applied sciences

MDPI

Article

Progress in Ski Jumping Technology Based on Biomechanical Sport Research Methods

Yuan Li [1,2,3], Lijuan Liu [1], Lili Xing [1], Jianzhong Chai [1] and Dong Sun [4,*]

[1] Hebei Institute of Sport Science, Shijiazhuang 050013, China; ly526628@126.com (Y.L.); ccliulijuan@163.com (L.L.); lilybd_2008@aliyun.com.cn (L.X.); 17732830523@163.com (J.C.)
[2] Hebei Key Laboratory of Neuromuscular Function and Strength Training, Shijiazhuang 050013, China
[3] Key Laboratory of Training Load Diagnosis and Regulation for Elite Athletes, Hebei Institute of Sports Science, General Administration of Sport, Shijiazhuang 050013, China
[4] Faculty of Sports Science, Ningbo University, Ningbo 315211, China
* Correspondence: sundong@nbu.edu.cn; Tel.: +86-574-87600208

Abstract: (1) Background: Previous studies have compared research into ski jumping in different motor processes, but there is a lack of comparative analysis of the biomechanical research methods used to investigate different ski jumping sports. (2) Content: Our study compared the advantages and disadvantages of six research methods and proposes future research directions. Motion video collection and analysis show that controlling angular momentum and achieving stable flight attitude in the take-off process are the most critical factors in ski jumping performance. Most research on force platforms focuses on dynamic performance at the time of take-off, but there are few training sites with an embedded force platform, and so, more empirical research is required. Wearable inertial measurement units, including gyroscopes and accelerometers, can be used to determine a series of forces, calculate the joint angle, and speculate the position of the centroid during motion. Surface EMG studies are primarily used to compare the activity characteristics of the lower limb muscles in the actual field of the jump, the exercise simulation, and the lack of complete training process data. Wind tunnel measurement can satisfy fluid mechanics simulation experiments and provide theoretical support for optimizing special ski jumping technology. Based on the theory of computational fluid dynamics, the optimal drag reduction posture data of ski jumpers can be derived using computer simulations. (3) Conclusions: Due to the wide range of ski jumping sports, the present research focused on the kinematics and dynamics of different movement stages, lacking the study of the complete exercise training process. The range of wearable inertial measurement and sensor equipment can cover the whole process of ski jumping, including kinematics and dynamics data, and is a feasible and reliable test method for monitoring ski jump training in natural environments. The simultaneous testing of surface electromyography, kinematics, and dynamics requires further exploration. (4) Future direction of development: Under computational fluid dynamics, wearable inertial measurement units and global navigation satellite systems (GNSSs), intelligent wind tunnel experimental training areas will become essential tools for ski jumping research.

Keywords: ski jumping; attitude; aerodynamics; take-off forces; wind tunnel

check for updates

Citation: Li, Y.; Liu, L.; Xing, L.; Chai, J.; Sun, D. Progress in Ski Jumping Technology Based on Biomechanical Sport Research Methods. *Appl. Sci.* **2024**, *14*, 2281. https://doi.org/10.3390/app14062281

Academic Editors: Mark King and Arkady Voloshin

Received: 9 January 2024
Revised: 23 February 2024
Accepted: 28 February 2024
Published: 8 March 2024

1. Introduction

Ski jumping is a technical event, and the accuracy and fluency of technical movements are crucial to performance in the sport [1]. The flight distance score determines the sports performance of ski jumping, the attitude score given by the referee, the departure gate score, and the wind compensation score [2,3]. The flight distance carries information about the departure gate and wind speed. Athletes who fly farther tend to have higher attitude scores. According to the kinematic characteristics, flight distance is usually divided into four stages: in-run, take-off, flight, and landing [4,5]. The flying distance of ski jumping is underpinned by the weight of the athlete, aerodynamic forces during flight, and the initial flight velocity after take-off [6].

The kinematics and dynamics data of the exercise process are essential to understanding the final results of ski jumping. The present study aims to obtain the kinematic and biomechanical expression characteristics of each stage of ski jumping. Ski jumping technology has rapidly developed in terms of flight technology and training quality [5]. Since the 1920s, scholars from various countries, including Norway, Austria, Germany, and Japan, have measured and studied sports performance [2]. The corresponding theoretical research results have also increased. In particular, the long-term research on ski jumping by scholars such as Muller of Austria [1,7–9], Virmavirta of Finland [10–17], and Seo of Japan has led to rich theoretical achievements [18–22].

The body posture of ski jumpers significantly impacts their flight distance. Thus, the kinematic characteristics of ski jumpers have been extensively studied in the field of sports biomechanics [5,23,24]. Some studies have shown that vertical CoM take-off velocity contributes to ski jumping distance [11,25]. Other studies have identified that not only the vertical CoM take-off velocity but also other parameters, such as the knee extension velocity and the angle between the body longitudinal axis and the ski after 20 m of the flight phase, are strongly correlated with the length of the jump [15,26,27]. The most significant correlation with flight distance in the flight phase was found in the angle between the skis and the body [15]. Certain scholars have asserted that the angle of attack of the ski dominates the optimal lift-to-drag ratio [28–30]. The research above serves as the foundation for imitation jumps during daily training. Various imitation jumps aiming to mimic the kinematic pattern of hill jumps appropriately are performed during daily training [5,31]. Some studies have suggested considerable differences between the take-off during hill jumps and imitation jumps [13,32]. However, Jakob Ketterer identified an imitation jump type that is not statistically different from the hill jump [5].

