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Analysis of Landing in Ski Jumping by Means of Inertial Sensors and Force Insoles †

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Abstract: Landing and its preparation are important phases for performance and safety of ski jumpers. A correct ski positioning could influence the jump length as also the cushioning effect of the aerodynamic forces that permits the reduction of landing impacts. Consequently, the detection of ski angles during landing preparation could allow for analyzing landing techniques that result in reduced impact forces for the athletes. In this study, two athletes performed with force insoles and inertial sensors positioned on the ski during training conditions on the ski jumping hill. The results confirmed previous studies, showing that impact forces can reach more than four times body weight. In the analyzed cases, the force distribution resulted to be more concentrated on the forefoot and the main movement influencing the impact was the pitch. The combination of inertial sensors, in particular gyroscopes, plus force insoles demonstrated to be an interesting set up for ski jumping movement analysis.

Keywords: safety; injury prevention; inertial sensors; force insoles; biomechanics; telemark landing; performance feedback

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1. Introduction

Ski jumping is a competitive winter sport in which a score evaluates the performance, considering jump length, wind, starting gate and technical execution of flight and landing. Telemark is the traditional required position during landing and is performed with a bent knee on the back and the other in front in squat position, while the body weight is equally distributed on both parallel skis and the upper body is stretched [1]. This movement has biomechanical advantages permitting the step position a softer landing [2]. However, telemark has been criticized as far as safety is concerned because more difficult to perform than a parallel leg landing, due to the higher coordination and experience required [2].

Previous studies demonstrated the importance of landing preparation phase for obtaining longer jumps and executing the telemark [3,4]. During this phase, a correct ski position could affect the jump length up to 3 m [5]. In fact, a larger angle of attack, i.e., angle between the ski and the air stream, increases the cushioning effect of the aerodynamic forces, with a consequent smaller loading on the musculoskeletal system of the athlete resulting in a reduction of injury risk [2]. Over this, together with an effective take-off, a high initial velocity and an optimal flying technique, delaying the landing preparation is one of the methods to achieve longer jumps [3]. However, this delay affected the landing preparation, leading to a technically incorrect telemark and to a decreased safety, owing to the high impact forces that can reach four times body weight depending on the landing technique [6]. Although the importance of landing for safety and performance is beyond any doubt, the majority of research focused on the in-run, take-off and flight phases, considering landing and its preparation of lower interest [6]. This may partly derive from the methodological challenges that come along with the measurement of flight and landing phases in ski jumping.

Despite the interest of studying kinetics in ski jumping, researchers faced technological problems during the years: force plates installed in the hill table allows only the analysis of the take-off phase, pressure insoles permitted the overall performance detection but interfering with jumper's movement due to the cables, while embedded transducers in the ski reduced safety [6]. Nowadays, the progress of wireless transmission, such as Bluetooth, permits the development of new force insoles that not require connections with a receiver. As a result, these devices decrease the interference with subject's movements, making them interesting for analyzing the whole ski jumping performance while not affecting safety.

Inertial sensors (IMU) are constituted of an accelerometer, a gyroscope and a magnetometer embedded in a small device. Thanks to their fast placement, small size and wide capture volume, their use in movement analysis for biomechanical research has become popular, especially in in-field measurements of sports performed in wide area [7]. In ski jumping, IMUs have been demonstrated to be a valid instrument to detect ski orientation angles in laboratory test as well as on the hill [7,8].

To the best of our knowledge, no study combined inertial sensors and force insoles to detect the kinematic and kinetic characteristics of landing, and in general, of ski jumping movements on the hill. In our study, we collected kinematical data from the IMUs positioned on the skis and kinetic data from force insoles during the entire ski jumping performance, focusing on the analysis of the landing and its preparation. Specifically, the focus of our case studies was to introduce and test the combination of the inertial sensors and the force insoles in order to develop a tool for the analysis of ski jumping, and in particular of the landing, during in-field measurements.

2. Materials and Methods

Two male ski jumpers competing at National and International Junior level performed the test while training on the K90 ski jumping hill of Oberhof (Germany). The athletes carried out telemark or parallel leg landings, depending on jump length, wind conditions and expertise. The subjects were verbally informed in full about the nature of the study and they were allowed to withdraw at any point without giving a reason.

2.1. Data Collection

The athletes jumped wearing Loadsol plantar force insoles (Novel GmbH, Munich, Germany) with a sample rate of 100 Hz for detecting the impact forces during landing. The insoles were connected via Bluetooth to the app Loadsol (Novel GmbH, Munich, Germany) installed on an iPod (Apple, CA, USA). The device worked as data logger and was positioned on the arm of the athlete with a smartphone running case (Figure 1). The force insoles detected the forefoot, rear foot and overall normal forces and their accuracy have been previously demonstrated [9]. Before each jump, the system was calibrated with the athlete body weight (BW) measured before the training using a body scale and including ski boots, helmet, gloves and ski suit.

