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Original research

Towards more valid simulations of slopestyle and big air jumps: Aerodynamics during in-run and flight phase

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ABSTRACT

Objectives: This study aimed to investigate air drag and lift during the in-run and flight phase of ski and snowboard slopestyle and big air, to allow more valid modeling of jumps and hence reduce injury risk.
Design: We present an experimental, multiple single athlete study based on wind tunnel measurements of 4 skiers and 3 snowboarders.
Methods: Measurements were carried out in a closed loop wind tunnel, measuring airflow speed and 3D forces acting on the athletes. Athletes performed trials in typical postures at 35, 60 and 85 km/h wearing slim-, regular- and wide fit apparel. Drag and lift area (c_DA; c_LA) were calculated and analyzed using linear and multiple regression to describe their dependencies on posture, apparel and speed.
Results: c_DA values were higher than earlier assumed and ranged from 0.3 to 0.95 m^2 for skiers and from 0.35 to 0.55 m^2 for snowboarders, primarily dominated by posture, and followed by apparel. c_LA ranged from -0.1 to 0.45 m^2 for skiers and from 0.04 to 0.17 m^2 for snowboarders. To facilitate more valid jump modeling posture- and apparel-dependent formulations for air drag coefficients were provided and the consequences of sport specific differences on modeling were highlighted.
Conclusions: Applying the air drag coefficients and relationships determined in this study will help to improve validity of jump modeling in big air and slopestyle. The variability in aerodynamic forces in slopestyle and big air is caused by differences between sports, posture and apparel.

Practical implications

- The presented data and models will help to improve jump design and thus prevent injuries.
- Skiers' capacity to compensate for low speed with changes in body posture and drag area is much larger than for snowboarders.
- Course builders should take care of the snowboarders' limited ability to compensate for low in-run speed in jump design.
- Athletes and coaches should be aware, that body posture and apparel can strongly influence take-off speeds.

1. Introduction

Ski and snowboard (SNB) slopestyle and big air (BA) are young but rapidly developing winter sports with high injury rates.[1–5] Jumps are considered a key injury risk factor.[6–8] Jump modeling was suggested as a method to help course builders to validate and improve jump design and enhance jump safety.[9–18] The principles of jump kinematics and kinetics are well established. Angle and speed of the center of mass trajectory at take-off, air drag and lift during the flight phase, and the shape of the landing are the initial determinants of jump length, height and impact. Take-off speed is regulated by the shape of the in-run, which determines the energy to accelerate the athlete by gravity, and the braking forces of snow friction and air drag.[19] Finally, athletes have a last chance to modify their trajectory by absorbing or pushing on his leg ('pop'), just before take-off.[20] In competitive alpine skiing, the relative contributions to energy dissipation from air drag and snow friction have been determined. The distribution is 23% for air drag and 77% for snow friction in giant slalom, and reaches 51% for air drag and 49% for snow friction in downhill.[21] Such information is entirely lacking for ski and snowboard slopestyle and BA, resulting in

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considerable uncertainties when modeling the take-off speed. Hence, to date, park designers have to rely on their experience when building in-runs for jumps. To improve the validity of jump modeling, realistic values for snow friction and air drag need to be established. This study aimed to establish realistic air drag and lift force values for BA and slopestyle ski and snowboard, to improve the validity of computer simulations of jumps in these sports. Air drag and lift are dependent on air properties, ambient wind, athlete speed, and the athlete's body posture and apparel.[22–27] Apparel and body posture are the factors athletes can influence to regulate take-off speed during the in-run. To date, air drag values have to be estimated from values available for other winter sports such as alpine skiing, where clothing and body posture and hence air drag are very different.[28,29] Therefore, the aim of this study was to measure typical mean values and the range of air drag and lift for elite level athletes in ski and snowboard, slopestyle and BA, as a function of the athletes' posture, apparel, speed and anthropometrics, using wind tunnel testing for postures typical for both the in-run and the airborne phase.