Using computer simulations, Remizov developed an optimal flight control model for H-style ski jumping, and presented the optimal time history for the angle of attack to maximize flight distance [33]. Schwameder H. attempted to determine the most favorable body attitude in flight using flight trajectory calculation and wind tunnel measurement [24]. Lin Zhang used computational fluid dynamics (CFD) methods to suggest that the optimal ski attitude is an angle of attack, yaw angle, and roll angle equal to 30°, 20°, and 0°, respectively [6].

Compared to past studies, current research methods are more complex, precise, and extensive. However, because of the wide range of movement involved in ski jumping—the horizontal distance and horizontal drop of about 100 m, coupled with the different environments of each ski jumping venue—it is difficult to conduct measurements in this field, leading to there being relatively few research results on ski jumping. Methods of measuring and providing feedback on the whole motion process in real time are urgently needed in this area.

Previous studies mainly analyzed the progress of research into various aspects of sports biomechanics in each ski jumping stage. This study took different research methods as the starting point, comprehensively analyzed the pros and cons of six research methods, and summarized the drawbacks of current ski jumping research and the direction of future research.

2. Progress of Different Research Methods

2.1. Motion Video Capture and Analysis

Motion video capture and analysis is one of the most essential research methods used to study ski jumping, which is mainly used for kinematic data analysis, including analyzing and describing the attitude of athletes and the speed and component of the centroid, and constructing the trajectory of the centroid. It can also push back the air force on athletes [34,35]. This method has made significant contributions to descriptions of attitude sequence diagrams of ski jumping and analyses of the critical parameters of flight posture. Some generally accepted conclusions have been obtained; for example, controlling angular momentum during take-off and achieving a stable flight attitude as soon as possible are the most critical factors in ski jumping performance. The angle between the body and the snowboard and the angle of attack are two key parameters that affect flight distance, and the attitude angle has a more significant influence on the flight distance than the ballistics data of the centroid [33,36].

Motion video capture and analysis can be used in mountain training and competitions, wind tunnels, simulation training, laboratory settings, and other settings. It will not affect subjects' sports performance. However, because ski jumping shows great variations in both longitudinal and radial dimensions and the conditions of each mountain are different, the attitude characteristics of different stages will also differ. A general video capture and analysis scheme for each site still needs to be established. Although three-dimensional cameras are often used, most studies' research objects and result descriptions are frequently provided in the form of two-dimensional image data.

In existing research, video capture schemes usually focus on a particular movement stage, including the take-off stage, early flight stage, or stable flight stage, but there are few studies on gliding and landing; there is only one example of image analysis covering the whole process. Arndt [25] used a high-speed camera and image analysis to analyze the K90 individual platform jumping technique in the 1994 Winter Olympics. The center-of-mass velocity and position of the centroid during the take-off and early flight stages were analyzed in order to study flight attitude (joint angle, relative horizontal position angle of each part of the body, angle of attack, snowboard V angle), 10 other angle parameters, and flight distance. Schmolzer used 11 cameras distributed along the flight slope from the start of the take-off slope to the 97-meter position in field measurement research on the K120 jumping platform used in the 2002 Winter Olympics; the distance between each camera and the athletes differed according to the terrain of the mountain, and the body attitude angle and snowboard attack angle during the flight were also recorded. This research also used a high-speed camera to study the take-off process [37]. In the same competition, another team, Virmavirta et al., set up two frame-synchronized high-speed cameras (HSC-200) at a frequency of 200 frames per second to capture the process of all jumpers from take-off to the end of their early flight. The field of view covered approximately one-third of the longest flight distance [15]. Virmavirta's group conducted a series of studies on ski jumping in the five Winter Olympics that occurred from 1988 to 2006. The primary method used was video collection, combined with other methods according to the purpose, to successively study take-off and early flight [10–13,16]. Januar et al. used a fixed camera to shoot video of the first straight stage of 656 players in the 1992–2001 World Cup held in Austria and analyzed the changes in the angles of knees, ankles, and torsos [38]. Nardello's group suggested that skiers focus on achieving a more considerable in-run speed to maximize performance in this discipline; none of the angular parameters correlated with flight distance [39]. Elfmark et al. used a differential global navigation satellite system (GNSS) to measure the difference between elite ski jumpers on a normal (HS106) and large hill (HS140). They concluded that the high lift–drag ratio had no significant effect on the flight distance of HS106 but significantly impacted the flight distance of HS140 [40].

It is a pity that the visual field of these images does not cover the stable flight stage and that there is also a lack of synchronous data on the different motion stages to describe overall motion performance. A new technology developed during the Beijing Winter Olympics—the Intel 3DAT athlete tracking system that assists scientific training, using video motion capture technology and an AI image processing system—can realize the three-dimensional attitude reconstruction of athletes, perform accurate quantitative evaluation of movements, and control measurement error below 5 mm [41]. Figure 1 inllstrated an "ultra-high-speed 4K orbital camera system" which was used in the Beijing Winter Olympics. It was developed by the China Central Television, called the Cheetah system, which uses "time slice" technology to freeze multiple key gestures of the complete motion process in the same picture and completes the key indicator analysis within 3 s [42].

