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Biomechanical Analysis of Ski Jumping Landing by means of Wearable Sensors

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Success isn’t always about greatness.
It’s about consistency.
Consistent hard work leads to success.
Greatness will come.
D. Johnson

La vita é una questione di equilibrio.
Sii gentile, ma non lasciarti sfruttare.
Fidati, ma non farti ingannare.
Accontentati, ma non smettere mai di migliorarti.
Buddha

Sei einfach ehrlich mit dir selbst,
das öffnet alle Türen.
V. Howard

La vie c’est comme une bicyclette,
il faut avancer pour ne pas perdre l’equilibre.
A. Einstein

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Summary

Background and aim: In ski jumping, landing plays an essential role for the performance and the safety of the athlete. In fact, a correct execution of the telemark landing phase and an effective position during the landing preparation can considerably influence the jump length and the judges' evaluation score. Moreover, an incorrect landing position could lead to high ground reaction force (GRF), one of the main reasons of knee injuries. However, despite its importance, the number of studies focused on this phase is limited, mainly due to technological problems. Therefore, the aim of the thesis was to perform a biomechanical analysis of the landing phase, by means of wearable sensors in order not to limit the movements and to provide feedback to the athletes. The aim of Study I and II was to introduce, during data collection on the ski jumping hill, the combination between inertial sensors (IMUs) positioned on the ski and wireless force insoles (Study I), and to detect the ski movements during the entire flying performance and their possible correlations with the impact's GRF (Study II). In Study III, the IMU-based system afterwards utilized in Study IV, was validated in order to evaluate its accuracy for its employment in further researches. Finally, in Study IV, the validated IMU-based system was utilized to detect possible correlations between landing kinetics and lower body kinematics and, in addition, the kinetics of over 100 jumps was collected by means of wireless force insoles.

Participants and methods: Ski jumpers (Study I: two athletes, Study II: 10 and Study IV: 22) competing at International level performed the tests. The athletes had all a comparable level, experience and age and belonged to the German National Junior Team. The tests were performed during summer training conditions on the ski jumping hill. The athletes were equipped with wireless force insoles to detect the landing impact and IMUs to detect the ski and lower body kinematics. The outcomes were then utilized to determine correlations (Pearson's and Spearman's) between kinetics and kinematics. In Study III, 14 subjects performed a validation study in the laboratory. The participants were equipped with 16 IMUs and 39 reflective markers in order to compare the collected data of the analyzed IMUs with a gold standard motion capture system (Vicon). The outcomes were compared using root mean square error, one dimensional statistical parametric mapping and Bland-Altman's bias and limit of agreement.

Results: Study I showed the potential of the combination between IMUs on the skis and wireless force insoles. The set up was therefore utilized in Study II, in which the pitch during the landing preparation phase was showed to be the ski movement that mainly influences the impact kinetics. Moreover, the results showed that each athlete owns his specific ski pattern during the flight phase. The results of Study III demonstrated that the accuracy of the considered IMU-based system varies according to the task performed, with a general accuracy of the knee, hip and pelvis joints. The study provides to the researchers the means to judge if the analysed IMU-based system is sufficiently accurate for their in-field applications. Finally, in Study IV the primary finding was that to longer jumps corresponded higher GRF and impulses. Moreover, the GRF and the impulse were not symmetrically distributed between the two feet, independently from the landing technique. Under the biomechanical point of view, correlations between the hip, knee and ankle angles and the kinetic variables were found.

Conclusion: The kinematics and the kinetics of the ski jumpers during the landing are directly connected. Therefore, in order to reduce the GRF magnitude, responsible of possible injuries, the athlete should focus on his/her kinematics before the landing, in particular, on the ski pitch during the landing preparation and, based on preliminary results, on the hip extension and, knee and hip rotations during the impact. Being fast to place and not invasive, the use of IMUs and wireless force insoles for the biomechanical analysis of ski jumping landing (and of the overall performance) resulted to be recommendable for further studies, as well as tool for training feedback.

List of scientific papers

The present manuscript is presented as a cumulative thesis composed of four peer-reviewed articles. Each paper will be referred in the text by its Roman numerals.

I. **Bessone, V.**, Petrat, J., Seiberl, W., Schwirtz, A. (2018). Analysis of landing in ski jumping by means of inertial sensors and force insoles. *Proceedings*, *2*(6), 311; DOI: 10.3390/proceedings2060311

II. **Bessone, V.**, Petrat, J., Schwirtz, A. (2019). Ski position during the flight and landing preparation phases in ski jumping detected with inertial sensors. *Sensors*, *19*(11), 2575; DOI:10.3390/s19112575
Impact factor: 3.076

III. **Bessone, V.**, Höschele, N., Schwirtz, A., Seiberl, W. (2019). Validation of a new inertial measurement unit system based on different dynamic movements. *Sport Biomech;* DOI: 10.1080/14763141.2019.1671486
Impact factor: 1.714

IV. **Bessone, V.**, Petrat, J., Schwirtz, A. (2019). Ground reaction forces and kinematics of ski jump landing measured with wearable sensors. *Sensors, 19*(9), 2011; DOI: 0.3390/s19092011
Impact factor: 3.076

During the dissertation the author of the thesis was involved also in the following publications:

- Bolger, C.M., **Bessone, V.,** Federolf, P.A., Ettema, G., Sandbakk, O. (2018). The influence of increased distal loading on metabolic cost, efficiency, and kinematics of roller ski skating. PloS ONE 13(5). DOI: 10.1371/journal.pone.0197592
Impact factor: 2.776
- Piprek, P., Glas, F., Fang, X., **Bessone, V.,** Petrat, J., Bittner, M., Holzapfel, F. (2018). Multi-Body Ski Jumper Model with Nonlinear Dynamic Inversion Muscle Control for Trajectory Optimization. *Proceedings*, *2*(6), 321; DOI: 10.3390/proceedings2060321

Moreover, the doctoral candidate contributed to the following works presented during International Congress:

- **Bessone, V.**, Göpfert, C., Linnamo, V., Lindinger, S. (2016). Contribution of arm swing on the kinematics and energy contribution characteristics of V2A ski skating in elite cross-country skiing. *Poster presentation* - International Congress of Science and Skiing - Arlberg (AUT).
1st place at the Young Investigator Award for the poster session
- **Bessone, V.**, Paternoster, F., Stanglmeier, M., Veith, M., Schwirtz, A., Seiberl, W. (2017). Biomechanical characteristics related to poling propulsion effectiveness in cross-country V2 skating technique. *Oral presentation* - Congress of the International Society of Biomechanics in Sports - Cologne (GER)
- **Bessone, V.,** Petrat, J., Fang, X., Piprek, P., Bittner, M, Holzapfel, F., Schwirtz, A. (2017). Optimal control methods in ski jumping. - *Poster presentation* - Deutschen Vereinigung für Sportwissenschaft - Munich (GER)

- Petrat, J., **Bessone, V.** (2017). Improving performance in juvenile ski jumping: optimization of ski angles in the flight phase. *Oral presentation* - Congress of the International Society of Biomechanics in Sports - Cologne (GER)
- **Bessone, V.,** Petrat, J., Seiberl, W., Schwirtz, A. (2018). Analysis of Landing in Ski Jumping by Means of Inertial Sensors and Force Insoles. *Oral presentation* - Congress of the International Sport Engineering Association - Brisbane (AUS)
- Piprek, P., Glas, F., Fang, X., **Bessone, V.,** Petrat, J., Bittner, M., Holzapfel, F. (2018). Multi-Body Ski Jumper Model with Nonlinear Dynamic Inversion Muscle Control for Trajectory Optimization. *Oral presentation* - Congress of the International Sport Engineering Association - Brisbane (AUS)
- **Bessone, V.** (2018). Research outcomes vs. Athletes' feelings during ski jump landing. *Oral presentation* - Conference of the European College of Sport Science - Dublin (IRL)
- **Bessone, V.**, Kocbach, J., Kodiyan, A., Sandbakk, Ø. (2018). Differences in force distribution between amateur and professional cross-country skiers using force insoles. A pilot study. *Poster presentation* - Open Day - Granasen, Trondheim (NOR)
- **Bessone, V.,** Petrat, J., Seiberl, W., Schwirtz, A. (2019). Torso and hip flexions influence ski jump landing impact. *Oral presentation* - International Congress of Science and Skiing - Vuokatti (FIN)
- Paternoster, F.**, Bessone, V.,** Schwirtz, A., Seiberl, W. (2019). Biomechanical analysis of G3 skating technique on a treadmill of world-class and national-elite female biathletes. *Oral presentation* - International Congress of Science and Skiing - Vuokatti (FIN)
- Kodyinian, A., Kocbach, J., **Bessone, V.,** Dadashi, F. (2019). Cross-country technique and sub-technique classification using a single inertial sensor placed on the ski. *Oral presentation* - International Congress of Science and Skiing - Vuokatti (FIN)

1. Introduction

The present thesis focuses on the biomechanical analysis of ski jumping (SkiJ) landing by means of wearable sensors, with final goal giving technical suggestions to athletes and coaches in order to improve safety and increase the performance of the ski jumpers. The thesis was accomplished on behalf of the project SkOPTing (Optimal control methods in ski jumping), promoted by the International Graduate School of Science and Engineering of the Technical University of Munich, with goal the biomechanical and flight dynamic modelling of a ski jumper and the application of optimal control methods, targeting the increase of competitive performance and, at the same time, the prevention of injuries. In the project, four doctoral candidates, respectively of the department of Biomechanics in Sports and of the Institute of Flight System Dynamics, collaborated for generating an optimized simulation of the SkiJ performance based on real in-field data. Beside the main project, each doctoral candidate had a specific dissertation focus; in the case of the author of the present thesis, the biomechanical analysis of SkiJ landing.

In this chapter, an inside overview about the sport of SkiJ is given, and a description of the landing and of its importance is reported in order to introduce the thesis.

SkiJ is a winter sport in which a score defined the performance, considering jump length, wind compensation, starting gate and technical execution of flight and landing, evaluated by five judges [1]. The performance is held on specific venue called SkiJ hill, on which depending on the size and design of the building, the athletes can reach different jump length (up to over 250 m on the flying hill).

The SkiJ performance is divided in different phases: in-run, take-off, early flight, stable flight, landing preparation and landing impact (Figure 1). These last two phases both belong to the landing phase. During the **in-run**, the athlete descents a ramp in an aerodynamic squat position with the arms at the side, trying to increase his/her speed. The **take-off**, performed on the SkiJ hill table, is the proper jump and is considered the most important phase [2]. The **early flight** is the transition phase between take-off and stable flight: The athlete needs to position his/her body in an aerodynamic position to maximize the surface area kept afterwards during the stable flight. In this phase, the athlete needs to limit the movements of his/her body and skis trying to adapt his/her configuration to aerodynamic changes. From a **stable flight** position, the athlete prepares to land (**landing preparation**) and, consequently, to dampen the ground reaction forces (GRF) that act on him/her during the **landing impact** by using the telemark position – one foot positioned ahead of the other (step position) with the arms stretched beside. The athlete should perform the connection between the phases with a smooth movement for optimizing the performance [1]. Moreover, in order to have an efficient execution, the ski jumper should focus on all the phases of SkiJ, affecting each phase the following one [2].

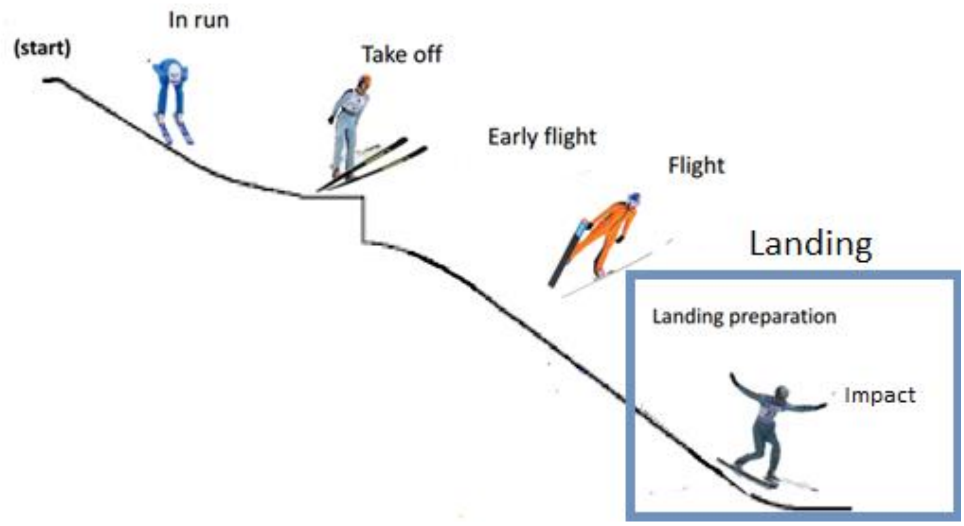


Figure 1. Representation of the SkiJ phases during the entire performance on the hill.