2. Methods

Wind tunnel measurements were carried out in an atmospheric closed loop wind tunnel with a closed test section of 7.5×11 m, at RUAG Aerospace Center at Emmen, Switzerland.[30] Four male athletes (37, 34, 32, 37 years; 90.2, 74.2, 90.3, 71.6 kg; 182, 184, 191, 175 cm) participated in the study and were labeled as athletes A to D. Their anthropometry was quantified by their body surface (A_b), calculated from body height and weight according to Boyd et al.[31]

To investigate drag and lift forces during ski and snowboard *slopestyle in-runs*, four *skiers* (A to D) and three *snowboarders* (A, C and D) performed two trials each with three typical in-run postures at 35, 60 and 85 km/h, wearing regular fit snow sports apparel. Three *typical postures* (Fig. 1) were chosen to capture the whole range of realistic in-run postures in ski and snowboard. For skiing, the postures were as follows. 1) In the low posture the athlete had fully flexed knees with the arms wrapped around the thighs. 2) In the mid posture athletes held their knees with straight arms and an extended upper body. 3) In

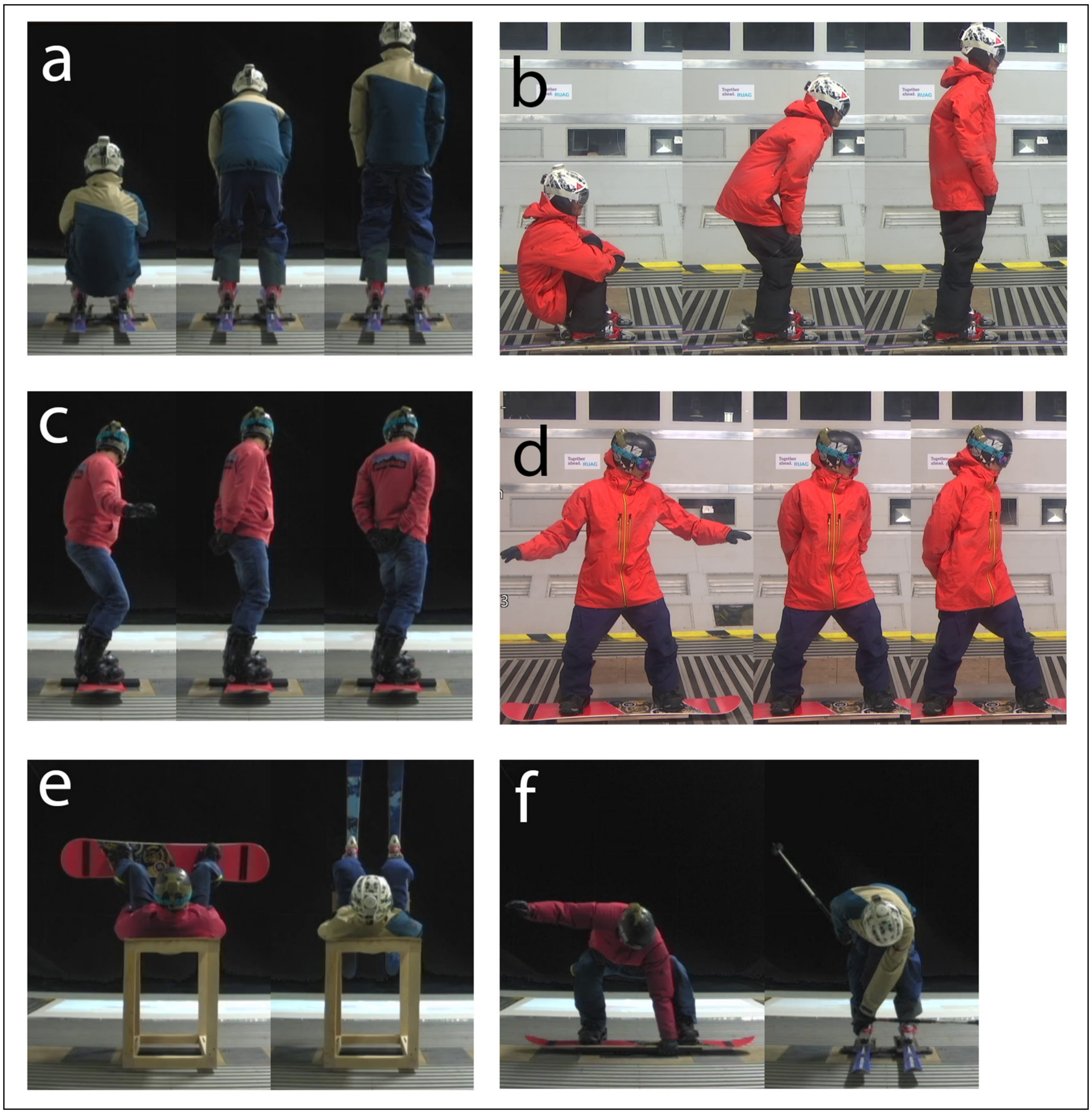

Fig. 1. a–b) Skier B in low (left), mid and extended (right) in-run posture wearing regular (a) and wide-fit (b) apparel. c-d) Snowboarder D in mid (left), extended and extended rotated (right) posture wearing slim (c) and wide-fit (d) apparel. e) Airborne postures measuring drag area at vertical inflow hitting the snowboard/ski from below. f) Left: Snowboarder D wearing regular apparel performing a mute grab with inflow direction from behind (rotated 90°). Right: Skier B performing a mute grab with inflow direction from behind (rotated 180°).

the high posture athletes stood upright with slight flexion of the knees and the hips, with arms held straight along the upper body. For snowboarding, we tested 1) a typical riding posture, characterized by considerable knee flexion, slight elbow flexion and upper arm abduction; 2) an upright posture with the trunk held parallel to the transverse axis; and 3) an upright posture with the trunk rotated 50° to 80° in the riding direction. For both