag. In addition, for many sports, the relative importance of aerodynamic drag and friction varies under different conditions and with time, for example, in connection with alpine and cross-country skiing, where ski–snow friction is influenced by the snow conditions (Buhl et al., 2001) and aerodynamic drag changes with body position and velocity (Barelle et al., 2004). In such cases, evaluation of these two factors under different conditions will provide a deeper understanding of the determinants of performance, thereby helping to improve racing techniques and optimize racing equipment. Our new approach enables measurements under realistic conditions, can provide rapid feedback to athletes following initial measurements in a wind tunnel, and consequently, can aid the efforts of coaches to enhance the performance of their athletes.

Key words: alpine skiing, force, GPS, Global Navigation Satellite System, mechanics, ski racing, wind tunnel.

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