In SkiJ, the landing biomechanics plays a central role for improving the performance and for reducing the injuries [2-8]. In this sport, in fact, injuries are frequent (around 21 every 100 jumps) and knees are the most involved joint (25% of the overall injuries) [9]. In particular, the anterior cruciate ligament (ACL) rupture is a frequent knee injury in SkiJ and could be caused by the high GRF during touch-down, ranging from 1.5 to over 3.0 body weight (BW) depending on the landing technique [2]. Besides the health problem, injuries caused staying out from competitions and trainings for more than four weeks in 25% of the cases, since 37.5% of them are involving joints and muscles, and 25% contusions [9].

As abovementioned, besides jump length, wind and starting gate, also the technique during the flight and landing phases are part of the total score that constitutes the jump performance during competition. In particular, according to the FIS competition rules [1], ski jumpers should prepare the landing as follows. *"From a stable flight position, raises head and upper body, moves the arms on the sides* […] *and turns the skis into a parallel position*", then just before the touch-down "*splitting the* *legs and bending the knees*". Reduce the impact by means of muscle power and "*increase the distance between the legs and bend the back leg* […], *(telemark position)* (Figure 2) *with the skis parallel and obtain the pressure equal on both legs and* […] *stretch both arms horizontally and forwards upwards*". However, in certain conditions as long jump distance, bad grooming of the landing area or wind, the athlete lands in a parallel squat position (parallel leg landing) that leads to a points' detraction to the final score.

Figure 2. Ski jumper doing telemark landing on the hill HS100 in Sapporo (JPN) [10].

Due to the lack of studies, further technical adaptations about landing are left to the athletes' experience and coaches' suggestions. However, knowing the most important biomechanical predictors that lead to injuries could permit to focus trainings and technical suggestions in order to reduce the GRF during landing, considered as one of the prevention factors in knee injuries as ACL rupture [11-13]. Therefore, an analysis of the biomechanics behind SkiJ landing is necessary to have a deeper understanding of the movement for further improvements of the technique and possible reductions of the injuries. In particular, quantifying the GRF magnitude that occurs during the landing and the kinematics that correlate to it, could provide pragmatic suggestions to the athletes in order to reduce the injury risk.

The thesis is composed of four studies. Firstly, a methodological paper introducing, during in-field studies on the SkiJ hill, the combination between inertial motion units (IMUs) on the skis and wireless force insoles positioned into the ski boots will be reported, followed by its application on an extensive study in order to understand the possible correlations between the landing kinetics and the ski kinematics. Afterwards, a laboratory validation study of one of the IMU-based systems employed will be introduced. Finally, the last study deals the analysis of the landing kinetics by means of force insoles, with an introduction of the combination of IMUs on the lower body combined and force insoles, in order to introduce possible correlations between impact force and lower body kinematics.

The goal of the thesis is to give an overview under the biomechanical point of view of SkiJ landing employing wearable sensors to quantify the kinetics during landing impact and to investigate possible correlations between the ski and body kinematics and the kinetics. Final goal is to give practical suggestions to the athletes as well as providing further knowledge to the scientific community about the ski jumper's performance.

2. Background

The following chapter gives an overview about the background related to this thesis. Consequently, an overview about the biomechanical research in SkiJ (2.1) and an introduction to how the SkiJ performance is usually analysed (2.2), with focus on the two main technologies utilized in the studies (IMUs (2.2.1) and wireless force insoles (2.2.2)), will be presented.

2.1 Biomechanical research in ski jumping

Since its birth in Scandinavia at the end of the 19th century, SkiJ has always been a competitive sport. Therefore, it evolved enormously in the years, always with the final goal of achieving greater jump distances. Consequently, different SkiJ techniques, firstly based on experience, and then on research, were introduced in the years [14]. For example, after World War I, Jacob Thulin Thams developed a new SkiJ style known as the Kongsberger technique, involving jumping with the upper body bent at the hips, a wide forward lean, and with arms extended at the front with the skis parallel to each other (Figure 3) [15]. In the 1950s, Andreas Däscher became the first jumper to hold the body with a more extreme forward lean. Then in 1985, Jan Boklöv started spreading the tips of his skis into a "V" shape. Initially ridiculed, this flying technique proved to be so successful that, by 1992, all Olympic medalists were using this style and it is still the main used ski shape configuration together with the "H" shape, adopted by some athletes in the most recent years.

Figure 3. Ski jumper using the Kongsberger technique [10].

Even though biomechanical research in SkiJ has a long tradition - starting back in the 1920s [16,17] –, the number of publications is limited, mainly due to the exclusive competitive nature of the sport, i.e. in many research centers, studies and technological development are carried out but the results are not shared among the scientific community and among national teams in order to avoid the possibility of giving advantages to the opponents [6]. Moreover, the majority of the studies focused on the first phases of the performance, i.e. in-run, take-off and flight [18]. Landing, on the other hand, is considered of minor importance and, in the past, it was not even described as a SkiJ phase [19-21].

SkiJ is a particular sport, under many points of view. For example, it is only a competitive (and elite) sport, needs a wide and specific area to be performed and few repetitions of the movement are done during both training and competition [22]. Therefore, under the biomechanical point of view, researchers have to face different problematics when analyzing SkiJ. For instance, the difficulty of covering the wide area of the SkiJ hill during the analysis, the limited number of repetitions or the difficulties in the detection of the correct joint angles due to the wide SkiJ suit, and so on. On the other hand, SkiJ is biomechanically particularly interesting and challenging being characterized by completely different movements during its performance: From a static squat position during the in-run followed by the squat jump during take-off, to the unconstrained flight and the high impact of landing.

Biomechanics plays an important role for making decisions and improvements related, for example, to equipment, wind and gate factors, technique and body mass index regulations in SkiJ (Figure 4, [22]). Equipment, specifically, had a huge evolution during the years. During the Winter Olympic Games of Vancouver 2010, for instance, the Suisse ski jumper Simon Ammann won the gold medal using new developed bindings, which are currently the only ones used by the athletes.

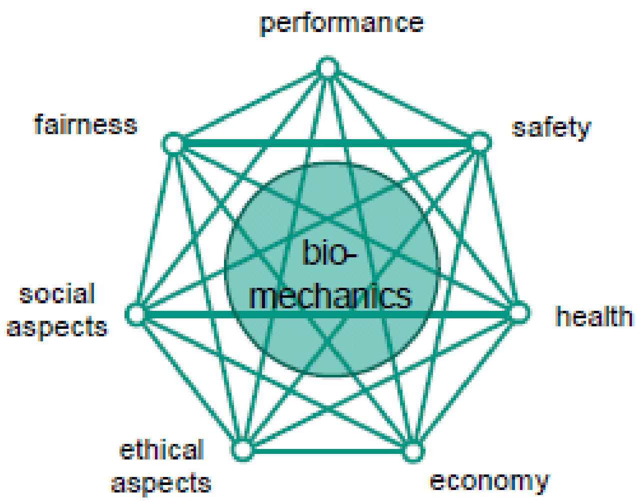


Figure 4. Biomechanics connects many aspects of SkiJ, according to Schwameder [22].

As above mentioned, SkiJ is characterized by a very high number of regulations. For example, the size of the suit is checked during competition, in order to avoid the “kite effect” in case of a too wide suit. Due to the importance of the weight of the system (athlete plus equipment) for improving the performance [23,24], strict regulations are also applied to the body mass index and the ski jump length that are constrained together [5], in order to avoid anorexia among the athletes, as well as the tumbling effect frequently registered during the competitions in the middle of the 90s [15]. Having a deeper biomechanical knowledge about the athlete kinematics during the performance can be helpful, not only for designing and making considerations about the regulations of new equipment, but also for regulating the technique that the athlete need to use, being connected to the performance and the safety.

Another important note is that the publications related to SkiJ deal only with male athletes. To the best of our knowledge, in fact, in only one case female athletes were involved [25]. Curiously, a higher number of researches dealing with SkiJ and women focused on the recognition of individual rights and sex discrimination [26-31]. Although some expedients, women started competing in SkiJ since the end of 19th century and revealed to be, in some case, more talented than men, as nicknames as ‘the Floating Baroness’ (Austrian Paula Lamberg) and the ‘Queen of Skis’ (Norwegian Johanna Kolstad) could suggest [30]. During 20th century, SkiJ saw a decrease of female participation. Reasons should be searched in the immoral movement of SkiJ, as well as the possible cause of infertility suggested by doctors [26]. As a result, although female alpine and cross-country skiers competed in an international circuit from the early 1950s onwards, female ski jumpers had their own international competitions only from the late 1990s and their first World Cups during the season 2011-2012. As a matter of fact, analyzing the biomechanics of female ski jumpers is recommendable, being women physiologically and biomechanically more inclined to joints’ injuries after landing impact [32,33].

2.2 Measuring ski jumping performance

As previously mentioned, the overall SkiJ performance is particularly challenging to biomechanically analyze for different reasons, above all the wide area of the SkiJ hill and the small number of repetitions. Therefore, to the usual in-field data collection, also computer simulations of the flight phase and investigations of simulation jumps in a laboratory or in a wind tunnel are performed [18]. Computer simulations could predict and answer many questions related to training methods, safety and health consideration without interfering with athlete’s safety. On the other hand, decomposing the ski jump in easier tasks that simulate part of the performance and that are easier to analyze indoor (Figure 5), researchers can obtain a high reliability of the test, but at the same time, reducing the validity [22,35]. Imitation jumps are simulated movements (mainly take-offs) of the SkiJ performance without ski equipment and in “dry” conditions (i.e. with training shoes). These movement simulations are important for training, diagnostics and research [22,34-36] and elite jumpers showed high consistency and reproducibility between the real and simulated take-off [22].

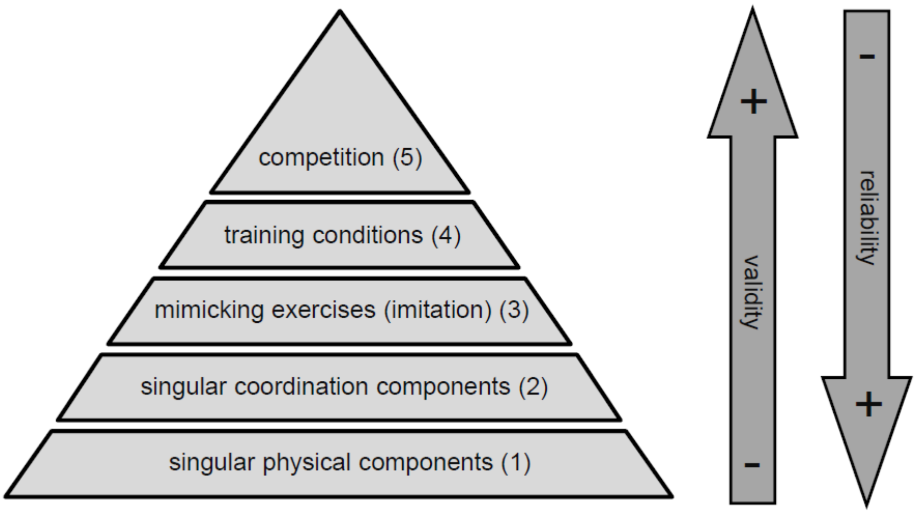


Figure 5. According to Schwameder [22], the levels of experimental biomechanical research and classification regarding validity and reliability can be summarized with a pyramid plot.