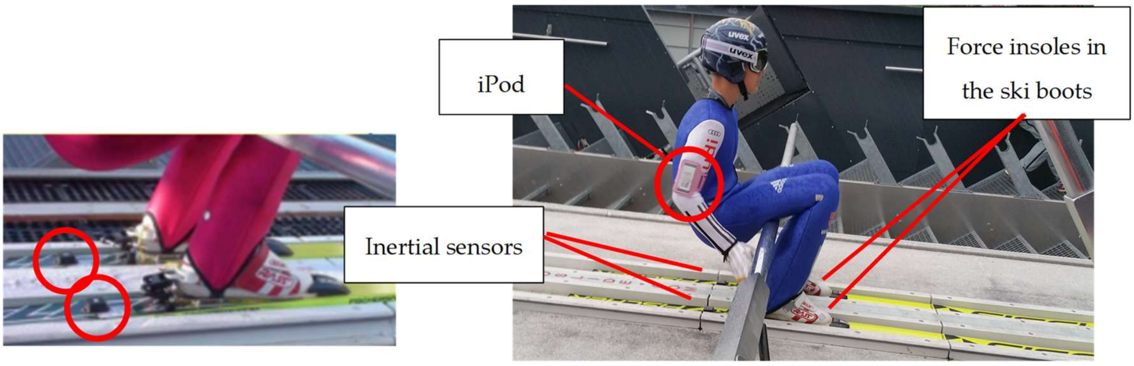


Figure 1. Placement of the iPod case, force insoles and inertial sensors on a subject.

An inertial measurement unit (MSR Solutions, Wangen/Allgäu, Germany) with a sample rate of 100 Hz was placed and fixed with tape on each ski 0.1 m behind the binding for detecting their angular movements (Figure 1).

Insoles and IMUs together had a weight of 0.3 kg. After activation, the insoles automatically stopped recording after 5 min, while the IMUs after 90 s.

2.2. Kinetic and Kinematic Variables

The overall, rear and fore foot forces during landing impact were normalized to the BW.

The movement of roll, pitch and yaw are defined as rotation around the longitudinal, frontal and vertical axis of the skis, respectively. We focused on the roll and pitch movements considering the roll internal rotation and the flection of the pitch as positive values (Figure 2). We presented the ski angular differences (Δ) between the angles recorded during landing impact (as reference) and the ones at defined times before it, in order to evaluate the range of motion made by the athletes. The times were 1.0 s, 0.5 s, 0.4 s, 0.3 s, 0.2 s and 0.1 s before landing touchdown.

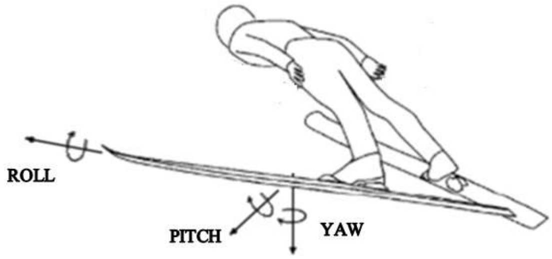


Figure 2. Representation of the roll, pitch and yaw ski movements (adapted from [11]).

2.3. Data Processing and Synchronization

The ski roll, pitch and yaw angles were computed integrating the gyroscopes' data, after having low-pass filtered the raw data (with cut-off frequency 5 Hz). The initial values of the integration were the angles reached by the ski at the table of the in-run, before starting the flight phase. Therefore, the roll and the yaw were set at 0°, considering the ski gliding flat in the tracks, while the pitch was set at −11°, according to the incline of the table reported in the ski jumping hill design certificate [11].