upright postures, the arms were held crossed on the back. The postures were further quantified by the extension height h_{ext}, defined as the vertical distance between the ski boot sole and the antenna mounted on the athletes' helmet (taken from side view). We found that h_{ext} was an inadequate descriptor of typical postures in snowboarding. We therefore introduced an ordinal scaled posture number ($n_{pos} = 1; 2; 3$ for mid, extended and extended rotated).

To investigate the influence of *different apparel* on the aerodynamic forces, skiers B and C and snowboarder D performed additional trials wearing slim-fit and wide-fit apparel. To provide apparel fitting categories that had practical relevance and were easy to apply, we introduced an ordinal scaled apparel fit number (n_{fit}) as follows: extra slim (1, race suit); slim (2, regular jeans and sweatshirt); regular (3, regular ski/SNB apparel); wide (4, oversized ski/SNB apparel); and extra wide (5, double oversized ski/SNB apparel). The difference between extra-large sized apparel and the athlete's regular size was used to distinguish between wide (skier B, D) and extra-wide fits (snowboarder D). The regular sizes were deduced from the athletes' chest and waist girth (A to D: 1.05/0.95 m, 0.95/0.815 m, 1.04/0.98 m, 0.955/0.815 m), based on the European norm 13,402–2:2002 for "Size designation of clothes" (A and C size large; B and D size medium).

Additional trials at 60 km/h were performed to investigate lift and drag in an *airborne-like position*, holding the skis/snowboard under inflow directions between 0° and 180° (Fig. 1f). To quantify drag forces in the late flight phase, when the vertical airflow component increases, another test trial was made, rotating the athletes' vertical axis into the horizontal direction, so that the airflow hit the skier/snowboarder from below (Fig. 1e).

For each trial drag force F_D, lift force F_L, dynamic pressure q, airflow speed v and air density ρ, were measured at 0.5 Hz during 20 s. The sensor accuracy was ±0.01 N for the forces and ± 0.01 Pa for the pressure. Drag area (c_DA) and lift area (c_LA) were calculated.