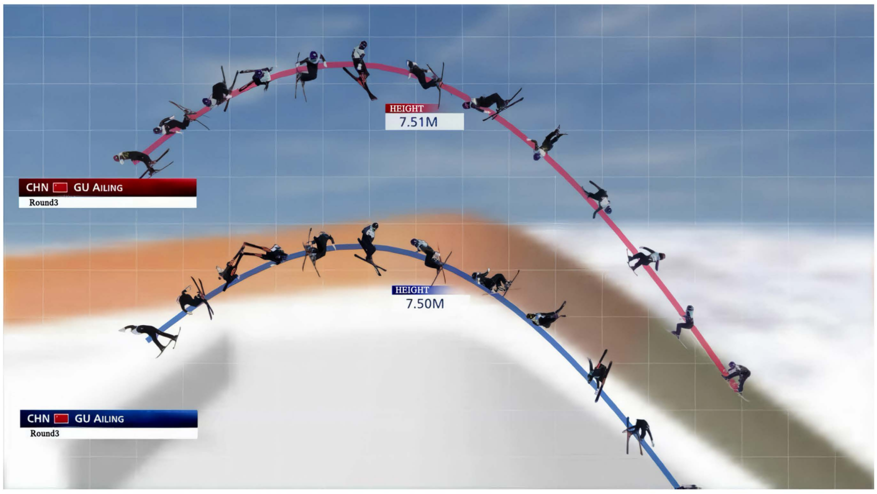

Figure 1. AI simulation diagram of Ailing Gu's third and first jumps in the Beijing Winter Olympic Games [42]. The red line is the trajectory of the third jump, with a maximum altitude of 7.51 m. The blue line is the trajectory of the first jump, with a maximum altitude of 7.50 m.

Kaps and his colleagues used the kinematic data inversion method to calculate the ground reaction force from the kinematic data collected during mountain platform jumps and compared it with the take-off force measured by the Pedar insole simultaneously. The results showed a reasonably high agreement between measured and calculated forces (less than 5% difference when considering aerodynamic lift), justifying the estimation of ground reaction forces from kinematic data [34]. Sasaki et al. used the inverse dynamics method to calculate the kinematics data collected during the competition: the external force on the centroid; the moment of the ankle joint, knee joint, and hip joint; and the torque on the snowboard during the take-off and early flight stages [43].

Multi-disciplinary principles underpin ski jumping performance; different mountain conditions, climate conditions, departure grids, and measurement tools will impact the research results. However, a consensus can be reached in kinematic research that the final velocity of each different motion stage becomes the initial velocity of the next stage and significantly impacts the final flight distance.

The main problem faced by motion video capture and analysis is measurement accuracy, such as errors in measuring the body attitude angle when wearing a ski suit, the measurement error of the snowboard angle, and the resulting attitude when the mountain background or protection fence interferes. Errors in angle measurement, centroid estimation, and the position of the centroid and the resultant moment in the flight system are essential reasons for determining flight. On the other hand, there needs to be more data consistency between different hardware systems and video analysis (parsing) software. At the same time, ski jumpers are limited by nerve fatigue, and the number of videos that can be collected in daily ski jumping training and sports technology are also limited. Most of the conclusions reached in the literature are qualitative descriptions and time series diagrams of various parameters in the motion process based on experimental data [37], and there are few clear conclusions regarding quantitative analysis.

2.2. Force Plate

The take-off is the technical stage that plays a decisive role in ski jumping performance. The force plate is the preferred measurement tool for gaining insight into an athlete's take-off technique and obtaining the ground reaction force during the take-off and landing stages. Using this measurement method in actual jumping venues is more complex than video capture, and it is more common in laboratory-designed tests, such as in wind tunnels or other simulated training environments. Installation of force plates in actual mountainous areas is common in the experimental sites of some research institutions, and they were also installed on the take-off slopes of the ski jumping hills of the 1988 Calgary Winter Olympic Games [10]. Although a series of force boards were installed under the Alps track at the beginning of this century, studies using these systems have yet to be published [24]. The primary focus of research when using force platforms is take-off, as well as a variety of simulated real ski jumping environments, such as low-friction conditions and air force conditions [5,10–12,14,17,32,43], to obtain the force–time and force–velocity curves at the moment of take-off and propose special training methods. The existing research mainly includes comparing simulated and actual jumps, identifying correlations between take-off force and flight technique, sports performance diagnosis, and other primary research.

Force plate tests simulating take-offs in wind tunnels have shown that wind conditions significantly shorten take-off times while compensating for final take-off speeds, thus emphasizing the importance of explosive power. The study of take-off force in the actual field shows that different players show very different strength characteristics during the take-off stage, suggesting that individual optimization should be carried out in take-off training; elite athletes show stronger strength growth ability when they are close to the take-off edge.

Although force plates can directly measure the ground force, actual sites with buried force plates are very rare, and no scientific papers using existing equipment on the track have been published. Snow surface conditions will affect the accuracy of mechanical measurements during the landing stage. In actual training or competitions, it is almost impossible to calibrate a force plate buried under the snow surface after each landing. Therefore, the possibility of obtaining accurate mechanical data from the landing stage is almost zero. However, the measurements carried out in simulated take-offs show great differences between the simulated means and the actual take-off environment, making interpreting and applying the results difficult.

2.3. Wearable Inertial Measurement and Sensor Equipment

Dynamic changes in athletes' bodies are the fundamental reason for changes in kinematics. Observing the dynamic changes throughout the ski jumping process is very important for studying the factors affecting the distance of movement. Wearable inertial measurement units (IMUs), including gyroscopes and accelerometers, are a powerful option for measuring human motion in natural environments, and a measurement system consisting of an IMU attached to the sacrum can be used to determine a variety of forces and work in the form of motion. With the development of inertial sensor technology, IMUs can also be used to calculate the joint angle and speculate the position of the centroid during motion. In ski jumping, Ohgi, Hirai, Murakami, and Seo [20] used seven IMU units affixed to the sacrum, thigh, calf, and snowboard and set up a camera to estimate the aerodynamics of the contestants during flight. Chardonnens J. et al. used a system based on wearable inertial sensors to calculate the kinematics and dynamic parameters of all stages of ski jumping, such as the force on the centroid during the take-off stage, the angular velocity of the roll, and the air force during the flight stage [44,45]. Grega used 10 IMU units, combined with force plates and morphometric methods, to analyze the forces and moments of the ankle, knee, and hip joints during the slide and take-off phases [46]. In recent years, wearable inertial measurement units have achieved promising results when measuring the kinematics and dynamics of ski jumping [44–47]. However, some studies have shown the possibilities GNSSs provide for collecting data efficiently from the start of the inrun to the landing [48,49]. Using this measurement, a trajectory with ± 0.05 m of global position accuracy can be achieved [50].