During in-field data collection, the kinematic analysis have been mainly focused on two-dimensional video capture and on small portion of the SkiJ hill to analyze the performance [6,8,21,37-39]. In fact, due to the wide area of the hill, a full jump performance required a high number of cameras, with a considerable time lost for their placement as well as for the post-processing of the videos. In addition, the suit of the athlete limits the detection of the joint centers, reducing the accuracy of the collected data (Figure 6). As a result, in the last years, the use of IMUs have been introduced for the analysis of SkiJ, permitting a faster set-up, post-processing and a reliable 3D analysis [40-48].

Figure 6. Sequences of the landing preparation of one athlete (in light blue) recorded using a video camera positioned on the landing area. The position of the athlete in the first sequence of the movement is highlighted with a red circle. It is notable the low definition quality of the body of the athlete.

The kinetic analysis on the SkiJ hill is challenging to perform, mainly due to technical reasons [2]. The majority of the studies focused on measuring the GRF at the take-off, using force plates integrated in the SkiJ hill table [49-54], by means of plantar pressure insoles [5,55-57] or of custom-made force measuring bindings [48,58]. However, the systems have, respectively, the disadvantage of recording only the take-off force, limiting the movements due to the weight and the cables, and having the necessity of being validated [2]. As for the above mentioned IMUs, thanks to the technological development of the last years, new sensors have been introduced to analyze the kinetics. In fact, the introduction of new force insoles equipment with embedded memory or Bluetooth connected to the receiver permit to perform in-field kinetic analysis without interfering with the kinematics of the athlete.

In the following subchapters, the characteristics of the IMUs and the wireless force insoles are introduced, being the two wearable sensors used during the studies of the present thesis. IMUs and wireless force insoles have been chosen as sensors being able to collect the entire SkiJ performance, and in particular, the landing that is a phase executed on a wide area (depending on jump length) and of which the kinetics is impossible to analyze without wireless sensors.

2.2.1 Inertial measurement units

IMUs are sensors that, in the last years, became more and more popular in biomechanical research, since they have no space limitation and cumbersome setup [59,60]. Moreover, they are portable, cheap, light and easy-to-use also during in-field measurements (Figure 7) [61]. Therefore, IMUs represent an optimal solution for analysing the SkiJ performance. In the present thesis, IMUs of two different companies (MSR Solutions and myolution GmbH) have been employed to analyse the kinematics of the athletes on the SkiJ hill.

Figure 7. IMU *aktos-t* as the ones used the studies of the thesis.

IMUs generally consist of an accelerometer, a gyroscope and a magnetometer. The components provide respectively the linear accelerations, the angular velocities and the local magnetic field vectors in the three directions. Despite the three components can be used separately, for example for event detection, their outcomes must be used combined. In fact, the components are characterized by different errors, as the drift that occurs after integrating the angular velocity for obtaining the orientation and after integrating twice the acceleration for obtaining the position, or the magnetic field distortion that interferes with the magnetometers. Therefore, sensor fusion algorithms are developed and permit the combination of the outcomes of the three IMUs' components, reducing their errors and obtaining information about the orientation of the body segment on which the IMUs are fixed. Once the IMUs' orientation are collected, the joint kinematics can be estimated based on a biomechanical multibody model, an anatomical calibration and the determination of the reference joint configuration [62].

The possibility of measuring movement outdoors created the opportunity of using IMUs in skiing (alpine and cross-country skiing, ski mountaineering, snowboard and SkiJ), in water sports (swimming, rowing, diving) and in team sports (baseball, basketball, ice hockey, soccer,…), as well as in sport for which indoor imitation devices have been designed, as cycling and running [63]. An advantage of the IMUs is that they can been used also for event detection, match analysis and activity classification [63].

In SkiJ, IMUs have been employed to analyse the lower body kinematics during in-field data collection. The use of IMUs in monitoring SkiJ will be more deeply described in the following chapter (*Current state of research*). In general, body orientation [44], hip and knee flexion/extension [43,48], sacrum, thigh and shank estimation [43,44] and ski angles [43,45] have been analyzed with the IMUs. Moreover, kinetic studies have been conducted using inverse dynamics and estimating the external aerodynamic force during stable flight [43], the take-off force [44,47] and the landing impact momentum [48].

2.2.2. Force insoles

During in-field data collection, the continuous kinetic analysis is possible by means of portable pressure or force insoles. However, the main limitation of these systems is the connection by cables to the receiver that can interfere with the movements of the athletes, interacting with both safety and performance.

In virtue of the technological development, force insoles have faced improvements, thus constantly assuring good capture quality without interfering with athletes' movements, thanks for example to memory and battery embedded in the insole itself or to Bluetooth connections with the receiver.

The *loadsol* system (Novel GmbH, Munich, GER) used in the studies of the present thesis, for example, is composed of force insoles by means of which is possible to measure the normal GRF on the plantar surface of the foot in both standing and dynamic movements (Figure 8). However, through this system is not possible to measure characteristics as the center of pressure, and the overall and local pressures.

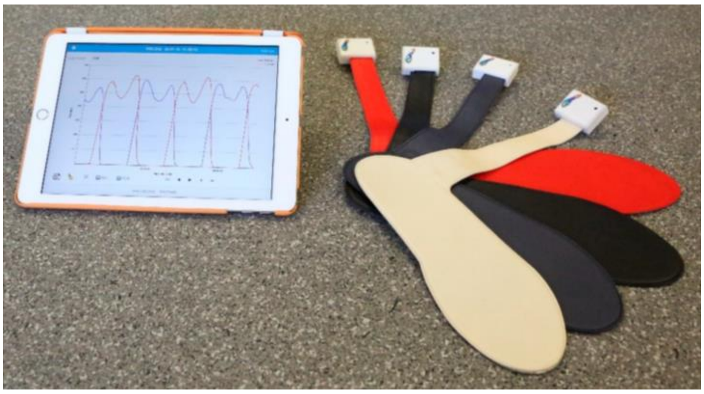


Figure 8. *loadsol* force insoles and interface of the app [64].

The flat insole sensor is composed of piezoelectric material that changes the electrical characteristics when subject to pressure and can be divided in different parts in order to detect the front/rear, medial/lateral or front/middle/rear forces. The present system has been previously validated [64-68], demonstrating to be a reliable technology to analyze kinetics during in-field measurements. The sensors can sample at a frequency of 100 or 200 Hz and are connected by Bluetooth to a smartphone or tablet that works as receiver as well as to start and stop the recording using the related *loadsol* app (Novel GmbH, Munich, GER) [69].

3. Current state of research

In the following chapter, the research state related to the biomechanical analysis of landing phase will be mentioned and reported in Table 1. Due to the limited literature on the topic, not only studies specifically addressing the landing are reported, but also studies that partially dealt or made considerations on this phase.

Table 1. Overview of the studies dealing partially (All: all SkiJ phases considered) or totally about SkiJ landing (Land) using simulation or a set up during hill competitions or trainings or in a wind tunnel. The employed technologies are showed (as inertial sensors (IMU), electromyographic sensors (EMG), Custom-made force-measuring binding, etc.), as well as the number of subjects (Subj) and the main contents.

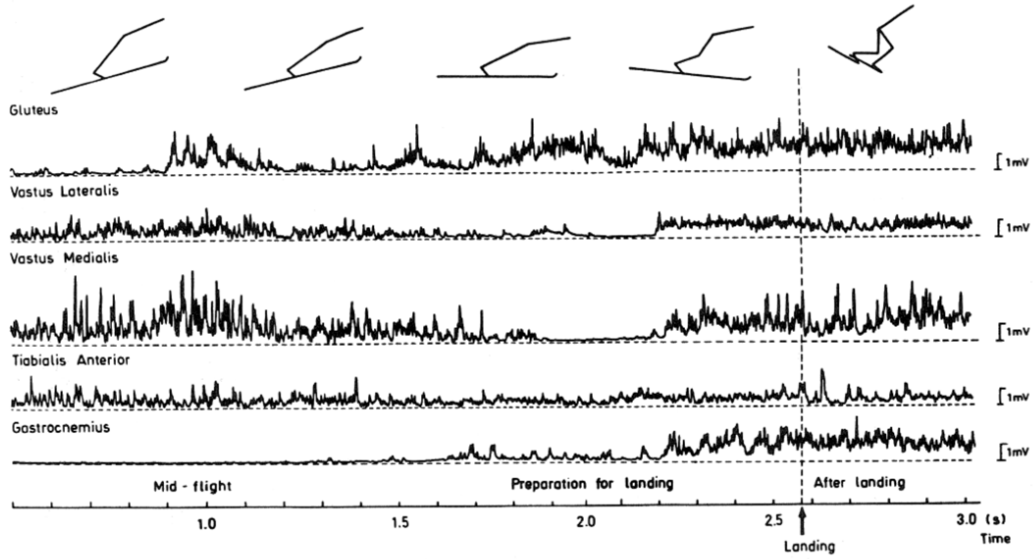
Publication	Topic	Phase	Technologies (Subjects) Setup	Main contents
Ward-Smith & Clements (1982) [4]	SkiJ aerodynamics	All	- - simulation	Consideration about aerodynamics before landing
Virmavirta & Komi (1991) [52]	EMG analysis during SkiJ performance	All	EMG sensor (4) training	Gastrocnemius, gluteus and tibialis anterior are more activated during landing impact than in all the other SkiJ phases
Schwameder & Müller (1995) [5]	Analysis of the V-technique	All	Force insoles (8) training	The landing peak reaches three times BW
Babiel et al. (1997) [57]	Reaction forces' frequencies in alpine skiing, cross-country skiing and SkiJ	All	Custom made bindings (1) training	During landing the frequency reaches 15 Hz
Hochmuth (1999) [6]	Telemark landing	Land	2D video analysis (10) training	Landing preparation distinguishes between soft and hard landing. Advantages and disadvantages of telemark movement; importance of skis' material elastic properties
Virmavirta & Komi (2000) [55]	Pressure force during take-off	Take-off	Pressure insoles (3) training	Kinetic analysis of take-off kinetic with presentation of the data referred to the entire performance
Seo et al. (2001) [7]	Aerodynamics of ground effect in SkiJ	Land	WT; force plate - wind tunnel	The V-style flight contributes to making a larger lift force, increasing the braking action and improving jump length up to three meters
Greimel et al. (2010) [8]	Difference in landing	Land	2D video analysis	Kinematics in landing and its preparation influence the

	preparation between top-/low-ranked athletes		(20) competition	performance; good jumpers keep a beneficial aerodynamic position longer; performance distinctive groups mainly differ in the landing preparation
Chardonnens et al. (2013) [42]	System to measure the all performance using IMUs	All	IMU (22) training	Validation of algorithm to analyze SkiJ with IMUs
Groh et al. (2018) [48]	Landing momentum estimation with IMUs	Land	Custom made bindings; IMUs (1) training	Possibility of estimating landing momentum using IMUs with a 90% accuracy

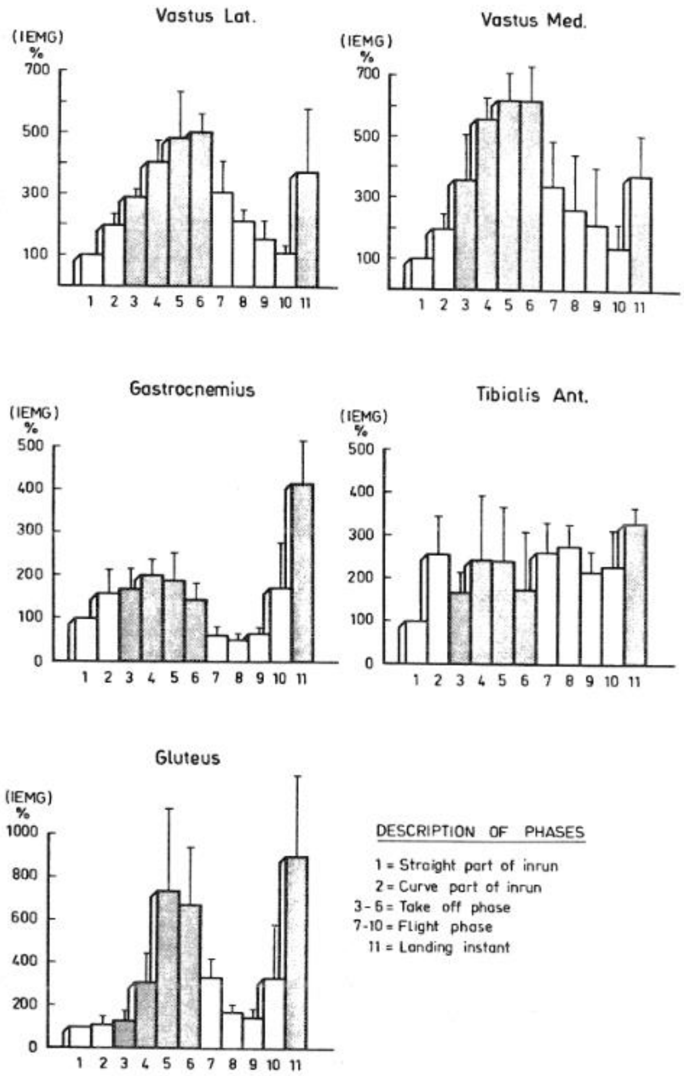
Mainly due to the previously mentioned technological problems, the number of publications related to landing has been limited. Moreover, since the SkiJ technique saw an important development among the years, the performed researches can be considered obsolete. Therefore, a further research addressed on this phase is necessary for increasing the understanding of the movement.