$$c_LA = F_L/q \qquad \text{with } q = 0.5 * \rho * v^2 \tag{1}$$

$$c_DA = F_D/q \tag{2}$$

The dependencies of c_DA and c_LA on posture and speed were analyzed for the regular apparel trials for skiers and snowboarders, using least squares first or second order regression. One-parameter models of the dominant variable were provided as a first approximation of the aerodynamic coefficients. Mean (±σ) c_DA and c_LA values were calculated for each posture. The means of the different postures were then compared by their relative differences to quantify the impact of posture on c_DA within the group of snowboarders and skiers. Beyond that, the dependencies of c_DA on the full set of explanatory variables (posture, apparel and speed) were analyzed separately for those athletes who conducted both posture and apparel tests, using multiple least squares linear regression. The ordered categorical variables n_{fit} and n_{pos} were implemented to the regression models using two indicator variables each (X_{p1}, X_{p2}; X_{f1}, X_{f2}) to represent the three tested posture and fit categories.[32,33] Mean (±σ) c_DA values were calculated for each posture and athlete, and were compared using relative differences. For all regression models, adjusted coefficients of determination (R^2_{adj}) and slopes of regression (m) were stated (partly in supplementary materials) if significant ($p \le 0.001$) to quantify the strength and relevance of those relationships. The uncertainties of the regression coefficients, as well as model outputs, were given by their 95% confidence intervals (±CI/2), partly as supplementary material (Table A5).

3. Results

For the skiers, change in *body posture* had the largest impact on c_DA. Posture-induced c_DA changes deviated from the mid posture by −41 ± 5% for the tuck posture to +36 ± 5% for the extended posture (Fig. 2; Table A1). For snowboarders, changes in posture influenced c_DA less but were still a main influence factor: c_DA deviated from the extended posture by −6 ± 2% for the mid posture to +15 ± 8% for the extended rotated posture (Fig. 2b; Table A1). We did not find a significant *influence of speed* on c_DA for ski and snowboard on the group level. For skiers and snowboarders wearing the most commonly used type of apparel (regular fit) Eqs. (3) and (4) were set up to calculate drag area as a function of body posture (h_{ext} for ski and n_{pos} for snowboard):

$$c_DA_{SKI} = -0.137 + 0.491 * h_{ext} \text{ for } 0.89\text{ m} \le h_{ext} \le 2.00\text{ m}; \left(R^2{}_{adj} = 0.91\right) \tag{3}$$

$$c_DA_{SNB} = 0.0466 - 0.027 * X_{p1} + 0.070 * X_{p2}$$
$$X_{p1} = \begin{cases} 1 \text{ if } n_{pos} = 1 \\ 0 \text{ if } n_{pos} > 1 \end{cases} X_{p2} = \begin{cases} 1 \text{ if } n_{pos} = 3 \\ 0 \text{ if } n_{pos} < 3 \end{cases} \text{for } \; n_{pos} = [1;2;3]; \; \left(R^2_{adj} = 0.53\right) \tag{4}$$

During the in-run, athletes commonly use the mid posture. Hence, to model the typical development of an athlete's in-run speed, Eqs. (3) and (4) propose drag areas of 0.634 ± 0.035 m^2 for skiers and 0.439 ± 0.014 m^2 for snowboarders, using an average mid posture as equation input ($h_{ext\_mid\_mean} = 1.571 \pm 0.072$; $n_{pos} = 1$).

Aerodynamic lift was measured to provide also data to model the snow friction force during the in-run revealing mean c_LAs of 0.319 ± 0.038 m^2 for the skiers and 0.081 ± 0.008 m^2 for the snowboarders, both in mid posture wearing regular clothes (Table A2). Posture influenced the c_LA strongly for the skiers ($R^2_{adj} = 0.80$), but only slightly for snowboarders ($R^2_{adj} = 0.37$) (see regression models and scatter plots in Table A5 and Fig. A1). For skiers, the c_LA peaked in mid posture when the airflow hit the inclined upper body.

Individual deviations from the generalized posture-dependent drag and lift models can be caused by *anthropometric differences*, deviations caused by *apparel of different fit* or by *individual speed dependencies* of the athletes' c_DAs (Fig. 3). The contribution of *apparel* to c_DA was analyzed for two skiers and one snowboarder. In all postures, apparel affected the c_DA of the tested skiers, but to a lesser extent than posture did (Table A3). The largest effects of apparel, averaged over all speeds, occurred in the mid posture, where c_DA changed from slim to wide apparel by −9% to +21% for skier B, and by −14% to +13% for skier C (Fig. 2a; Table A1). For snowboarder D, apparel changed c_DA by approximately the same amount as posture, inducing c_DA changes in the most common mid posture from −8% to +15% (Fig. 2b; Table A1). Applying individual two-parameter models including *apparel* in addition to the *body posture* (Eqs. (5) to (7)) increased the explanatory power distinctively ($0.05 \le \Delta R^2_{adj} \le 0.35$; Table A3), which confirmed the importance to consider apparel fit when estimating c_DAs of BA or SS athletes. In contrast, adding speed as third explanatory variable, did not improve the models remarkably ($\Delta R^2_{adj} \le 0.01$). Therefore, speed was not retained as regressor of the individual c_DA models.

