Unobtrusive and Wearable Landing Momentum Estimation in Ski Jumping with Inertial-Magnetic Sensors

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***Abstract*— An unobtrusive and low-cost landing analysis could not only support sports science research and ski jumping training but also decrease the risk of overuse and injuries. Although ski jumping biomechanics has been extensively researched, there is no known study on an unobtrusive analysis of the landing phase of actual ski jumps. In this work, we propose a landing momentum determination with inertial-magnetic measurement units (IMMUs) attached to the skis. We evaluate the calculated momenta against a mobile force plate and achieve accuracies of more than 90 % for three out of four jumps. Although the robustness of the measurement process can still be improved, our proposed algorithm builds the first step towards an IMMU-based landing analysis in ski jumping.**

I. INTRODUCTION

The measurement and analysis of forces in ski jumping have been extensively investigated research topics over the past decades [1]–[9]. Although the landing is a crucial state in the jump process, only a few publications focused on the analysis during the landing phase [10]–[13]. A more detailed analysis and possibly direct feedback could lead to an improved training, deeper insight in performance-related aspects and a more attractive visualization for spectators. Furthermore, injuries due to overuse and high forces could be analyzed and ultimately avoided.

Typical methods for measuring ground reaction forces in sports settings are presented by force plates and insole pressure sensors [14]. However, both reach their limitations in ski jumping. The permanent installation of force plates would require covering a large possible landing area and additionally, must not provide any risk during the landing procedure. Using mobile force plates and insole measurements is feasible but there is no known concept available that is unobtrusively wearable and applicable to various training and competition scenarios. Another technique is provided by inertial-magnetic measurement units (IMMU). These wearable devices can be unobtrusively attached to the skis of the athlete (and thus, not provide any risk by an attachment to the body) and automatically provide continuous jump data. These jump data can be processed for the estimation of the applied landing force for each jump.

The direct method for processing IMMU data to a force estimation is the multiplication of the mass of the athlete with the acceleration during the landing phase. However, the high acceleration during landing often reaches the sensor's saturation and the calculation based on the acceleration is therefore not sufficiently accurate. An alternative method for IMMU-based landing analysis and the first step towards an accurate force determination is given by determining the momentum during the landing phase. The momentum can be calculated based on the continuously monitored velocity and does not rely on data of the landing phase. Thus, its calculation is robust against landing impact measurement errors but still contains relevant information about the landing.

In the literature, there are several publications on the measurement of ground reaction forces in ski jumping. A detailed overview of publications on biomechanics and force measurement was provided by Schwameder [5]. Amongst others, Schwameder and Müller [10] as well as Virmavirta and Komi [12] focused on force monitoring with pressure insoles. A more recent approach with a two-dimensional force measurement was proposed by Fritz [15]. In his work, custom-made force plates were mounted between the binding and the skis in order to measure horizontal and vertical forces.

Although such constructions provide accurate data for scientific research, they cannot be applied to mass production, training scenarios and competitions. For these purposes, low-cost inertial and inertial-magnetic sensors are more beneficial. Their application to ski jumping is well established for a wide range of ski jumping biomechanics and performance analyses. Chardonnens et al. [16], [17] proposed a jump phase segmentation, determined body segment orientations and further jump parameters with sensors attached to body and skis. Brock et al. [18], [19] incorporated biomechanical parameters for the establishment of a motion analysis and automated scoring system. In previous publications of our group, we proposed a ski orientation computation [20] and the automatic determination of the continuous jump velocity and jump length [21].

In summary, multiple studies with pressure insoles and force plates were performed as well as IMMU-based research with the focus on the determination of take-off and aerodynamic forces. However, none of them analyzed the landing phase with IMMUs. In this work, we propose the computation of the landing momentum with data of IMMUs as the first step towards a force estimation approach in ski jumping. We furthermore evaluate the calculated momentum by comparing to the state-of-the-art force measurement system of Fritz [15].