The first considerations about the landing were made by Ward-Smith and Clements in 1982 [4] and based on computer simulation and on wind tunnel measurements. In the study, the authors concentrated on the aerodynamic pitching moment, lift and drag forces acting on the athlete during the whole phase.

In 1991, Virmavirta and Komi [52] performed an electromyographic (EMG) analysis during the entire jump performance, showing how during landing, the muscles are more active than in all the other phases, since contrasting the impact force. The gluteus (GL), the tibialis anterior (TA) and the gastrocnemius (GA) in particular, showed the higher activation of the entire performance during landing (Figure 9). During landing preparation, EMG analysis showed a decrease of the knee extensor and TA muscles [52]. During the landing impact, the vastus medialis and lateralis, TA, GL and GA muscular activities increase for damping the landing (Figure 9a). The authors discussed how an early landing preparation can be seen by a decrease of TA and knee extensors and an increase of the EMG signal of GA and GL, that can be connected to the fact that the athlete is afraid to maintain the optimal flying position as long as possible or that a smooth landing could require a long time to be executed [52].



a.



b.

Figure 9. Gluteus, vastus lateralis and medialis, tibialis anterior and gastrocnemius muscle activation during the landing preparation and landing (a.) and during the all performance (b.), according to Virmavirta and Komi [52].

Under the kinetic point of view, Schwameder and Müller [5] showed the proceeding of the force during the entire performance, while Babiel and colleagues [57] the frequency contribution of the vibrations during SkiJ landing impact in comparison to alpine and cross-country skiing.

The first studies that specifically dealt, respectively, with the landing impact and with the landing preparation, were the ones of Hochmuth [6] and Seo and colleagues [7]. Hochmuth [6] discussed the use of telemark landing based on biomechanical considerations and kinematic data collected during the landing phase by means of video cameras. The telemark has been positively and negatively critized by the author, being biomechanically more efficient than the parallel leg landing, i.e. landing with the leg in a squat position. In fact, telemark landing with its step position gives more balance and permits to reduce the impact. On the other hand, at the same time, the lack of experience of the athletes in performing the gesture could lead to an incorrect movement and therefore, to a possible injury. Analyzing the landing impact and its preparation at certain time before the touchdown, Hochmuth [6] described the soft and hard landing approaches: The longer the duration of the braking process, the softer the landing. Moreover, the bigger is the flexion angle between skis and landing area during the impact, the longer is the braking action due to the elastic properties of the skis. During wind tunnel experiments, Seo and colleagues [7] found important contribution to jump length and landing stability acting on the ski positioning during landing. Keeping the V-style for a longer time permits in fact to increase the lift action of the air, braking the speed and improving the jump length up to three meters.

Greimel and colleagues [8] analyzed the kinematic differences during landing preparation between top and low ranked athletes, collecting videos during one of the Olympic Games competitions of Turin 2006. The outcomes showed that 0.40 s circa before the landing impact, the first lower body joint movements (hip and ankle) are detected, while 0.16 s before the landing the knee variations were observed. Moreover, top-ranked athletes demonstrated to keep the flying position for a longer time than the low-ranked athletes, having in this way, a shorter landing preparation time. However, delaying the landing preparation could lead to an incorrect telemark landing position and to high impact forces.

Thanks to the introduction of IMUs during in-field studies, Chardonnens and colleagues [45] overcame the limitation of video analysis on the SkiJ hill. However, despite collecting the entire performance by means of the IMUs, the focus was not on the kinematic analysis of landing phase, but on the flight.

Finally, Groh and colleagues [48] introduced new methods to estimate the landing impulse (I) based on inverse dynamics. Using the acceleration recorded by IMUs, and comparing the outcomes with the ones of a custom made force binding system, the group obtained an accuracy around 90%.

4. Rationale for the thesis and aims

The current state of the research about SkiJ landing phase permits further investigation (Figure 10). The aim of this thesis was to quantify the kinetics during landing impact, and to investigate possible correlations between the ski and body kinematics and the kinetics, while using wireless technologies. Moreover, in order to shorten the gap between scientists and sport professionals, after each data collection, a biomechanical feedback was given to the athletes and coaches providing useful information for improving the technique and showing a direct application of the employed technologies to the field. In the following, the rationale of the thesis and the aims of the single studies will be presented.

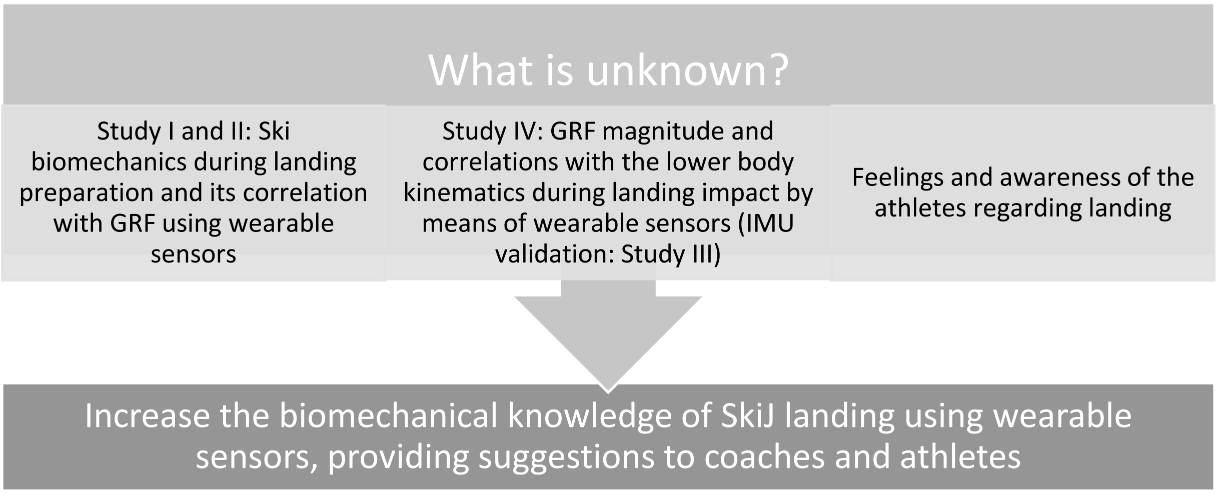


Figure 10. Consequence of the unanswered questions regarding the landing phase in SkiJ.

The main challenge regarding the analysis of landing was related in the past to the technological limitation. For this reason, a deep biomechanical analysis of landing is missing and the few information regarding it are related to studies that focus on other SkiJ phases [4,5,42,52,55]. This being stated, a better understanding of the movement could permit to give technical suggestions to coaches and athletes for improving the performance and reducing the injury risk.

Beside the mentioned technological limitation, the importance of landing (both the impact and the landing preparation phases) seems underestimated by athletes and coaches. Therefore, before starting the proper in-field biomechanical investigation, the doctoral candidate questioned the skiers for having an overview of their feelings during these phases' execution. The results were reported to the scientific community during the European Congress of Sport Science Conference 2018 (Dublin, IRL), in the presentation “Research outcomes vs. athletes’ feelings during ski jump landing”, and here resumed as part of the rationale for the present doctoral thesis.

In the study, the doctoral candidate shared with the ski jumpers an online questionnaire, composed of 46 questions (37 related to landing). The questions spaced from the kind of training to the perception of the skiers during the performance.

Forty-three (♂: 29, ♀: 14; 17 ± 4 years) ski jumpers and Nordic combiners competing at different levels answered to the questionnaire. All the athletes did train on the hill at least twice per week and jumped at least five times per session. 49% of the interviewed had at least one common injury connected to a bad landing, in accordance with Flørenes and colleagues [9], in particular broken bones, ACL rupture and ligament contusion.

The pool ranked the take-off, in-run, early flight, flight, landing preparation and landing from the most to the least important SkiJ phase. The take-off was classified as the most important, as reported in literature [2]. Experience leads the start of landing preparation for 43% of the athletes (Figure 11a). Being easier to perform than telemark [6], the athletes performed parallel leg landing in difficult conditions, in this order: when the jump is too long, when the landing area has a bad grooming and/or a bad visibility, and strong wind (Figure 11b).

Figure 11. Chart from 1 to 4 of the reasons that lead the athletes to start the landing preparation (a.). Chart from 1 to 4 of the reasons that lead the athletes to choose using the parallel leg landing rather than the telemark (b.).

81% of the pool preferred to land on the synthetic grass/mat during summer conditions, being more stable to land on. However, it has been observed how the low friction (static: 0.10; dynamic: 0.05; [70]) between skis and snow could reduce the posterior GRF, that it is considered to protect the ACL [71]. Moreover, it is interesting to notice how the lack of visibility and a bad grooming of the landing area are important for athletes' safety, according to their experience. Therefore, in order to have a possible decrease of the number of injuries, the organizers should try to guarantee to the athletes better environmental condition around the landing area.

The questionnaire was an interesting overview for documenting the feelings of the athletes about landing. This knowledge is an important aspect for focusing further researches and before proposing technical changes to the athletes. However, in order to improve their performance, the athletes should focus on all the phases of SkiJ, being each phase strictly related to the subsequent one [2].

Aim of Study I and Study II

To introduce the combination of IMUs positioned on the ski with wireless force insoles for the in-field use on the SkiJ hill (Study I). To detect the ski movements during the entire flying performance and its possible correlations with the GRF during landing, using the setup of Study I (Study II).

During SkiJ landing preparation, as well as during the entire flight phase, ski position plays an important role for performance and safety [3,6-8,75,76]. The ski jumper usually tries to keep a V-style ski position, but he/she needs to continuously adjust the ski movements in order to compensate external factors (as the change of air pressure and wind) that are acting on him/her, finding a compromise between a steady position and angular adjustments [76]. Therefore, knowing the ski positioning during the performance could be a promising tool for training. Moreover, knowing possible correlations between the ski positioning during the landing preparation and the normal GRF could lead to technical adaptations. Thanks to their accuracy and weight, IMUs placed on skis have been applied in previous studies dealing with cross-country skiing [77-82] and ski mountaineering [83]. In SkiJ, IMUs have been previously employed [43-48], as described in the subchapter 2.2.1. However, before using extensively a new setup and combination of sensors, their validation needs to be performed.

Aim of Study III

To validate the IMU-based system *aktos-t* (myolution GmbH, Ratingen, GER) comparing the outcomes with a gold-standard motion capture system.

IMUs offer the solution of outdoor measurements thanks to their ease of use, light weight and lack of capture volume limitation [59,60,64,72]. Due to their components' problems, different algorithms of sensor fusion have been developed in order to reduce their disadvantages [72]. Consequently, each commercial system available on the market has its own algorithm [73] and biomechanical model [74] that needs to be validated. Therefore, in the study the validation of the IMU-based system *aktos-t* was performed in order to check its accuracy before being used in further studies.

Aim of Study IV

To quantify the magnitude of the GRF during landing and to introduce the combination between IMUs on the lower body and wireless force insoles for determining possible correlations between kinetics and kinematics.