These measurement methods can achieve data monitoring in the moving process, which is very suitable for data recording in actual field training. The primary disadvantage of wearable equipment is that it cannot be used in competitions. The background technology for this measurement technology is the use of extrapolation methods, so the reliability of the data needs to be verified. The consistency of data generated by different measurement units and systems must be considered.

2.4. Surface EMG Measurement

There are few reports on electromyography (EMG) of muscle activity during actual mountain training, and most reports concern the study of muscle activity through simulating jumps in the laboratory. At present, the contribution of surface EMG research is limited to the basic description of the time sequence and coordination mode of muscle activity in the jump process, as well as the comparison between mountain platforms and simulated jumps. Virmavirta and Komi have conducted continuous research on take-offs in ski jumping from the late 1980s to the present. In a study in 1991, surface electromyography was used to measure several muscle groups of athletes, such as the gluteus maximus, medial vastus, lateral vastus, tibialis anterior, and gastrocnemius, from the preparation stage of take-off to landing, combined with a foot pressure insole, force platform, and another strength measurement. These papers provide a more comprehensive biomechanical description of ski jumping using the parameters of strength, pressure distribution, and muscle activity [11–13,51]. This kind of measurement method cannot be used in a competitive environment. In addition, research on the relationship between surface EMG data and mechanical and kinematic parameters still needs to be conducted.

2.5. Wind Tunnel Measurement

Aerodynamics is one of the determinants of flight distance in ski jumping. However, because human skiing systems are not rigid, with a complex and changeable attitude in the process of movement, any attitude adjustment of athletes will change aerodynamic parameters such as windward area, lift, and resistance, making them difficult to express by function. Therefore, scholars have conducted detailed studies on the acquisition of air force through wind tunnel measurements and calculations. In a large wind tunnel with a 5×5 m cross-section, Muller aimed to conduct mechanical measurements of all possible flight attitudes [9]. Their research combined the flight attitude data of all rounds of the top ten athletes in the Winter Olympic Games and took the mean value of each time in the flight stage as the flight attitude angle data. The lift and resistance data of the flight process were measured in the wind tunnel. In a follow-up computer simulation study, these data results were used as the input for solving the equation of motion to speculate on the flight trajectory and calculate the flight distance. A measuring device built by Seo et al. in a 3×3 m low-speed wind tunnel measures the air force of the full-size model under different attitudes during the flight phase; establishes the polynomial models of attack angle, forward inclination angle, V angle, and air force; and analyzes the stability of radial flip [19]. Maryniak et al. measured the attitude's airlift, drag, and overturning momentum under several critical angles in the flight phase [52]. Park M.J. et al. measured hydrodynamics in a wind tunnel, established the Navier–Stokes equation of the airflow field, and studied the optimization of the lift–drag ratio at four critical angles of flight attitude using computational fluid dynamics [53]. Meile et al. calculated the CFD of the models with various angles of attack under the condition of the full-scale Reynolds number, and the results were in good agreement with the experimental results of athletes in a large wind tunnel. This CFD code, AVL SWIFT, is used for simulations. The code employs the finite volume discretization method, which rests on the integral form of the general conservation law applied to the polyhedral control volumes (cells) [28].

In the 1980s, many sports competitions, such as ball games, throwing, and swimming, used various parameters related to improving equipment performance and improving sports performance through aerodynamic wind tunnel tests, numerical simulation calculations, and field measurements, providing technical support for enhancing training methods [54].

The main factors affecting aerodynamics include the attitude of the human ski system, ski jumping suits, and ski boards. During sliding, the athlete's aerodynamic resistance should be as low as possible to maximize acceleration [30]. Virmavirta et al. conducted wind tunnel tests of different athletes' skating postures. They found that a higher height of the athletes does not necessarily mean more significant air resistance. The results show remarkable differences in the aerodynamic characteristics of the two types of athletes, and the difference in aerodynamic lift is more significant [14]. Some scholars suggest that when the lift-to-drag ratio reaches its peak, the athlete should maintain a flatter body attitude, leading to a relatively low lift area and drag area [55].

Applying wind tunnel measurements can provide a good simulation environment for ski jumpers' diagnosis, evaluation, and optimization technology.

2.6. Computer Simulation Calculation

Computer simulation is mainly related to the attitude optimization of ski jumping flight; the human body–ski system is simplified to a centroid or segmented model. Hubbard et al. simplified the human ski system into four segments in the plane: the skis, legs, torso (including head), and arms [36]. The simulation system takes the joint torque when changing the body attitude as one of the input parameters, combined with the aerodynamic data, such as lift, resistance, and pitch torque measured in the wind tunnel, to construct the motion equation of the flight system. The simulation results are qualitatively consistent with the excellent flight trajectory, which provides a basis for future optimization analysis. Many types of research have been simplified to the centroid, including simulating flight trajectory [37], constructing ski-jumping mountains [1], analyzing the influence of flight attitude on motion performance (mainly flight distance), and the optimal solution for flight attitude. Under specific mountain parameters, the functional relationship between flight distance and landing impulse can be calculated, and the take-off force can be pushed back in the take-off stage. The theoretical basis of kinematic and biomechanic computer simulation comes from the Newtonian force–kinematics equation and aerohydrodynamics theory, such as the kinematics equation in the in-flight stage and motion equation in the sliding stage. Computational simulation systems developed by Muller et al. [8,9,56,57], using lift and drag areas as inputs, can calculate flight paths; conversely, flight path data, as a function of flight time, can also be used to calculate lift and drag or area [7]. Sasaki et al. [58] collected kinematic competition data of 10 world-class ski-jumpers as input for a mathematical model to elucidate the influence of aerodynamics during stable flight. They concluded that the mathematical approach was well suited for approximating empirically observed airlift and drag during stable flight.