$$c_DA_{SKI_B} = -0.142 + 0.461 * h_{ext} - 0.043 * X_{f1} + 0.098 * X_{f2} \; \left(R^2_{adj} = 0.96\right)$$
$$X_{f1} = \begin{cases} 1 \text{ if } n_{fit} = 2 \\ 0 \text{ if } n_{fit} > 2 \end{cases} X_{f2} = \begin{cases} 1 \text{ if } n_{fit} = 5 \quad n_{fit} = [2;3;5] \\ 0 \text{ if } n_{fit} < 5 \quad 0.95\text{ m} \le h_{ext} \le 2.00\text{ m} \end{cases} \tag{5}$$

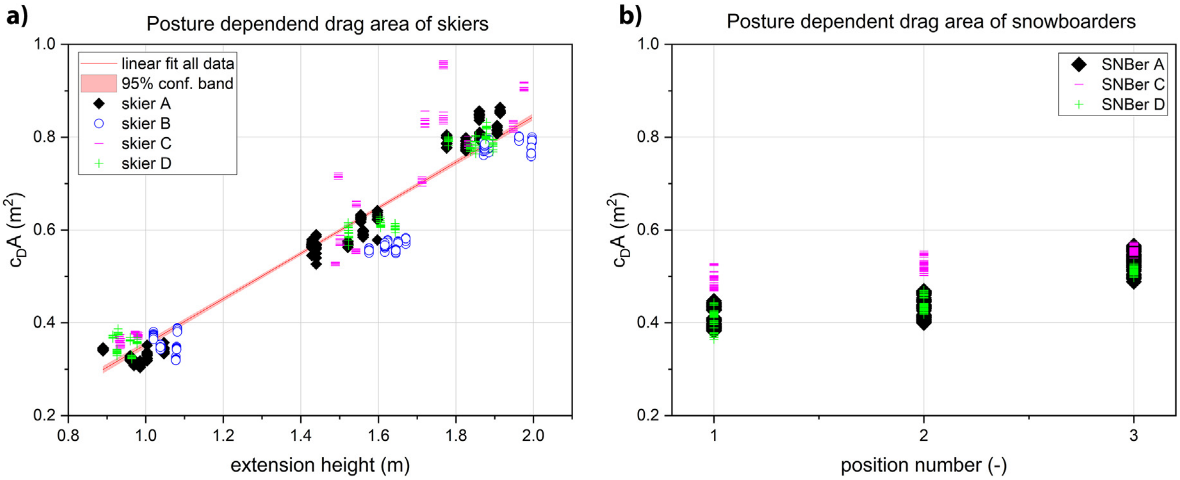

Fig. 2. Measured drag areas and extension heights ($n = 720$) of four skiers wearing regular apparel in low, mid and extended postures at speeds of 35, 60 and 85 km/h. b) Measured drag areas (n = 720) of three snowboarders wearing regular apparel in mid ($n_{pos} = 1$), extended ($n_{pos} = 2$) and extended rotated ($n_{pos} = 3$) postures at speeds of 35, 60 and 85 km/h.

$$c_DA_{SKI_C} = -0.141 + 0.523 * h_{ext} - 0.114 * X_{f1} - 0.012 * X_{f2} \quad \left(R^2_{adj} = 0.91\right)$$
$$X_{f1} = \begin{cases} 1 \text{ if } n_{fit} = 2 \\ 0 \text{ if } n_{fit} > 2 \end{cases} \quad X_{f2} = \begin{cases} 1 \text{ if } n_{fit} = 4 \\ 0 \text{ if } n_{fit} < 4 \end{cases} \quad \begin{matrix} n_{fit} = [2;3;4] \\ 0.93\text{ m} \le h_{ext} \le 1.98\text{ m} \end{matrix} \tag{6}$$