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II. METHODS

A. Data collection

1) Hardware components: The IMMU data were acquired with the miPod device [22]. The miPod contains the InvenSense MPU9150 inertial-magnetic measurement unit, a real-time-clock (RTC) and a temperature sensor. The IMMU was set to a sampling rate of 200 Hz and a sensing range of $\pm$ 16 g for the accelerometer, $\pm$ 2000 °/s for the gyroscope and $\pm$ 1200 μT for the magnetometer with a 16-bit resolution per sensor axis. Three miPod devices were attached to the skis of the athlete: two to the left ski (one before and one behind the binding) and one to the right ski (behind of the binding). A schematic sketch of the sensor attachment and the IMMU's coordinate system definition is shown in Fig. 1. In addition, the two-dimensional force measurement system of Fritz [15] was installed on the skis. The system contains two separated force plates under the front and rear part of each binding. In total, four force plates were incorporated. All of them measured forces in vertical and horizontal direction with a sampling rate of 1000 Hz. The force measurement system was used as ground truth for the momentum evaluation and will in the following be referred to as *reference system*.
Two cameras were incorporated in the study: one GoPro Hero 2 and one CASIO Exilim EX-ZR200, set to high-speed recording mode with 120 fps.

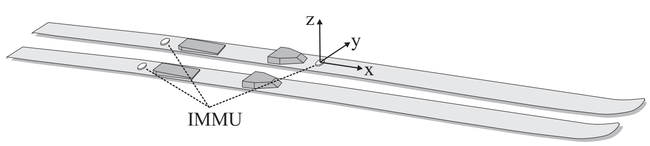

Fig. 1. Sketch of the IMMU's coordinate system and the attachment positions of the three devices on the skis.

2) Study design: The data acquisition with the described components was performed at the HS64 jumping hill in Berchtesgaden, Germany. The jumping hill's take-off platform contained a light barrier-based take-off velocity measurement. Furthermore, a magnetic gate was installed at the end of the take-off platform to mark the take-off instant in the IMMU's magnetometer data [21]. The take-off procedure and the velocity measurement were captured for every jump with the GoPro video camera. The CASIO high-speed camera was focused on the landing area in order to extract the jump length in the video post-processing, based on permanently installed jump length indicators along the landing slope.
Before the data acquisition started, the entire jumping hill was measured with a tachymeter (Trimble S6 Total Station), which was necessary for the determination of the slope inclination in the landing area. Furthermore, a calibration and alignment procedure for the IMMU devices was performed. For the calibration, an adjustable calibration cube (see Fig. 2) was moved and positioned in predefined motion and rest states. A possible misaligned sensor attachment was corrected by the following alignment procedure. Both skis were brought to rest states in two positions: lying flat on a straight table (+z axis pointing upwards) and standing on one side (+y axis pointing upwards).
Subsequently, data were collected during ski jumps. The jumps were performed by one experienced athlete (male, age: 26 years, experience: 20 years, weight incl. all jumping gear: 62.7 kg) who was familiar with the system due to previous studies. He was aware of jump-related risks and gave written consent to for the collected data to be published. In total, IMMU data, force measurements and video recordings of four jumps were captured.

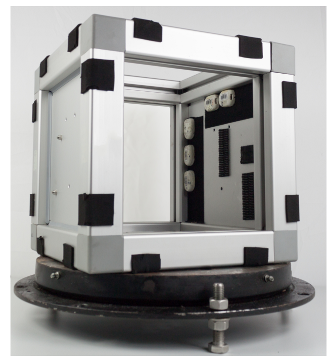

Fig. 2. Calibration cube for the stable calibration of multiple IMMUs.

B. Processing of IMMU data

For the comparison of the IMMU-based system to the reference system, the IMMU-based landing velocity was processed to the landing momentum $p_{land,imu}$.