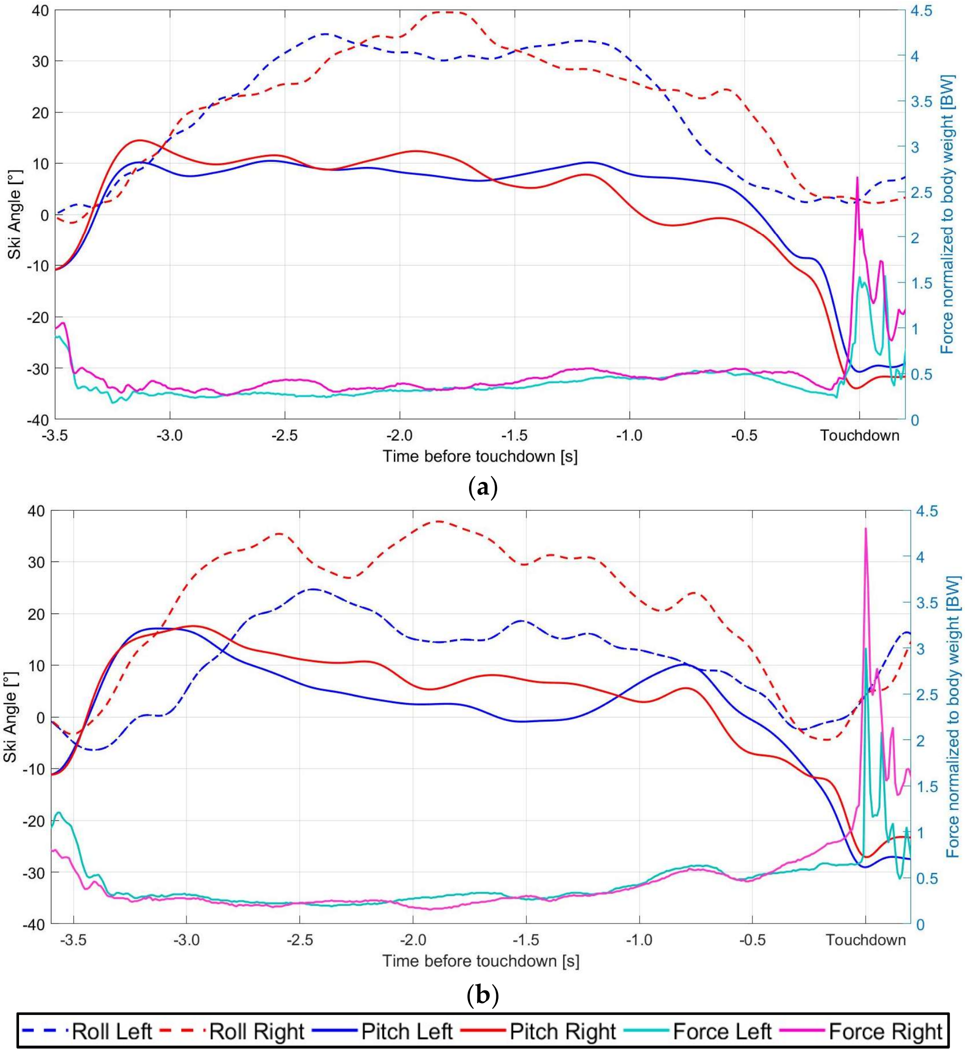
The kinetic data were used as outcomes from the Loadsol app, where the values are rounded in steps of 5 N.

During touchdown, the force insole recorded the highest force (impact) while the ski pitch reached the minimum value after the flight phase hitting the inclined surface of the hill landing area. Therefore, the minimum ski pitch angle and the respective maximum force were used to synchronize the IMUs with the insoles. During the flight, the ski kinematics changes the pressure beneath the skis and, consequently, it could be assumed that also the forces recorded by the insoles varies. As a result, in order to check the synchronization, for each side, two local maximum/minimum of the pitch were detected and their timings compared with the correspondent local maximum/minimum of the force. The average between the differences was calculated.

The data processing and synchronization were conducted using self-coded Matlab 2017a scripts (Mathworks Inc., Natick, MA, USA).

3. Results and Discussion

In the Results, one jump example of low (Subject A) and high impacts (Subject B) are presented, where both the athletes landed with telemark (right foot positioned in front). The overall force, roll and pitch movements during flight and landing phases are shown in Figure 3 and were comparable with the ones reported in earlier studies [4,6]. The flight times were 3.50 s and 3.62 s for subject A and B, respectively.



(**a**)

(**b**)

Figure 3. Roll, pitch and overall forces of two jumps characterized by a low (Subject A (**a**)) and a high impact (Subject B (**b**)) during flight and landing phases.

After a fast angle increase coinciding with the early flight, the pitch movement stabilized during the flight phase, before decreasing in order to prepare the landing. In this phase, the force insoles detected the air pressure that changed in relation to the ski movement and the wind conditions. As a result, the trends of the insoles and ski angles are comparable despite a delay of 15 ms for both sides in subject A and of 25 ms and 5 ms for the left and right side, respectively, in subject B. The difference can be considered acceptable and partially justified by the mechanics of the binding that may delay the transfer of pressure variation acting on the ski to the boot and, vice versa, from the athlete movement to the ski.