$$c_DA_{SNB_D} = 0.410 + 0.031 * X_{p1} + 0.103 * X_{p2} - 0.028 * X_{f1} + 0.062 * X_{f2} \quad \left(R^2_{adj} = 0.94\right)$$
$$X_{f1} = \begin{cases} 1 \text{ if } n_{fit} = 2 \\ 0 \text{ if } n_{fit} > 2 \end{cases} \quad X_{f2} = \begin{cases} 1 \text{ if } n_{fit} = 5 \\ 0 \text{ if } n_{fit} < 5 \end{cases} \quad n_{fit} = [2;3;5]$$
$$X_{p1} = \begin{cases} 1 \text{ if } n_{pos} = 1 \\ 0 \text{ if } n_{pos} > 1 \end{cases} \quad X_{p2} = \begin{cases} 1 \text{ if } n_{pos} = 3 \\ 0 \text{ if } n_{pos} < 3 \end{cases} \quad n_{pos} = [1;2;3] \tag{7}$$

The contribution of *anthropometric differences* was relatively small for the skiers with c_DA variations of up to 10% between athlete A and C in mid and extended posture, but considerably for the snowboarders with up to 21% deviation between A and C in mid posture (Table A1).

In contrast to the group level, significant *speed dependencies* were found for individual athletes (Table A4). Among the skiers, negative speed dependencies existed only for the larger athletes A and C in mid and high postures. For skier C, wearing wide fit apparel, a maximal c_DA variation was found from +15% to −13% over the tested speed range (referred to c_DA average over all speeds). This correlation disappeared wearing slim fit apparel. A slightly positive relationship between c_DA and speed was observed in low postures for all skiers, which was only significant for athlete B and D causing maximal c_DA variations from −5% to 7% (B, regular). For all tested snowboarders, a slight positive speed dependency was found for mid and extended postures causing maximal c_DA variations from −6% to 5% (D, regular), which weakened or disappeared when an upright rotated posture was adopted (Fig. 3b; Table A4).

In summary, the c_DA of skiers were dominated primarily by posture (77% c_DA variation), followed by apparel (30%), speed (28%) and individual differences (10%) (Fig. 2a). For snowboarders, posture (21%), apparel (23%), and individual differences (21%) influenced c_DA to a comparable extent, whereas speed (11%) had a smaller impact (Fig. 2b).

Drag areas for typical *airborne postures*, performing a mute grab at inflow directions of zero, 90 and 180° were 0.379 ± 0.005 m^2, 0.567 ± 0.010 m^2, and 0.382 ± 0.005 m^2 for skier B and 0.325 ± 0.013 m^2, 0.453 ± 0.014 m^2, and 0.419 ± 0.009 m^2 for snowboarder D. Corresponding lift areas were 0.104 ± 0.011 m^2, 0.134 ± 0.018 m^2, and 0.044 ± 0.004 m^2 for skier B and 0.008 ± 0.019 m^2, 0.057 ± 0.014 m^2, and 0.040 ± 0.014 m^2 for snowboarder D. The drag areas due to *vertical inflow* were 0.412 ± 0.071 m^2 for skier B and 0.635 ± 0.004 m^2 for snowboarder D.

4. Discussion

To our knowledge, this study is the first to analyze air drag and lift in snowboard. Until now, modeling of BA and slopestyle jumps were performed using *c_DA values from alpine skiing*. This study showed that c_DA issued from alpine skiing studies (ranging from 0.25 to 0.5 m^2 for giant slalom,[34] and 0.15 m^2 for downhill discipline[35]) underestimated the true c_DA for BA and slopestyle.