In jumping, a high GRF has been indicated as one of the main factors in non-contact ACL rupture [12], but also for other knee injuries [11,13], especially when landing on an inclined surface [84]. Therefore, the quantification of the magnitude of the GRF, as well as the determination of the kinematics of the lower body during SkiJ landing, could play an important role in injury prevention, providing feedback to the athletes and technical indications to coaches to optimize the landing gesture.

5. Methods

Different methodologies were used in the studies constituting the thesis. In this chapter, a summary with the utilized technologies, a description of the participants, and the analysed variables is presented. A detailed description of the methods can be found in the original manuscripts of the scientific papers.

5.1 Study outlines

Table 2 reports an overview with the design, the participants' description and number, the technologies and the statistical methods used in the studies. The subjects participated voluntarily to the studies, signing a participation consent and were able to withdraw without giving a reason. The protocol of the studies obtained the Ethical approval from a designated Commission of the Faculty of Sport and Health Sciences of the Technical University of Munich.

Table 2. Studies' overview of the designs, participants (male: ♂, female: ♀), technologies (IMU: inertial motion units) and statistical methods (1D SPM: one dimensional statistical parametric mapping) utilized to analyze the three dimensional kinematics and kinetics.

Study	Research	Participants	Techn.	Outcomes	Statistical analysis
I	Original	2 (♂: 2) ski jumpers (17 years)	IMU Force insoles	Kinetics Ski kinematics	Pilot study
II	Original	10 (♂: 10) ski jumpers (17 ± 1 years)	IMU Force insoles	Kinetics Ski kinematics	Descriptive statistics Pearson's correlation
III	Original	14 (♂: 7; ♀: 7) healthy subjects (29 ± 5 years)	IMU Motion capture system Force plate	Full body kinematics	Descriptive statistics 1D SPM statistics Bland-Altman plot Independent samples t-tests Root mean square error Pearson's correlation
IV	Original	22 (♂: 22) ski jumpers (17 ± 1 years)	IMU Force insoles	Kinetics Lower body kinematics	Descriptive statistics Pearson's correlation

A deep description of the characteristics of the employed wireless technologies (IMUs and force insoles) have been reported in 2.2. The force insoles, placed inside the ski boots, have been employed in combination with IMUs placed, respectively, on the skis in Study I and II (Figure 12a) and on the body of the athlete in Study IV (Figure 12b).

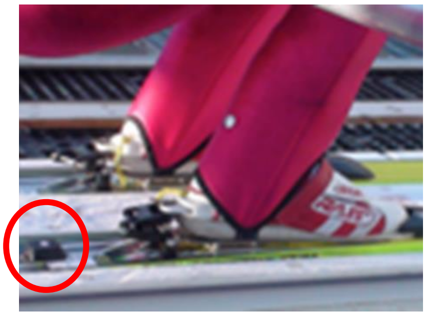
a.  b. 

Figure 12. Placement of the inertial sensor (highlighted by the red circle) on the ski (a.). Lateral *aktos-t* sensors' placement on the body of the athlete (b.).

Study I, II and IV were performed during summer training conditions on the SkiJ hill, i.e. performing on the hill while gliding on the in-run covered by ceramic and water (Figure 13a) and landing on synthetic grass (Figure 13b). Study III was performed into a laboratory.

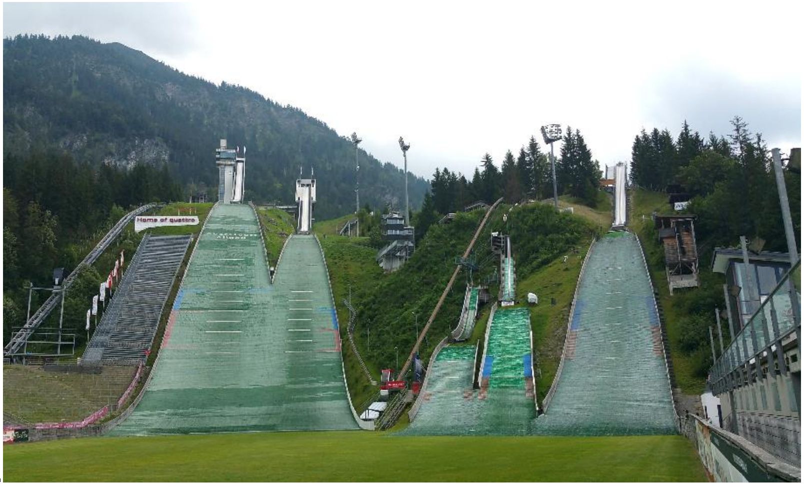
a.  b. 

Figure 13. SkiJ hills during summer conditions. In-run of the HS100 in Oberhof (GER) where are notable the ceramic tracks in which water is flowing (a.). Landing area of the SkiJ hills of the Audi Arena in Oberstdorf (GER). The hill used in the study is the second from the left (HS106) (b.).

Table 3 reports the different employed software employed in the studies for capturing and post-processing the data.

Table 3. Overview of the employed software and the task for which they were used.

Software	Task	Study
MATLAB 2017a (MathWorks Inc., Natick, MA, USA)	General post processing (normalization, detection of threshold, average…) Statistics (one dimensional statistical parametric mapping, Bland-Altman analysis) Processing of inertial sensor raw data	I, II, III, IV III I, II
SPSS Statistics Version 20.0 (IBM Corp., Armonk, NY, USA)	Normality Root mean square error Pearson's and Spearman's correlations Descriptive statistics	III III II, III, IV II, III, IV
iSen 3.08 (STT System, San Sebastian, Spain)	Processing of inertial sensor raw data	III, IV
Vicon Nexus (Vicon Motion Systems, Oxford, UK)	Collection and processing of motion capture and force plate raw data	III

5.2 Analysed variables

Table 4 shows an overview of the analysed variables in the studies, and the used methods and/or technology to detect them.

Table 4. Overview of the analyzed variables during the studies (flex-: flexion, ab-: abduction).

Objective	Method	Measured variables	Study
Demography		Sex Age	I, II, III, IV I, II, III, IV
Anthropometry	Physical examination	Body weight Height Plug-in-Gait segment's length	I, II, III, IV III III
Kinetics	Force insoles and force plate	Normal ground reaction force (GRF) Fore/rear normal GRF Impulse (I) Flight time (t_{flight}) Landing time ($t_{landing}$) Start of the landing (t_s) End of the landing (t_f) Symmetry Index (SI) normal GRF Symmetry Index (SI) I GRF distribution in % on the front foot	I, II, III, IV I, IV II, IV I II, IV II, IV II, IV IV IV IV
Kinematics	Motion capture system and inertial sensors	Flight time (t_{flight}) **Ski** Trajectory description Roll, pitch and yaw **Skier's lower body** Knee, hip and trunk flex-/extension	I, II, IV I, II I, II IV

	Ankle dorsiflexion	IV
	Gait analysis	
	Knee, hip, elbow, shoulder and wrist flex-/extension	III
	Ankle dorsiflexion	III
	Ab-/adduction of hip and shoulder	III
	Pelvis tilt, rotation and obliquity	III

6. Results

In this chapter, the individual author contribution and the summary of the main results of Study I-IV will be presented. Due to the employment of the same methods, Study I and II are presented together. Further results not reported in the original article will be also included in the summary of the study itself. Detailed results and considerations can be found in the related scientific papers, attached at the end of the related section.

6.1 Analysis of landing in ski jumping by means of inertial sensors and force insoles (Study I)

Authors:	Veronica Bessone, Johannes Petrat, Wolfgang Seiberl, Ansgar Schwirtz
First author:	Veronica Bessone
Current status:	Published in Proceedings MDPI

6.2 Ski position during the flight and landing preparation phases in ski jumping detected with inertial sensors (Study II)

Authors:	Veronica Bessone, Johannes Petrat, Ansgar Schwirtz
First author:	Veronica Bessone
Current status:	Published in Sensors MDPI

Individual contribution

The author of this thesis is the main author of these papers and was the main responsible for the design and conceptualization of the studies in agreement with Johannes Petrat, Dr. Wolfgang Seiberl and Prof. Dr. Ansgar Schwirtz. The doctoral candidate performed the data acquisition with Johannes Petrat on the SkiJ hill K90 of Oberhof (GER) (Study I and II) and Ramsau am Dachstein (AUT) (Study II). The first author performed the data analysis and interpretation and wrote most of the manuscripts indipendently. All authors approved the final version of the manuscripts before the submission. The doctoral candidate was mainly responsible for the submission process, replying to the reviewer’s comments and changing/adding the manuscript in agreement with all coauthors. The doctoral candidate presented the

Study I during the International Sport Engineering Association congress, hold in Brisbane (AUS) in March 2018.

Summary and main results

The purpose of Study I was to introduce and test the use of IMUs and force insoles during in-field measurements. The setup has been afterwards extensively used in Study II for detecting the possible correlations between the impact kinetics and the ski position during the landing preparation phase. Study II was the first one to describe the ski position during the entire flight phase by means of IMUs on the skis.

In Study I, two male ski jumpers competing at International level were tested during summer training conditions on the SkiJ hill K90 of Oberhof, while in Study II, ten male ski jumpers were tested on the SkiJ hill K90 of Oberhof and Ramsau am Dachstein. The athletes performed while wearing the *loadsol* wireless force insoles (described in 2.2.2) and two IMUs positioned on the skies. The IMUs' data were analysed using the algorithm proposed by Fang and colleagues [85], that used a post-calibration of the sensors based on the SkiJ hill design [86].

Each athlete owns his specific ski pattern during the flight phase (Study I and II). 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. During the impact, the athletes landed with an internal rotation of the ski and with an asymmetric BW distribution that could lead to an increase of the ACL injury risk. The pitch during the landing preparation phase is the ski movement that mainly influences GRF_{max} and t_{flight} ($r \geq .509$; $r \geq 0.499$, $p < .005$, respectively). Significant ski pitch variations happened between 0.36 and 0.16 s before the landing impact, with the consequent consideration that the landing preparation starts during this time frame (Study II). The roll angle kept during the landing did not influence the impact kinetics (Study II). Finally, some of the kinetic variables correlated differently with the kinematic variables on the two different SkiJ hills.

The studies showed how the use of IMUs and force insoles can represent a promising tool for the biomechanical analysis of landing in SkiJ and that the ski kinematics influences the GRF_{max} on the athletes. Therefore, the identification of the relationships between ski positioning and impact forces can lead to the optimization of landing technique with improvements under the technical and safety point of view.

Proceedings

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.

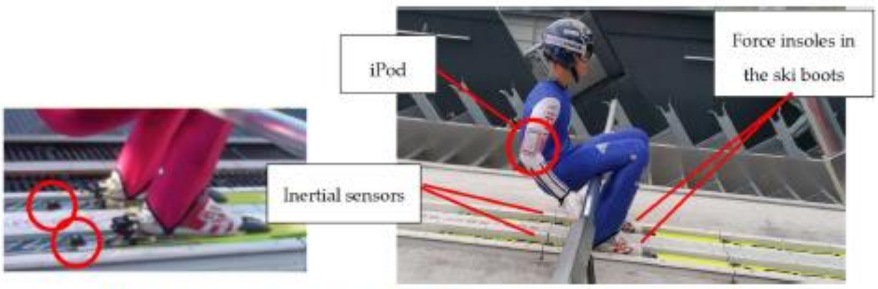

Figure 1. Placement of the iPod case, force insoles and inertial sensors on a subject.

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.

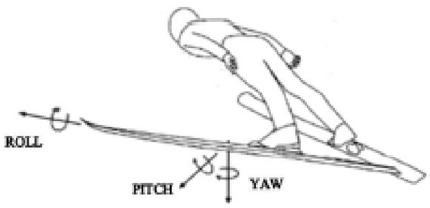

Figure 2. Representation of the roll, pitch and yaw ski movements (adapted from [11]).

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.