During flight, athletes are subject to the combined effects of their gravity and aerodynamic force. The aerodynamic force can be decomposed into the lift F_l perpendicular to the speed direction and the resistance F_d along the opposite direction of the athlete's speed. The calculation formula is as follows:

$$F_l = 1/2\rho C_l A v^2 \tag{1}$$

$$F_d = 1/2\rho C_d A v^2 \tag{2}$$

where ρ is the air density, which is related to the altitude of the platform; v is the athlete's speed; A is the upwind area of the athlete; C_l is the lift coefficient; and C_d is the resistance coefficient. Lift and drag coefficients are related to athlete's flying attitude and the ski clothing material [59]. According to this calculation formula, we can deduce that the lift–drag ratio is determined by the ratio of the lift coefficient and the drag coefficient.

In the flight stage, athletes must find a suitable attitude to be subjected to greater lift and less resistance to fly farther. The "V" flight attitude can increase the lift–drag ratio of the man–plate system in a certain range to obtain a longer flight time and maximum flight distance. With changes in the angle between the skis and the human body between 0 and 45°, the value of the spring dynamometer decreases gradually with the increase in the angle; that is, the lift increases slowly, which indicates that the flying distance of the athlete will also increase gradually.

Hu regards ski jumpers and snowboards as a multi-body system. The fluid mechanics calculation method was used to study the upper body bending angle (10°, 14°, 18°, 22°, and 26°) and the body and snowboard angle (8°, 12°, 16°, 20°, and 24°)—the aerodynamic changes in the board system. The results show that the optimal range of the bending angle of the upper body is 14~18°, and the optimal range of the angle between the body and the snowboard is 16~20° [29,60]. Chen's simulation calculation of the flight stage shows that to obtain the best competitive performance in the initial flight stage, athletes should pass through this period with minimum head-on resistance and prolong the duration of this period as much as possible. During a stable flight period, it is necessary to maintain the balance and stability of the "man–board" system and adjust its posture to obtain the maximum lift–drag ratio.

When discussing the effect of flight attitude parameters on flight distance, the computer simulation method has higher credibility than the results of other experimental methods, such as video analysis and empirical data. However, the premise of using this method is that the theory is correct, and the proper expression of the simplified theoretical model to the actual process of the jumping platform must first be verified.

3. Discussion

Kinematic research shows that the initial speed of the take-off stage is provided by the in-run stage. The take-off attitude can only form a stable flight attitude after the adjustment in the early flight stage. The quality of the stable flight attitude also affects the landing attitude [23]. Therefore, each different stage of movement will impact the next stage of movement.

Take-off is the most critical stage of ski jumping [5], in which the initial speed and forward angular momentum determine the final flight distance in ballistics. In contrast, the squatting position in the in-run stage provides the initial conditions for take-off. The competitor must compromise between a low centroid and their individual muscle ability [31,32]. Going back to the take-off parameters, the optimal values of the initial velocity and angular momentum of the contestant do not have a fixed result, which must be considered together with the contestant's other parameters. In the flight stage, neither the optimal lift–drag ratio nor the maximum lift coefficient can be proven to be necessary and sufficient conditions for obtaining the farthest flight distance. Therefore, analyzing ski jumping performance in an independent comparative study is complex. However, association analysis should be considered, which puts forward some primary data collection and recording requirements.

Too long of a sports distance poses a significant challenge for biomechanical research, especially in collecting data on hill jumps in ski jumping [61]. To date, under the conditions of real ski jumping, only the kinematic data of the stage motion sequence can be obtained [15]. Under the condition of competitions, we can consider synchronous video capture by multiple cameras covering the whole course and recording the wind data of the flight path. When building a new ski jump site, burying a force-measuring platform at the take-off platform and landing slope should be considered in order to observe the take-off and landing forces. Wearable inertial measurement units and global navigation satellite system (GNSS) receivers can be used under the training conditions of real ski jumping [48,62].

Outdoor field environmental factors mainly include the wind environment and the air pressure environment. Computational fluid dynamics can simulate the process of ski jumping under different meteorological conditions and is considered an important tool for improving the cognition of the ski jumping process in the future [63]. The ultimate goal of any research is to enhance athletic performance, and the study of the effect of wind and air pressure on aerodynamic characteristics and stability may become a future research focus in the field of ski jumping aerodynamics. As an essential venue for ski jumping simulation training, intelligent wind tunnel experimental training halls can provide a large amount of monitoring data for outdoor field environment simulation, aerodynamic measurement, athlete technical action assistance training, sports equipment optimization design, and other experimental research. It will become an essential tool for ski jumping research in the future.

Therefore, based on the existing biomechanical research, considering the critical technical problems affecting ski jumping, to construct a feasible collection and real-time feedback scheme for kinematics and dynamics in an actual platform environment, different measurement techniques are synchronously combined in each link and targeted index parameters. At the same time, the industry standards for different measurement methods of ski jumping are constructed to standardize the expression of the sport. Improving the evidence from various research conclusions, helping coaches and athletes enhance their understanding of mechanical and biomechanical problems, improving the level of competitive performance, and improving daily training methods are some of the main problems to be solved in future research into ski jumping.