Due to the current lack of any comparable data and the fact that regular apparel is most frequently worn during elite level competitions[36] (observations of 163 athletes at FIS World Cup at Seiser Alm 2018; Fig. A2), we are convinced that the models derived in this study provide a useful contribution to *improve the understanding and modeling of in-run mechanics* in slopestyle and BA. For skiers and snowboarders, wearing regular fit apparel, posture-dependent formulations were deduced for c_DA and c_LA. The speed dependency of c_DA was largely significant in the individual models, but not consistent in direction, and had smaller effect than apparel and posture. For skiers in mid and extended posture the c_DA was mostly negatively related with speed, which corresponds to findings on alpine skiers,[37] whereas for snowboarders all significant relations of c_DA with speed, were positive. This discrepancy might be caused by the different inflow (frontal vs. lateral) affecting the Reynolds Number range or slight changes of posture at higher speeds.[37] As speed effects were small compared to the other factors influencing c_DA in the in-run, these were neglected in our model.[15,19] We suggest that course builders use the posture-dependent models (Eqs. (3), (4), A1 and A2) to simulate an average in-run, and the individual, apparel and posture-dependent data (Fig. 3, Tables A1 & A2) as estimates for extreme aerodynamic coefficients. Course builders need to build jumps that allow for a certain range of speed at take-off, with a critical lower limit of take-off speed. However, this lower limit is not sharp, since it changes with external conditions and user groups. Therefore, a certain range is needed to compensate for headwind, snow conditions and differences in mass between sexes and snow friction between snowboards and skis. If in-run speed is at the low end, athletes have some capacity to compensate for this by pushing off at the start and reducing air drag by choosing a low posture during the in-run. This study shows that the capacity to compensate for limited speed in the in-run is substantially smaller for snowboarders than for skiers as the range of c_DA for realistic postures is about tripled for skiers compared to snowboarders and minimum c_DAs of skiers are approximately 0.1 m^2 smaller than of snowboarders. The reason for this difference may be that snowboarders' balance setting allows them to manipulate h_{ext} only in a small range compared to skiers. In addition, squatting does not lead to overlapping of body segments, and consequently does not