1) Data preparation: The IMMU data were preprocessed by a sensor calibration and alignment. For the calibration, an extended version of the algorithm of Ferraris [23] was applied. The extended version contained multiple rotations about each sensor axis, which was feasible in the stable calibration cube environment and assumed to lead to more accurate calibration results. The alignment was performed with data of the two rest states (first: +z axis pointing upwards, second: +y axis pointing upwards). Based on the expected and the actual measurements of the accelerometer, the sensor system was rotated to the ski system [24], [25]. With the calibrated and aligned jump data, all necessary kinematic parameters could be determined.

2) Velocity calculation: Following the data processing of our previous work [21], the continuous velocity estimation was established during the jump phase. The data processing contained a continuous estimation of the ski orientation (in the global frame) $\boldsymbol{C}^{g}_{ski,t}$ at all times t. The ski orientation was used to remove the gravity influence on the accelerometer measurements. The resulting motion acceleration (in the body frame) $\boldsymbol{a}^{b}_{motion,t}$ was then integrated from take-off to landing in order to obtain the velocity $\boldsymbol{v}^{b}_{t}$. For discrete measurements, the integral can be approximated by

$$\boldsymbol{v}^{b}_{t} = \boldsymbol{v}^{b}_{0} + \sum \boldsymbol{a}^{b}_{motion,t} \cdot \Delta t. \tag{1}$$

As prior velocity $\boldsymbol{v}^{b}_{0}$, the jumping hill's take-off velocity measurement was incorporated. In order to obtain the continuous velocity in the global frame $\boldsymbol{v}_t^g$, a rotation with the current ski orientation was performed at all times t. If not stated otherwise, all further vectors will refer to the global frame. For the landing analysis, the velocity at landing impact v_{land} is of major interest. However, to avoid the processing of impact-related erroneous measurements, v_{land} was obtained shortly (in this work: 0.15 s) before the landing impact instead of at the actual landing impact. Only the vector component vertically to the landing slope inclination at the landing position $\boldsymbol{v}_{land,vert}$ was relevant for the analysis because only the vertical component influences the landing momentum and force. The required landing slope inclination for the calculation of $v_{land,vert}$ was obtained from the initial tachymeter-based slope inclination measurement for the current jump length. The jump length of each jump could be established with two methods: calculated automatically based on the algorithms of [21] or taken directly from the video analysis. For matters of accuracy, the latter option was chosen for this work.

3) Momentum of landing phase: For the evaluation of our system, the vertical landing velocity $v_{land,vert}$ was computed to the IMMU-based landing momentum $p_{land,imu}$ by a multiplication with the athlete's mass $m_{athlete}$ (including all equipment on top of the skis, here: $m_{athlete}$ = 62.7 kg).

$$p_{land,imu} = m_{athlete} \cdot v_{land,vert} \tag{2}$$

C. Processing of force measurement data

Similarly to the IMMU-based system, the landing momentum $p_{land,ref}$ for the reference system was established.

1) Force calculation and landing duration definition: The force measurements were continuously extracted from the two force plates per ski. The combined force F_t of all components at time t was the sum of all four force plates. In order to compute the momentum of the landing impact, the start and end of the landing interval t_s and t_e had to be extracted. An example force signal of one jump is visualized in Fig. 3. For a more accurate identification of relevant instants, the signal is additionally visualized after applying a low-pass filter. The start of the landing was defined as the first increase in the force signal, which represents the first ground contact. The end of the landing was defined as the end of the eccentric phase, which typically occurs in the minimum of the signal after the second force peak.