4. Conclusions

Based on the literature research and the analysis of research methods such as motion video capture analysis, force plates, wearable inertial measurements, sensor equipment, surface EMG measurements, wind tunnel measurements, and computer simulation calculations, the technical requirements and research progress of ski jumping are summarized as follows:

1. A high level of sports performance is attributed to the ski jumper's tuning of their overall flight system at each stage of the exercise sequence, and a change in one parameter will affect other parameters. Under computational fluid dynamics, research methods using wearable inertial measurement units and global navigation satellite system (GNSS) receivers will become essential for future ski jumping research.
2. Ski jumping requires solid technical stability, and the timing of the center-of-gravity movement when the athlete takes off is crucial. In theory, the factors that affect the flight distance of athletes are the ratio of lift and the resistance of the "man–board" system during the flight process; air density, windward area, and flight speed jointly affect the lift and resistance during the flight process; and the factors that determine the lift–drag ratio coefficient are the body attitude and the material of the ski suit. In the flight stage, the angle between the ankle and cervical vertebra connects to the horizontal line, and the flight angle of attack can lead to an excellent aerodynamic drag reduction effect.
3. Ski jumping research, influenced by long distances, is mostly conducted in laboratory settings, including take-off force tests and computer simulations of air flight drag reduction technology. Motion video capture analysis can be applied to training and competition analysis, but a motion video capture analysis system covering the complete motion process needs to be developed. AI image processing systems can realize the three-dimensional posture reconstruction of athletes, which can be used as a supplement to sports technology analysis. Wind tunnels can be used to carry out drag reduction technology optimization training and strength and technical testing, the most widely used training research methods for athletes. The development of wind tunnel venues with comprehensive performance and intelligence has broad application prospects for athletes to correct technical posture and adapt to the environment. Wearable inertial measurement units have a wide test range and can cover the complete motion process. Their test content covers kinematics and dynamics data, making them a test method with high feasibility and reliability for training and monitoring ski jumping. With higher accuracy and a more stable transmission speed, compact and portable wearable inertial measurement and sensor equipment will be the primary methods for future research on ski jumping.

Author Contributions: Writing—original draft preparation, Y.L. and L.L.; writing—editing, L.X.; literature collection, J.C.; topic design and writing review, D.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the key R&D plan of China for Winter Olympics (Ministry of Science and Technology of the People's Republic of China, Grant No. 2020YFF0304605-3).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Muller, W. Determinants of ski-jump performance and implications for health, safety and fairness. *Sports Med.* **2009**, *39*, 85–106. [CrossRef] [PubMed]
2. Francesco, B.; Federico, C.; Stefano, M.; Stefano, M.; Eaoardo, S. *The Engineering Approach to Winter Sports*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 153–181.
3. Virmavirta, M.; Kivekas, J. Is it still important to be light in ski jumping? *Sports Biomech.* **2021**, *20*, 407–418. [CrossRef] [PubMed]
4. Chowdhury, H.; Alam, F.; Subic, A. Aerodynamic performance evaluation of sports textile. *Procedia Eng.* **2010**, *2*, 2517–2522. [CrossRef]
5. Ketterer, J.; Gollhofer, A.; Lauber, B. Biomechanical agreement between different imitation jumps and hill jumps in ski jumping. *Scand. J. Med. Sci. Sports* **2021**, *31*, 115–123. [CrossRef] [PubMed]