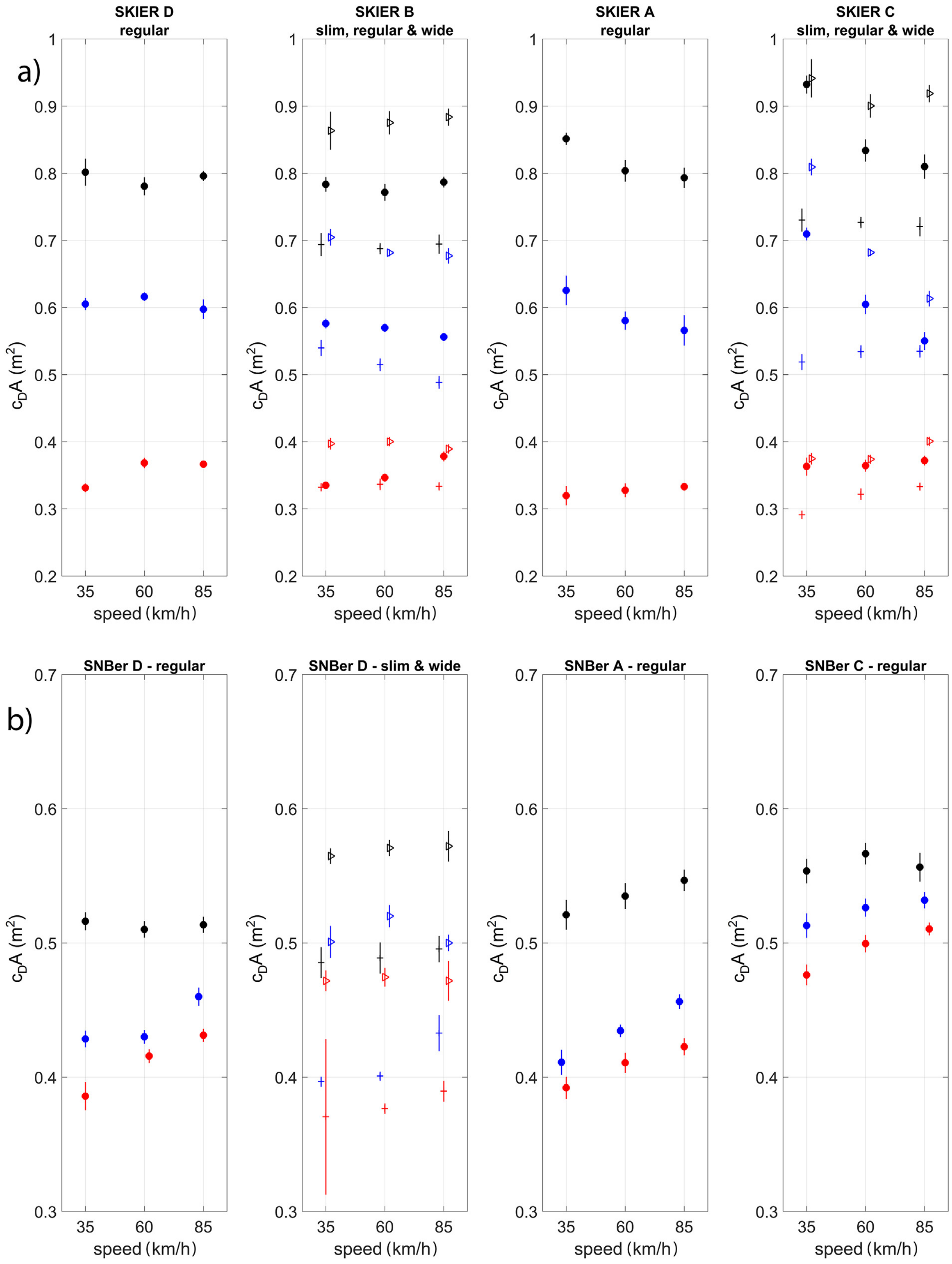

Fig. 3. a) Mean c_DA values ($\pm 2\sigma$) of one (wide/slim fit) or two trials (regular fit) for skiers A to D for low (red), mid (blue) and extended posture (black) with regular (circle), slim (bar) and wide fit (triangle) apparel. b) Mean c_DA values ($\pm 2\sigma$) of one (wide/slim fit) or two trials (regular fit) for snowboarders A, C and D for mid (red), extended (blue) and extended rotated (black) posture with regular (circle), slim (bar) and wide fit (triangle) apparel. Note the differently scaled y-axes for skiers and snowboarders.

affect the frontal area as it does in skiing. However, snowboarders should be aware that upper body orientation has a strong influence on the c_DA, and can be used to reduce air drag when speed is critical. As more and more high-level competitions are held using the same course for males and females, ski and snowboard course construction should pay particular attention to snowboarders' limited ability to compensate for head winds and elevated snow friction using alterations in body posture. However, this study also shows that athletes can substantially reduce air drag with their choice of apparel, if take-off speed is critical: Wearing wide fit apparel compared to slim fit increased c_DA as much as changing from the mid to the extended posture for skiers and changing to the extended rotated posture for snowboarders (Fig. 2).

For modeling of the flight phase, this study contributed the first values for drag and lift. For compact posture holding a grab, we recommend using rounded averages over all tested inflow directions for c_DA and c_LA of 0.44 m^2 and 0.09 m^2 for skiers, and 0.40 m^2 and 0.04 m^2 for snowboarders. Although the results show distinct differences depending on the inflow direction, we consider averaging from 0° to 180° is reasonable, as athletes mostly aim to rotate full numbers of semi twists.

The limitations of the test design included the small number of athletes, the lack of small and female athletes as well as a rather rough quantification of the apparel fit. The number and choice of athletes was constrained by the financial means for wind tunnel testing and the fact, that the athletes tested in the wind tunnel were included in a second study on snow friction, where the individual air drag values from wind tunnel testing were applied to distinguish air drag and snow friction for these athletes. Although the tested athletes did not represent the overall population of slopestyle and BA athletes, the test efficiency was kept as high as possible within the study's financial limits.

5. Conclusion

This study presented for the first time a data set that describes the aerodynamic coefficients for slopestyle and BA athletes. The presented models allow the calculation of aerodynamic coefficients as a function of the main influencing factors posture and apparel. The models and data allow the estimation of typical air drag values including the upper and lower limits and differences between snowboarders and skiers, and can hence be applied to improve the validity of jump simulations.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsams.2021.05.005.

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Declaration of interest statement

The authors have no conflict of interest to report.

Confirmation of ethical compliance

The study was approved by the ethics committee at the Norwegian School of Sport Sciences, and the Norwegian Centre for Research Data, and conducted according to the Declaration of Helsinki. All subjects gave their written informed consent prior to participation.

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