2) Momentum of landing impact: Based on the measured force F_t and the landing instants t_s and t_e, the landing momentum of the reference system was computed by

$$p_{land,ref} = \int_{t_s}^{t_e} F_t \cdot \delta t. \tag{3}$$

D. Evaluation

The momenta of the IMMU-based calculation were compared to the reference system for all four jumps. Each jump was measured by three IMMUs, so that three values could be evaluated. The attachment positions of all devices are presented in Table I. Furthermore, the average of all established IMMU-based momenta was computed for each jump and additionally compared to the reference system by

$$accuracy = 1 - \frac{|p_{land,imu} - p_{land,ref}|}{p_{land,ref}} \tag{4}$$

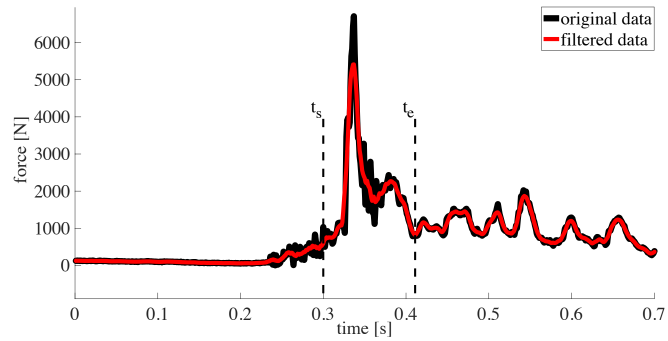

Fig. 3. Force measurement during the landing impact (black: original, red: low-pass filtered). The dashed lines indicate the defined landing interval between t_s and t_e.

TABLE I
IMMU DEVICE ATTACHMENT

device	ski	position
IMMU 1	left	front
IMMU 2	left	rear
IMMU 3	right	rear

III. RESULTS

The results for all IMMU calculations and their average per jump as well as the reference values are shown in Table II. In addition, the accuracy of the IMMU average measurement is provided.

TABLE II
RESULTS: MOMENTA OF ALL SINGLE AND AVERAGE MEASUREMENTS COMPARED WITH GROUND TRUTH.

momentum [kg · $\frac{m}{s}$]	jump 1	jump 2	jump 3	jump 4
IMMU 1	233	216	219	224
IMMU 2	285	209	296	186
IMMU 3	274	271	357	267
IMMU average	**264**	**232**	**291**	**226**
reference	**242**	**228**	**198**	**238**
accuracy	*0.91*	*0.98*	*0.53*	*0.95*

IV. DISCUSSION

The momenta of four different jumps were computed with two independent measurement systems with different measurement principles. The results of three out of four jumps show an error of less than 10 % when comparing the IMMU average to the force measurement reference system. Furthermore, no systematic difference between left and right ski and between the attachment to the front and the rear could be determined. The larger deviation of jump 3 was analyzed and an offset in the velocity signal was found for IMMU 2 and IMMU 3, shortly after the take-off. For more detailed analyses, further data acquisitions with more sensors and possibly video coverage of the entire jump would be required.

The evaluation of the IMMU-based system was based on the momentum, which was sufficient for a first comparison to reference data. However, for the practical application to training, performance analyses and competitions, the computation of the actual force is required. The relation between momentum and force is given by the landing duration (see II-C.1). Hence, either a method has to be established to determine the landing duration with IMMU data or the landing duration has to be estimated based on jumping hill or athlete-specific parameters.

In both cases, the IMMU-based momentum and force calculation depends on the velocity processing. In this work, the landing velocity was chosen by manual signal analysis to be 0.15 s before the landing impact. However, a more general approach should be developed for a permanent application. With a more general solution, the proposed system can work as a stand-alone application during sessions and competitions. The jumping hill has to be prepared once with the magnetic gate at the take-off platform. The landing slope inclination is known for most jumping hills or can be measured once with a tachymeter as in the case of this work. All other components and computations are contained in the IMMUs and the IMMU data processing.

V. CONCLUSIONS

In this work, we proposed an IMMU-based landing momentum computation and achieved an accuracy of more than 90 % for three out of four jumps. Although further algorithm development and data acquisitions are necessary in order to compute the actual landing force, our work demonstrates that a landing analysis with IMMUs attached to the skis is feasible. We therefore present the first step towards an unobtrusive and low-cost landing analysis system for ski jumping.

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