During the impact, both the athletes landed with an internal rotation of the ski, described by the roll angles (Figure 3). This movement could be explained by the mechanics of the binding that limited the range of motion of the ankle. At the same time, further analysis of the force directions is of high interest, as these are important for predicting injury risk, like for the anterior cruciate ligament rupture (ACL) [12], one of the most common injures in ski jumping. The pitch movements showed differences between the left and right sides, justified by the asymmetry of the telemark position and by the ski deflection. As showed in Table 1, both subjects reported a higher impact on the foot positioned in the front during the telemark landing (the right), showing an asymmetrical body weight distribution, differently from what theoretically is required by the competition rules [1]. The distribution of impact forces was higher in both cases and sides on the forefoot, justified by the forward position required by the telemark and by the angulation of the landing area. The analysis of the asymmetry as well as of the force distribution on the foot rear/front part can be an important factor for injury prevention. In fact, landing asymmetry was demonstrated to be a risk factor for ACL [12]. On the other hand, forefoot landing could permit to the soft-tissue components of the leg to dampen the force, having more time to absorb and distribute the force [12,13].

Table 1. Kinetic data of overall, fore and rear foot of one specific sample jump with low (subject A) and high (subject B) impact.

Subject	Side	Overall [BW]	Fore Foot [BW]	Rear Foot [BW]
A	Left	1.6	1.1	0.5
	Right	2.7	1.6	1.1
B	Left	3.0	2.0	1.0
	Right	4.3	3.2	1.1

After the touchdown, the force insoles recorded high kinetic values related to the impulse (Figure 3), identified as a risk factor for ACL rupture [12,13]. In addition, in this phase, the pitch presented an unexpected difference between the two sides, being the skis gliding on the same inclined surface (Figure 3). This difference could be connected to an offset of the IMUs due to the high touchdown impact and, partially, to the telemark, in which the athlete keeps a step position and, therefore, the two gyroscopes on the skis are recording the hill incline with a delay.

Table 2 shows ski differences of roll and pitch between landing (set as reference) and specific time before it. While the roll angles did not show a specific trend, the pitch differences of subject A were higher than the ones of B, especially in the last 0.5 s before landing. This means that subject A kept a larger angle of attack for a longer time than subject B. Therefore, subject A prepared the landing in a shorter amount of time. This likely explains why, athlete A showed a lower impact force, profiting of the cushioning and braking effect of the aerodynamic forces for a longer time [4,5]. As already demonstrated [4], the landing preparation time distinguished between high and low level athletes. For that reason, further research should focus on the individuation of common ski movements that define the start of the landing preparation.

Table 2. Differences (Δ) between the ski angles recorded during landing touchdown (as reference) and the ones recorded at 0.1, 0.2, 0.3, 0.4, 0.5 and 1.0 s before the touchdown. The values belong to two specific sample jumps with a low (subject A) and high (subject B) landing impacts, respectively (L: left; R: right side).

Time before Landing [s]	ΔRoll L [°]	ΔRoll R [°]	ΔPitch L [°]	ΔPitch R [°]
Subject A				
0.1	−0.5	−0.5	−12.5	−9.1
0.2	0.1	−1.1	−22.1	−27.7
0.3	−0.9	−6.1	−23.8	−31.0
0.4	−2.5	−13.4	−29.5	−34.4
0.5	−4.2	−19.1	−34.2	−31.9
1.0	−28.0	−23.3	−38.7	−37.4
Subject B				
0.1	4.5	7.0	−6.6	−9.6
0.2	5.7	8.8	−15.6	−15.3
0.3	6.6	6.5	−20.9	−17.0
0.4	2.5	−0.6	−25.4	−19.4
0.5	−1.0	−8.3	−28.4	−20.0
1.0	−8.7	−18.2	−35.7	−30.0

4. Conclusions

The study showed how the use of IMUs and force insoles can represent a promising tool for the biomechanical analysis of landing in ski jumping. The identification of the relationships between ski positioning and impact forces can lead to the optimization of landing technique and thus, improvements in technical execution and reduction of injury risks.

The case studies showed that the ski kinematics influence the impact landing forces on the athletes. Important for further studies, the impact forces resulted to be not necessarily equally distributed between the feet. The combination of inertial sensors and force insoles is a promising assisting tool for the analysis of the performance and for giving technical support to the athlete in real ski jumping conditions, as these devices are light, efficient and not influencing the movement.

Further research should additionally include a more specific analysis of ski movements considering also their angular speed and acceleration, the touchdown vibration and impulse and differentiation between telemark and parallel leg landing technique.

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