6. Zhang, L.; Li, X.; Wang, X.; Chen, L.; Zhao, T. Performance and Biomechanics in the Flight Period of Ski Jumping: Influence of Ski Attitude. *Biology* **2022**, *11*, 671. [CrossRef] [PubMed]
7. Müller, W. Computer simulation of ski jumping based on wind tunnel data. In *Courses and Lectures—International Centre for Mechanical Sciences*; Springer: Wien, Austria, 2008; pp. 161–182.
8. Müller, W.; Schmölzer, B. Computer simulated ski jumping: The tightrope walk to high performance. In Proceedings of the Fourth World Congress of Biomechanics, Calgary, AB, Canada, 8 August 2002.
9. Müller, W.; Platzer, D.; Schmolzer, B. Dynamics of human flight on skis: Improvements in safety and fairness in ski jumping. *J. Biomech.* **1996**, *29*, 1061–1068. [CrossRef]
10. Virmavirta, M.; Komi, P.V. The Take-off Forces in Ski Jumping. *J. Appl. Biomech.* **1989**, *5*, 248–257.
11. Virmavirta, M.; Komi, R.V. Measurement of take-off forces in ski jumping: Part II. *Scand. J. Med. Sci. Sports* **1993**, *3*, 237–243. [CrossRef]
12. Virmavirta, M.; Koml, P.V. Measurement of take-off forces in ski jumping: Part I. *Scand. J. Med. Sci. Sports* **1993**, *3*, 229–236. [CrossRef]
13. Virmavirta, M.; Komi, P.V. Plantar pressure and EMG activity of simulated and actual ski jumping take-off. *Scand. J. Med. Sci. Sports* **2001**, *11*, 310–314. [CrossRef]
14. Virmavirta, M.; Kivekas, J.; Komi, P.V. Take-off aerodynamics in ski jumping. *J. Biomech.* **2001**, *34*, 465–470. [CrossRef] [PubMed]
15. Virmavirta, M.; Isolehto, J.; Komi, P.; Brüggemann, G.P.; Müller, E.; Schwameder, H. Characteristics of the early flight phase in the Olympic ski jumping competition. *J. Biomech.* **2005**, *38*, 2157–2163. [CrossRef] [PubMed]
16. Virmavirta, M.; Isolehto, J.; Komi, P.; Schwameder, H.; Pigozzi, F.; Massazza, G. Take-off analysis of the Olympic ski jumping competition (HS-106m). *J. Biomech.* **2009**, *42*, 1095–1101. [CrossRef] [PubMed]
17. Virmavirta, M.; Kivekas, J.; Komi, P. Ski jumping take-off in a wind tunnel with skis. *J. Appl. Biomech.* **2011**, *27*, 375–379. [CrossRef] [PubMed]
18. Seo, K.; Watanabe, I.; Igarashi, M.; Kimura, S.; Murakami, M. Aerodynamic study for the ground effect of ski jumping. In Proceedings of the ISBS-Conference Proceedings Archive, San Francisco, CA, USA, 3 February 2010.
19. Seo, K.; Watanabe, I.; Murakami, M. Aerodynamic force data for a V-style ski jumping flight. *Sports Eng.* **2004**, *7*, 31–39. [CrossRef]
20. Estivalet, M.; Brisson, P. *The Engineering of Sport 7*; Springer Paris: Paris, France, 2008; Volume 1, pp. 157–164.
21. Seo, K.; Murakami, M.; Yoshida, K. Optimal flight technique for V-style ski jumping. *Sports Eng.* **2004**, *7*, 97–103. [CrossRef]
22. Murakami, M.; Iwase, M.; Seo, K.; Ohgi, Y.; Koyanagi, R. High-speed video image analysis of ski jumping flight posture. *Sports Eng.* **2014**, *17*, 217–225. [CrossRef]
23. Cao, L.; Guo, Y.; Li, X.; Chen, L.; Wang, X.; Zhao, T. Optimization of Ski Attitude for the In-Flight Aerodynamic Performance of Ski Jumping. *Biology* **2022**, *11*, 1362. [CrossRef]
24. Schwameder, H. Biomechanics research in ski jumping, 1991–2006. *Sports Biomech.* **2008**, *7*, 114–136. [CrossRef]
25. Arndt, A.; Brüggemann, G.P.; Virmavirta, M.; Komi, P. Techniques Used by Olympic Ski Jumpers in the Transition from Take-off to Early Flight. *J. Appl. Biomech.* **1995**, *11*, 224. [CrossRef]
26. Psycharakis, S.G.; Cooke, C.B.; Paradisis, G.P.; O'Hara, J.; Phillips, G. Analysis of selected kinematic and physiological performance determinants during incremental testing in elite swimmers. *J. Strength Cond. Res.* **2008**, *22*, 951–957. [CrossRef] [PubMed]
27. Jost, B.; Coh, M.; Janez, P. Analysis of correlation between selected kinematic variables of the take-off and the lenght of the ski-jump. In Proceedings of the ISBS-Conference Proceedings Archive, Hong Kong, China, 25–30 June 2000.
28. Meile, W.; Reisenberger, E.; Mayer, M.; Schmölzer, B.; Müller, W.; Brenn, G. Aerodynamics of ski jumping: Experiments and CFD simulations. *Exp. Fluids* **2006**, *41*, 949–964. [CrossRef]
29. Hu, Q.; Zhang, W.; Chen, Q. Research progress on aerodynamics of ski jumping. *China Sport Sci. Technol.* **2018**, *54*, 132–139.