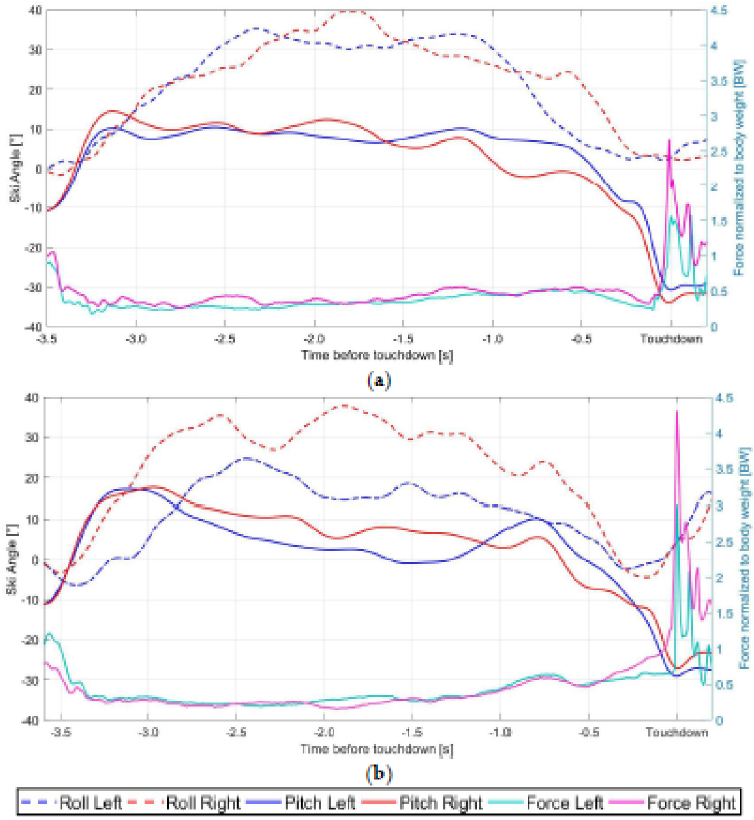

Figure 3. Roll, pitch and overall forces of two jumps characterized by a low (Subject A (**a**)) and a high impact (Subject B (**b**)) during flight and landing phases.

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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sensors

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Article

Ski Position during the Flight and Landing Preparation Phases in Ski Jumping Detected with Inertial Sensors

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Abstract: Ski movement plays an important role during landing preparation, as well as in the whole ski jumping performance. Good landing preparation timing and correct ski position increase the jump length and reduce the impact forces. Inertial motion units (IMUs) placed on the skis could constitute a promising technology for analyzing the ski movements during training. During regular summer trainings, 10 elite athletes (17 ± 1 years) performed jumps while wearing IMUs and wireless force insoles. This set-up enabled the analysis of a possible correlation between ski movements and ground reaction force (GRF) during landing impact. The results showed that the pitch during the landing preparation is the most influential movement on the impact kinetic variables since it is related to the angle of attack, which affects the aerodynamics. The ski position at 0.16 s before landing did not influence the kinetics because the athlete was too close to the ground. During the impact, the roll angle did not correlate with GRF. Moreover, each athlete showed a different movement pattern during the flight phase. Concluding, the combination of IMUs and force insoles is a promising set-up to analyze ski jumping performance thanks to the fast placement, low weight, and high reliability.

Keywords: kinematics; kinetics; injury prevention; performance; feedback; ski movements; landing; impact; telemark

1. Introduction

During ski jump landing preparation, as well as during the entire flight phase, ski position plays an important role in performance and safety. The ski position during landing preparation has been shown to increase the jump length by up to three meters [1]. In fact, a larger angle of attack (i.e., the angle between the ski and the air stream) enables the ski jumper to exploit the aerodynamic lift force and its cushioning effect. This effect permits the athlete to decelerate, with a consequent reduction of the impact forces [1] and, consequently, of the injury risk [2]. Delaying the landing preparation time has been demonstrated to be one of the performance factors, together with an effective take-off, a high initial velocity, and an efficient flying technique [3], and what distinguishes the high-ranked jumpers from the low-ranked ones [4]. The start and duration of the landing preparation have not been defined yet, but major differences of the ankle and hip angles were observed at 0.4 s before the landing impact, while knee joint variations were found at 0.14 s before the landing [4]. Moreover, during competitions, the landing technique is evaluated according to the Competition Rules of the International Ski Federation [5], and constitutes part of the points of the final score, together with jump length, wind factor, flight technique, and starting gate [5]. In particular, the athlete should land using the so-called "telemark", a step landing position, difficult to perform but biomechanically more advantageous than the parallel leg landing (i.e., landing with the feet at the same height in a squat position) [2]. As a consequence, a correct ski positioning and timing of the start of the landing preparation permit the athlete to execute a correct telemark position, as well as reduce the impact force acting on the lower limbs [2].

During the flight phase, having a stable ski position is essential for performance and safety [3,6,7]. The ski jumper usually tries to keep a V-style ski position, since it has been shown to be more effective than the parallel position [6]. To achieve aerodynamic efficiency and stability, the athlete needs to continuously adjust his/her ski movements in order to compensate for external factors (such as the change of pressure and wind) that are acting on him/her, finding a compromise between a steady position and angular adjustments [7].

Consequently, the goal of the present study was to investigate the ski position during the ski jumping performance due to the aforementioned important role played during the flight and the landing preparation phases. The detection of the ski orientation could support trainers and athletes in improving technique and performance. The ski opening angle and the movement regulating the angle of attack have been determined using 3D video analysis. However, the rotation around the longitudinal axis of the ski (roll), responsible for the tilting movement, appeared to be inaccurate using video cameras, due to the difficulties of visually determining the ski rotation [8]. Compared to the 3D video analysis, the use of wearable sensors, such as inertial motion units (IMUs), could constitute an interesting set-up for in-field ski movement analysis, being able to detect the orientation of the skis more accurately.

IMUs placed on skis have been applied in previous studies dealing with skiing sports, in particular, cross-country (XC) skiing, ski mountaineering, and ski jumping. In XC skiing [9], a fixed sensor on the ski has been used to determined cycle duration, speed, and distance. In addition to these variables, skin off and on, kick-turns, slope angle, and elevation gain have been detected by IMUs in ski mountaineering [10,11]. With or without further sensors on body segments, IMUs placed on the skis have been used to detect the sub-techniques of classic [12,13] and skating [12,14] XC skiing techniques. Moreover, IMUs on the skis have been used to analyze the friction between skis and snow [15]. Finally, in ski jumping, inertial sensors have been employed by different authors, being light and with a wide recording volume [16], two important characteristics of wearable sensors for their use in this sport. Previous publications carried out data collections using IMUs on skis and on body segments in order to analyze the overall performance [17–19], or the take-off and in-run [20], or the lower body kinematics during the landing impact [21], but without deeply concentrating on the ski angular movement. The potential of the use of inertial sensors placed only on the skis to detect their position has been introduced and tested on one subject by Kreibich and colleagues [8]. Always with the sensors placed on the skis, Groh and colleagues [22] were able to detect the ski speed and the jump length. Moreover, the same author introduced the use of inertial sensors on the skis to detect the angular momentum during landing, validating it with custom-made force-measuring bindings [23].

To the best of our knowledge, no studies investigated the skis' movement during landing preparation and the possible correlations with the landing kinetics, important factors for injury prevention and performance improvement. Therefore, a combination of IMUs placed on the skis and wireless force insoles could represent an interesting set-up for this analysis. This combination has been previously introduced by the authors of the present paper, and the first results showed that the ski position influences the vertical ground reaction force (GRF) [24]. The combination of IMUs and force insoles proposed in [24] was utilized in the present study on a higher number of ski jumpers to detect possible correlation between ski position and impact kinetics. Moreover, an overview of the ski movements during the flight phase was presented.

The goal of the study was to achieve greater insight into the ski position during the flight phase by means of inertial sensors, with a particular focus on the landing preparation in order to detect correlations with the impact kinetics. We hypothesize that:

(i) Each athlete owns his specific ski pattern during the flight performance, depending on the competition level and expertise [7];
(ii) The pitch (rotation around the frontal axis) during the landing preparation is the ski movement that mainly acts on the impact kinetics, being related to the angle of attack [1];
(iii) The roll (rotation around the sagittal axis) during the impact influences GRF, since it influences the direction of GRF resultant vector;
(iv) Around 0.40 s before the landing impact as in [4], the main ski movements that lead to the start of the landing preparation happen.

2. Materials and Methods

2.1. Set-Up Description

Ten male ski jumpers competing at the National and International Junior level (17 ± 1 years) performed the test voluntarily during regular summer training conditions. Within the summer training preparation, the athletes perform on the regular ski jumping hill, while gliding in the in-run on watered ceramic tracks and landing on synthetic grass. Six athletes jumped on the ski jumping hill HS100 in Oberhof (Germany) and four athletes on the hill HS98 in Ramsau-am-Dachstein (Austria), during different days of data collection. Each jumper performed three jumps and landed using telemark or parallel leg landings, depending on jump length, wind conditions, and his expertise. The participants were verbally informed in full about the nature of the study and they were allowed to withdraw at any point without giving a reason. The protocol used in the study obtained the ethical approval from a designated Commission of the Faculty of Sport and Health Sciences of the Technical University of Munich.

The athletes jumped wearing force insoles and IMUs, with an overall weight of 0.3 kg. Both the wearable sensors were able to stop automatically after a predetermined period of time. The loadsol plantar force insoles (Novel GmbH, Munich, Germany) detected the normal GRF during landing, sampling at a rate of 100 Hz. The insoles were connected via Bluetooth to the app loadsol (Novel GmbH, Munich, Germany) installed on an iPod (Apple, Cupertino, CA, USA). The device worked as a data logger and was positioned on the arm of the athlete with a smartphone running case (Figure 1a). The force insoles have been previously validated [25–28] and detected the normal overall force (i.e., the force between the plantar side of the foot and the shoe) (Figure 1b) [29]. Before each jump, the force insole system was calibrated with the athlete's body weight (BW) measured before the training using a body scale and including ski boots, helmet, gloves, and ski suit. During the calibration of the insoles, the athlete had to stand firstly on one foot, raising the other, and then vice versa. The values, collected by the force insole of the raised foot, were zeroed considering no forces acting on the foot.

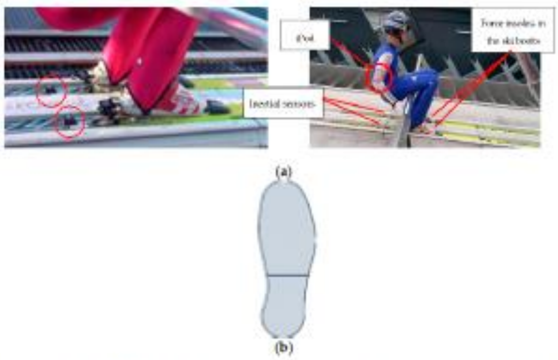

Figure 1. (**a**) Placement of the iPod case, force insoles, and inertial sensors on a subject; (**b**) Detecting area division of the fore and rear foot part in loadsol force insole (adapted from [29]).

Two IMUs (MSR Solutions, Wangen/Allgäu, Germany) were placed 0.1 m behind the binding and fixed with tape, one on each ski (Figure 1a). The sensors had a sample rate of 100 Hz and were composed by an accelerometer (±8 g), a gyroscope (±2000 °/s), and a magnetometer (±8 G). An operator activated the inertial sensors by Bluetooth using a laptop while the participant was sitting on the bench of the in-run. The IMUs stored the data on their internal memory.

2.2. Data Processing and Variable Definition

The data processing was conducted using custom-written Matlab 2017a (Mathworks Inc., Natwick, MA, USA) scripts.

The normal overall GRFs recorded by each insole were normalized to BW and used as outcomes from the loadsol app, where the values are rounded by the app in steps of 5 N. The GRF_{max} was the maximal normal ground reaction force collected during the landing impact. The impulse I (1) was defined as

$$I = \int_{t_s}^{t_f} GRF \, dt \quad (1)$$

where, as reported by [23], the start of the landing impact t_s was defined as the first increase of the normal GRF (i.e., when GRF was higher than 0.5 BW). t_f coincided with the minimum of the signal after the second GRF peak after touchdown, corresponding with the end of the eccentric phase (Figure 2) [23]. The difference between t_f and t_s defined the landing time ($t_{landing}$).

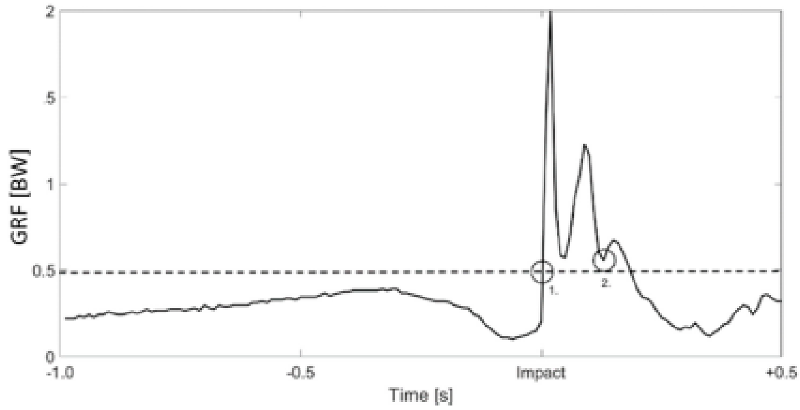

Figure 2. Normal ground reaction force (GRF) outcomes from one side, with the start (1.) and the end (2.) of the landing impact. The dashed line represents the 0.5 body weight (BW) threshold.

The raw IMU measurement data were postprocessed by using the algorithm presented in [30]. Firstly, the outcomes were low-pass filtered with cut-off frequency of 5 Hz. Subsequently, the algorithm reconstructed the attitude angles of skis offline by fusing gyroscope and magnetometer measurements with the geometric shape of the in-run [31], through an extended Rauch–Tung–Striebel smoother and maximum-likelihood principle-based state and parameter estimation algorithm. Therefore, the roll and yaw were set at 0° at the end of the in-run, considering the ski gliding flat and parallel in the tracks during this phase, while the pitch was set at −11°, according to the incline of the table reported in the design certificates of both ski jumping hills [31]. The reconstructed Euler angles of roll, pitch, and yaw were defined respectively as rotation around the longitudinal, frontal, and vertical axis of the skis (Figure 3) [9]. Thanks to this algorithm, before the start of the data collection, the calibration of the sensors was not necessary.

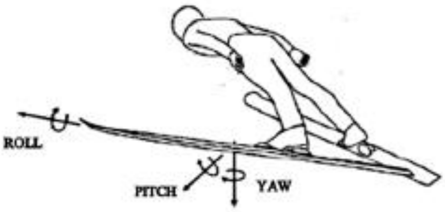

Figure 3. Representation of the roll, pitch, and yaw ski angles (adapted from [7]). The rotation arrows indicate how the positive directions of the ski angular movements were defined.

The roll angle of the left ski was defined positive when internally rotated, and negative for the right ski. The ski flexion defined a positive pitch for both the left and the right ski. The right ski opening angle was defined as positive when the tip of the ski was rotated in a clockwise direction, while for the left ski, when rotated anticlockwise. For analyzing the landing preparation, we calculated the ski angular range of motion (ROM) between ski angle during landing impact t_s (set as reference) and at 1.00 s ($t_{1.00}$), 0.76 s ($t_{0.76}$), 0.56 s ($t_{0.56}$), 0.36 s ($t_{0.36}$), and 0.16 s ($t_{0.16}$) before t_s. Except for the 1.00 s before landing, the other time points were chosen according to a previous publication [4], in order to have the possibility of comparing the results on the base of the same time points. Due to the importance of the ski pitch during the landing preparation as in all of the flying phase, its differences (Δ) in the last second (1.00 s) before the landing were calculated between $t_{1.00}$–$t_{0.76}$, $t_{0.76}$–$t_{0.56}$, $t_{0.56}$–$t_{0.36}$, and $t_{0.36}$–$t_{0.16}$ in order to determine when the main movement variations for preparing the landing are performed. The difference between $t_{0.16}$ and t_s was not calculated as this period is too close to the impact.

For describing the ski movements during the flying phase, for each athlete, the ski angles of the three jumps were normalized to 100 samples, averaged, and visualized for each athlete separately.

The flying time (t_{flight}) was calculated using the insoles and defined as the time between the end of the take-off and t_s. The end of the take-off was defined when the normal GRF recorded by the insoles was below 0.5 BW after the in-run. The flying times calculated for the left and right side were averaged to obtain t_{flight}. Due to the lack of video analysis around the landing area, t_{flight} was utilized to determine the jump performance, assuming that a longer t_{flight} corresponds to a longer jump length in comparable environmental conditions (same wind and weather) [21].

2.3. Statistical Analysis

The mean and standard deviation (SD) are reported in order to show the magnitude of the detected variables. The data collected on the two ski jumping hills were analyzed separately, due to the difference of the ski jumping hill design and the environmental conditions (such as different air pressure and wind). The kinematic and kinetic data were specified when related to the left (L) or right (R) side. The threshold for statistical significance was set at $p < 0.05$. To determine relationships between the kinematic and kinetic variables, Pearson correlations were calculated, considering each jump as a single case, even when performed by the same athlete. Paired sample t-test was applied to detect variations among the pitch movement differences during the landing preparation. The statistical analysis was performed using IBM SPSS Statistics (IBM Corp., Armonk, NY, USA).

3. Results

3.1. Ski Movement during the Flight Phase

For visualization, three normalized ski angular movements of roll, pitch, and yaw during the flying phase (from end of take-off until the landing impact) collected for each of the 10 athletes are reported in Figures 4 and 5 (jumps recorded in Ramsau-am-Dachstein: **a**–**d**, and in Oberhof: **e**–**j**, respectively), after being normalized on 100 samples and averaged.

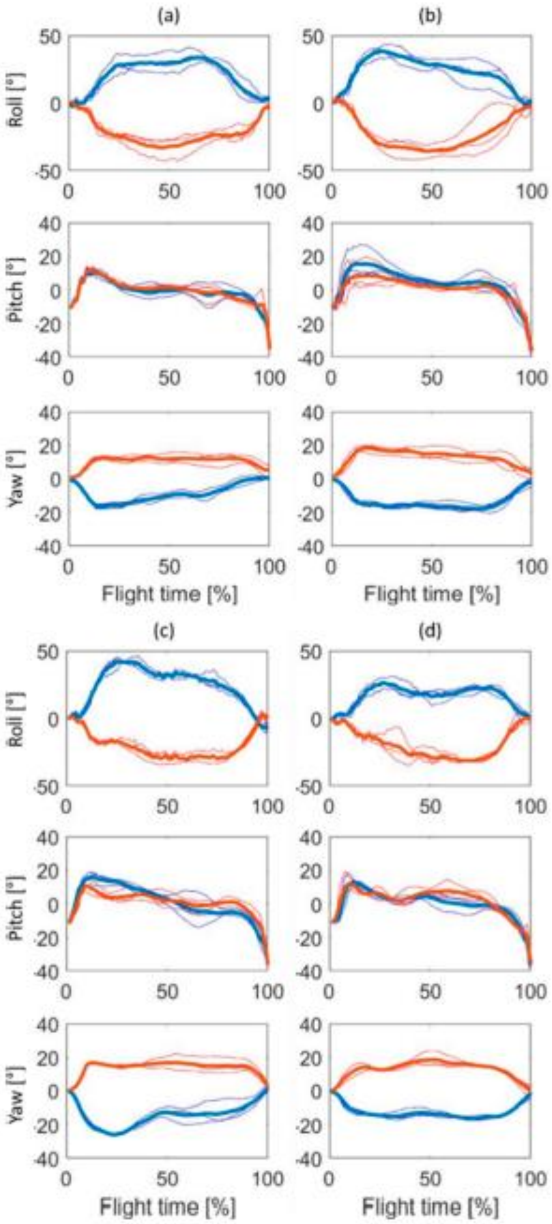

Figure 4. Normalized ski angular movements of roll, pitch, and yaw for three jumps of the four athletes collected in Ramsau-am-Dachstein (**a**–**d**). The blue line represents the left ski, the red line represents the right ski. The thick lines represent the average of the three normalized trajectories of each athlete, while the thin lines show the trajectory of a single jump.

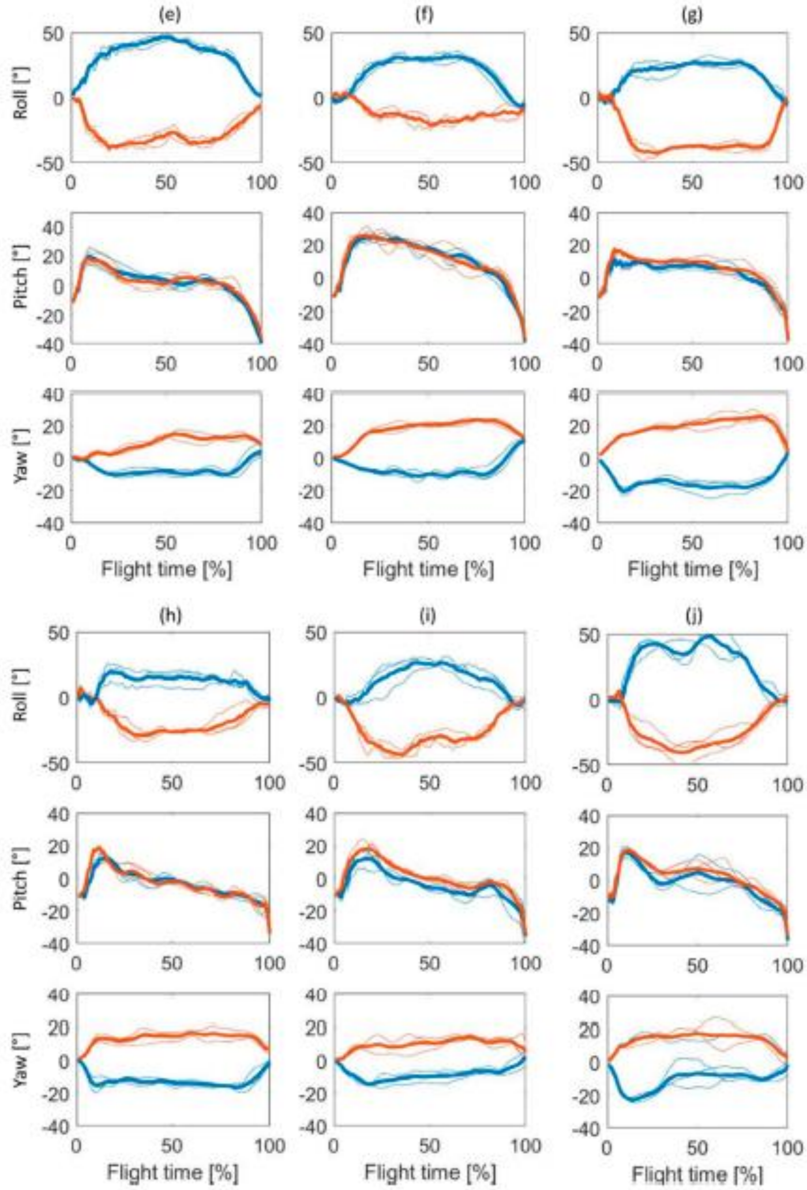

Figure 5. Normalized ski angular movements of roll, pitch, and yaw for three jumps of the six athletes (**e**–**j**) collected in Oberhof. The blue line represents the left ski, the red line represents the right ski. The thick lines represent the average of the three normalized trajectories of each athlete, while the thin lines show the trajectory of a single jump.

3.2. Ski Movement during the Landing and Its Preparation Phases and Influence with the Kinetics

The average t_{flight}, $t_{landing}$, normal GRF_{max}, and impulse I are reported in Table 1. Longer t_{flight} did correspond to higher normal ground reaction forces (on the L foot: $r = 0.774$, $p = 0.003$; on the R foot:

$r = 0.580$, $p = 0.048$ in Ramsau-am-Dachstein; on the L foot: $r = 0.729$, $p = 0.001$; on the R foot: $r = 0.519$, $p = 0.027$ in Oberhof).

Table 1. Average ± SD of t_{flight}, $t_{landing}$, normal GRF_{max}, and I of 3 jumps of 10 athletes (n = 10) who performed on the ski jumping hills of Ramsau-am-Dachstein and Oberhof.