30. Virmavirta, M. Aerodynamics of Ski Jumping. In *The Engineering Approach to Winter Sports*; Springer: New York, NY, USA, 2016; pp. 33–52.
31. Ettema, G.; Braaten, S.; Danielsen, J.; Fjeld, B.E. Imitation jumps in ski jumping: Technical execution and relationship to performance level. *J. Sports Sci.* **2020**, *38*, 2155–2160. [CrossRef] [PubMed]
32. Ettema, G.; Hooiveld, J.; Braaten, S.; Bobbert, M. How do elite ski jumpers handle the dynamic conditions in imitation jumps? *J. Sports Sci.* **2016**, *34*, 1081–1087. [CrossRef] [PubMed]
33. Remizov, L.P. Biomechanics of optimal flight in ski-jumping. *J. Biomech.* **1984**, *17*, 167–171. [CrossRef]
34. Kaps, P.; Schwameder, H.; Engstler, C. Inverse dynamic analysis of take-off in ski-jumping. In *Science and skiing*; E & FN Spon: London, UK, 1997; pp. 72–87.
35. Sasaki, T.; Tsunoda, K.; Koike, T. Kinetic Analysis of Ski Jumping in the Period of Transition Area. 2004. Available online: https://www.researchgate.net/publication/221723820_Kinetic_Analysis_of_Ski_Turns_Based_on_Measured_Ground_Reaction_Forces (accessed on 1 December 2023).
36. Hubbard, M.; Hibbard, R.L.; Yeadon, M.R.; Komor, A. A Multisegment Dynamic Model of Ski Jumping. *J. Appl. Biomech.* **1989**, *5*, 258–274. [CrossRef]
37. Schmolzer, B.; Muller, W. Individual flight styles in ski jumping: Results obtained during Olympic Games competitions. *J. Biomech.* **2005**, *38*, 1055–1065. [CrossRef]
38. Janura, M.; Cabell, L.; Elfmark, M.; Vaverka, F. A 10-year longitudinal study of the in-run position kinematic changes in ski jumping. *J. Biomech.* **2006**, *39*, S553. [CrossRef]
39. Nardello, F.; Ferrari, C.; Spinelli, L.; Zamparo, P. A kinematic analysis of water ski jumping in male and female elite athletes. *Sports Biomech.* **2021**, *20*, 985–1000. [CrossRef]
40. Elfmark, O.; Ettema, G.; Gilgien, M. Assessment of the steady glide phase in ski jumping. *J. Biomech.* **2022**, *139*, 111139. [CrossRef]
41. Meng, C.; Ming, M. Beijing Winter Olympics Out of an AI Black Technology. 2022. Available online: https://baijiahao.baidu.com/s?id=1728266246869375100&wfr=spider&for=pc (accessed on 1 December 2023).
42. China Central Television. Trajectory Analysis of Gu Ailing's Final Three Jumps. 2022. Available online: https://content-static.cctvnews.cctv.com/snow-book/video.html?item_id=17236332578558502720 (accessed on 1 December 2023).
43. Sasaki, T.; Tsunoda, K.; Uchida, E.; Hoshino, H.; Ono, M. Joint power production in take-off action during ski-juming. In *Science and Skiing*; Taylor & Francis: Abingdon, UK, 2003.
44. Chardonnens, J.; Favre, J.; Cuendet, F.; Gremion, G.; Aminian, K. Measurement of the dynamics in ski jumping using a wearable inertial sensor-based system. *J. Sports Sci.* **2014**, *32*, 591–600. [CrossRef]
45. Chardonnens, J.; Favre, J.; Cuendet, F.; Gremion, G.; Aminian, K. A system to measure the kinematics during the entire ski jump sequence using inertial sensors. *J. Biomech.* **2013**, *46*, 56–62. [CrossRef]
46. Logar, G.; Munih, M. Estimation of joint forces and moments for the in-run and take-off in ski jumping based on measurements with wearable inertial sensors. *Sensors* **2015**, *15*, 11258–11276. [CrossRef]
47. Chardonnens, J.; Favre, J.; Le Callennec, B.; Cuendet, F.; Gremion, G.; Aminian, K. Automatic measurement of key ski jumping phases and temporal events with a wearable system. *J. Sports Sci.* **2012**, *30*, 53–61. [CrossRef]
48. Elfmark, O.; Ettema, G.; Jølstad, P.; Gilgien, M. Kinematic Determination of the Aerial Phase in Ski Jumping. *Sensors* **2022**, *22*, 540. [CrossRef] [PubMed]
49. Elfmark, O.; Ettema, G.; Groos, D.; Ihlen, E.A.; Velta, R.; Haugen, P. Performance Analysis in Ski Jumping with a Differential Global Navigation Satellite System and Video-Based Pose Estimation. *Sensors* **2021**, *21*, 5318. [CrossRef]
50. Gilgien, M.; Spörri, J.; Limpach, P.; Geiger, A.; Müller, E. The effect of different Global Navigation Satellite System methods on positioning accuracy in elite alpine skiing. *Sensors* **2014**, *14*, 18433–18453. [CrossRef] [PubMed]
51. Virmavirta, M.; Komi, P.V. Electromyographic analysis of muscle activation during ski jumping performance. *Int. J. Sports Biomech.* **1991**, *7*, 175–182. [CrossRef]
52. Maryniak, J.; Adyyńska-Kozdra, E.; Tomczak, S. Configurations of the Graf-Boklev (V-Style) SKI Jumper Model and Aerodynamic Parameters in a Wind Tunnel. *Hum. Mov.* **2009**, *10*, 130–136. [CrossRef]
53. Park, M.J.; Lee, K.D.; Kim, K.Y. Optimization of ski jumper's posture considering lift-to-drag ratio and aerodynamic stability in pitch. In *Proceedings of the International Mechanical Engineering Congress and Exposition*; Elsevier: Amsterdam, The Netherlands, 2012; pp. 1285–1292.
54. Jia, Q.; Cui, E. Aerodynamics in sports. *Mech. Pract.* **2008**, 84–86.
55. Li, X.; Wang, X.; Chen, L.; Zhao, T. Effects of body angles on the aerodynamic characteristics in the flight period of ski jumping: A simulation study. *Sports Biomech.* **2023**, 1–15. [CrossRef]
56. Müller, W.; Platzer, D.; Schmölzer, B. Scientific approach to ski safety. *Nature* **1995**, *375*, 455. [CrossRef]
57. Schmolzer, B.; Muller, W. The importance of being light: Aerodynamic forces and weight in ski jumping. *J. Biomech.* **2002**, *35*, 1059–1069. [CrossRef]
58. Sasaki, T. Aerodynamic force during flight phase in ski jumping. In *Science and Skiing II*; Kovac: Hamburg, Germany, 2001.
59. Virmavirta, M.; Brüggemann, G. Ski Jumping: Aerodynamics and Kinematics of Take-Off and Flight. In *Handbook of Human Motion*; Springer: Cham, Switzerland, 2018; pp. 1681–1701.
60. Hu, Q.; Liu, Y. The effect of Athlete's posture on the aerodynamic characteristics of ski jumping in the air. *J. Med. Biomech.* **2021**, *36*, 407–414.

61. Groh, B.H.; Warschun, F.; Deininger, M.; Kautz, T.; Martindale, C.; Eskofier, B.M. Automated Ski Velocity and Jump Length Determination in Ski Jumping Based on Unobtrusive and Wearable Sensors. *Proc. ACM Interact.* **2017**, *1*, 1–17. [CrossRef]
62. Link, J.; Guillaume, S.; Eskofier, B.M. Experimental Validation of Real-Time Ski Jumping Tracking System Based on Wearable Sensors. *Sensors* **2021**, *21*, 7780. [CrossRef] [PubMed]
63. Gardan, N.; Schneider, A.; Polidori, G.; Trenchard, H.; Seigneur, J.M.; Beaumont, F. Numerical investigation of the early flight phase in ski-jumping. *J. Biomech.* **2017**, *59*, 29–34. [CrossRef] [PubMed]