	Ramsau-am-Dachstein (n = 4)	Oberhof (n = 6)
t_{flight} [s]	3.33 ± 0.20	3.33 ± 0.27
$t_{landing}$ [s]	0.19 ± 0.03	0.16 ± 0.03
Normal GRF_{max} [BW]	3.1 ± 1.0	2.8 ± 0.8
I [BWs]	154.5 ± 33.1	146.4 ± 30.5

The normal GRF_{max} did not correlate with any of the ski angular movements at t_s (landing impact) in Ramsau, but correlated with the pitch in Oberhof (GRF_{max}_L vs. L ski pitch: $r = 0.610$, $p = 0.007$; vs. R ski pitch: $r = 0.581$, $p = 0.011$; GRF_{max}_R vs. L ski pitch: $r = 0.590$, $p = 0.010$; vs. R ski pitch: $r = 0.585$, $p = 0.011$). On the other hand, $t_{landing}$ did not correlate with any ski movements at t_s in Oberhof, while it did correlate in Ramsau. $t_{landing}$_R correlated with the roll ($r = -0.628$, $p = 0.029$) and yaw ($r = 0.606$, $p = 0.037$) of the right ski.

The correlations between the ski angular ROM at $t_{1.00}$, $t_{0.76}$, $t_{0.56}$, $t_{0.36}$, and $t_{0.16}$ and t_{flight} and the kinetic variables $t_{landing}$, normal GRF_{max}, and I of the data collected on the two ski jumping hills are shown in Tables 2 and 3. For clarity, only the correlations where statistical significance was found are shown. Since no correlations were found with the ROM at $t_{0.16}$ in Ramsau ($p > 0.05$), the data were not reported.

Table 2. Correlations between t_{flight}, $t_{landing}$, normal GRF_{max}, and impulse I acting on the left (L) and right (R) foot, and the ski roll, pitch, and yaw ROM of the L and R side at $t_{0.16}$, $t_{0.36}$, $t_{0.56}$, $t_{0.76}$, and $t_{1.00}$ of the data collected in Oberhof ($n = 18$). The variables in bold showed a correlation between kinematics and kinetics in both the data collection of Ramsau-am-Dachstein and Oberhof.

			t_{flight}	$t_{landing}$		Normal GRF_{max}		I	
				L	R	L	R	L	R
$t_{0.16}$	Roll	L						$r = 0.639^{**}$	
		R						$r = 0.596^{**}$	
	Pitch	L						$r = 0.492^{*}$	
		R			$r = 0.510^{*}$	$r = 0.520^{*}$			
	Yaw	L	$r = 0.525^{*}$					$r = 0.519^{*}$	
		R							
$t_{0.36}$	Roll	L							
		R						$\mathbf{r = 0.618^{**}}$	
	Pitch	L						$r = -0.595^{*}$	
		R	$r = 0.526^{*}$	$r = 0.557^{*}$				$r = 0.602^{*}$	
	Yaw	L							
		R	$r = 0.504^{*}$			$r = 0.509^{*}$		$r = 0.629^{**}$	
$t_{0.56}$	Roll	L						$r = 0.664^{**}$	
		R						$r = 0.517^{*}$	
	Pitch	L	$\mathbf{r = 0.714^{*}}$			$r = 0.608^{**}$		$r = 0.685^{**}$	$r = 0.500^{*}$
		R	$\mathbf{r = 0.499^{*}}$					$r = 0.615^{**}$	
	Yaw	L						$r = 0.697^{**}$	
		R						$r = 0.482^{*}$	

Table 2. *Cont.*

			t_{flight}	$t_{landing}$ L	$t_{landing}$ R	Normal GRF_{max} L	Normal GRF_{max} R	I L	I R
$t_{0.76}$	Raw	L						$r = 0.714^{**}$	
		R							
	Pitch	L	$\mathbf{r = 0.755^{*}}$			$r = 0.623^{**}$		$r = 0.736^{**}$	
		R						$r = 0.634^{**}$	
	Yaw	L						$r = 0.690^{*}$	
		R						$r = 0.478^{*}$	
$t_{1.00}$	Roll	L		$r = 0.482^{*}$		$r = 0.494^{*}$		$r = 0.715^{**}$	
		R							
	Pitch	L	$\mathbf{r = 0.708^{*}}$			$\mathbf{r = 0.623^{**}}$		$r = 0.736^{**}$	
		R	$r = 0.522^{*}$			$r = 0.477^{*}$		$r = 0.575^{*}$	
	Yaw	L						$r = 0.702^{**}$	
		R							

* $p < 0.05$; ** $p < 0.005$; *** $p < 0.001$

Table 3. Correlations between $\mathbf{t_{flight}}$, $t_{landing}$, normal GRF_{max}, and impulse I acting on the left (L) and right (R) foot, and the ski roll, pitch, and yaw ROM of the L and R side at $t_{0.36}$, $t_{0.56}$, $t_{0.76}$, and $t_{1.00}$ of the data collected in Ramsau-am-Dachstein (n = 12). The variables in bold showed a correlation between kinematics and kinetics in both the data collection of Ramsau-am-Dachstein and Oberhof.

			T_{flight}	$t_{landing}$ L	$t_{landing}$ R	Normal GRF_{max} L	Normal GRF_{max} R	I L	I R
$t_{0.36}$	Roll	L							
		R	$r = 0.699^{*}$					$\mathbf{r = 0.712^{*}}$	
	Pitch	L	$r = 0.656^{*}$						
		R			$r = 0.577^{*}$				
	Yaw	L							
		R							
$t_{0.56}$	Roll	L							
		R							
	Pitch	L	$\mathbf{r = 0.887^{***}}$						
		R	$\mathbf{r = 0.611^{*}}$		$r = 0.588^{*}$		$r = 0.634^{*}$		$r = 0.662^{*}$
	Yaw	L							
		R							
$t_{0.76}$	Raw	L	$r = -0.678^{*}$						
		R							
	Pitch	L	$\mathbf{r = 0.844^{*}}$						
		R	$r = 0.660^{*}$		$r = 0.628^{*}$	$r = 0.611^{*}$	$r = 0.631^{*}$		$r = 0.715^{**}$
	Yaw	L				$r = -0.592^{*}$			
		R							
$t_{1.00}$	Roll	L	$r = -0.736^{**}$						
		R							
	Pitch	L	$\mathbf{r = 0.599^{*}}$	$r = 0.664^{*}$		$\mathbf{r = 0.631^{*}}$			
		R							
	Yaw	L							
		R			$r = 0.632^{*}$				

* $p < 0.05$; ** $p < 0.005$; *** $p < 0.001$

The average pitch movements and SD (n = 30) of the left and right skis from 1.00 s until the landing are reported in Figure 6.

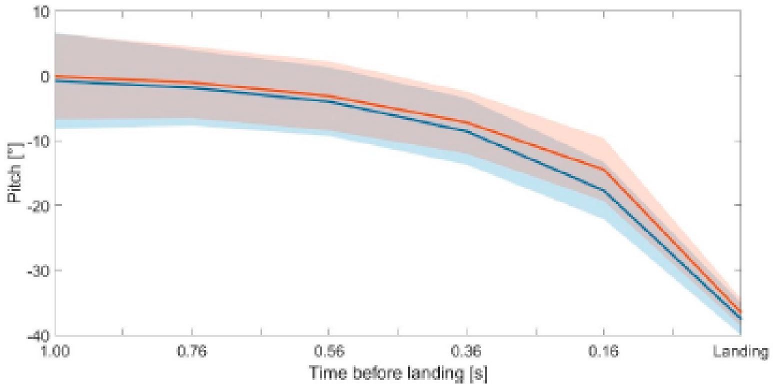

Figure 6. Average pitch movement and its SD from 1.00 before the landing impact until the landing for the left (in blue) and right (in red) ski at $t_{1.00}$, $t_{0.76}$, $t_{0.56}$, $t_{0.36}$, $t_{0.16}$, and $t_{0.00}$ (landing impact) for the 30 collected jumps. A pitch angle of 0° corresponded to a horizontal/flat position of the ski in the air. Negative values corresponded to a movement of the ski tips in a clockwise direction (pointing down).

The pitch difference Δ between $t_{1.00}$–$t_{0.76}$, $t_{0.76}$–$t_{0.56}$, $t_{0.56}$–$t_{0.36}$, and $t_{0.36}$–$t_{0.16}$ for the left and right skis are reported in Figure 7 with the related statistics. The statistical difference was calculated only between contiguous ranges (i.e., $t_{1.00}$–$t_{0.76}$ and $t_{0.76}$–$t_{0.56}$, $t_{0.76}$–$t_{0.56}$ and $t_{0.56}$–$t_{0.36}$, and $t_{0.36}$–$t_{0.16}$).

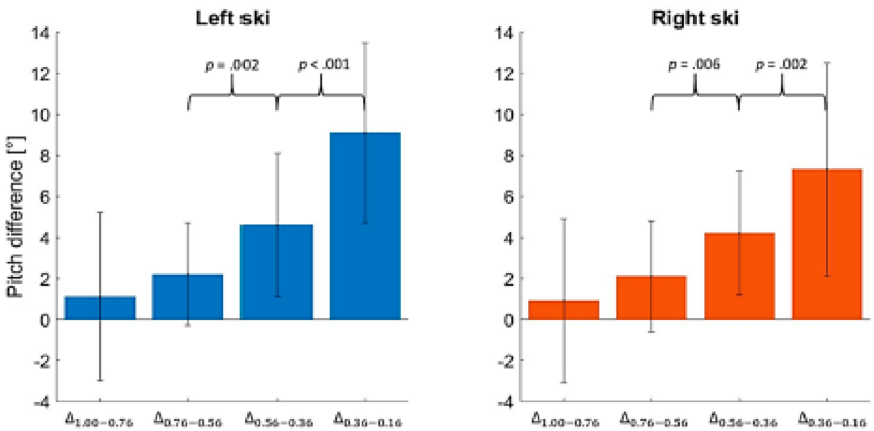

Figure 7. Difference Δ of the pitch movement between $t_{1.00}$–$t_{0.76}$, $t_{0.76}$–$t_{0.56}$, $t_{0.56}$–$t_{0.36}$, and $t_{0.36}$–$t_{0.16}$ for the 30 collected jumps for the left and the right ski. The p-values indicate the statistical difference between the variations of contiguous ranges.

4. Discussion

Referring to our hypotheses, the results showed that: (i) each athlete owns his specific ski pattern during the flight phase; (ii) the pitch during the landing preparation is the ski movement that mainly acts on the impact kinetics; and (iv) significant ski pitch variations happened between $t_{0.36}$ and $t_{0.16}$, leading to the consideration that around 0.36 s before the landing there is the start of the landing preparation. However, different from the hypothesis (iii), the roll during t_s did not correlate with any of the kinetic variables during landing impact.

4.1. Ski Movement during the Flight Phase

As visually notable from the reported cases (Figures 4 and 5), the curves of the ski angles are distinctive among the participants, owning their personal movement patterns depending on the expertise of the athlete [7].

During the phase of the first flight (i.e., the transition phase between the end of the take-off and the start of stable flight), the athlete needs to open the ski in a V-shape to rotate the ski internally and to raise the ski tips in order to increase the aerodynamic force acting on himself (Figures 4 and 5). Each ski jumper attained stable flight in a different way. For example, subjects **a**, **d**, **e**, **f**, and **j** had a steep and symmetric pitch angle in comparison to the other subjects during the first flight (from 0% to 20% circa of the flight time in Figures 4 and 5). After the first flight phase, some athletes kept a wide angle of attack (corresponding to a high angular value of ski pitch), reducing smoothly the angle during the flight phase (as **b** and **f**). Other athletes brusquely moved the ski in a horizontal position (around 0°), as athlete **e** (Figure 5). Moreover, some athletes (**c** in Figure 4 and **j** in Figure 5) showed an asymmetrical yaw angle.

During the flight phase (between 20% and 90% circa of the flight time in Figures 4 and 5), the athlete should keep a stable and symmetrical position [5–7]. Referring to Figures 4 and 5, it is possible to notice how some athletes kept an unstable position, with a lot of adjustment during the flight phase, as, for instance, subjects **f**, **h**, and **j** (Figure 5). At the same time, subjects **f** and **h**, together with subject **i**, never kept the same pitch angle during the flight, decreasing it constantly during the entire phase (Figure 5). The ski opening angle ranged between 30° and 40°, as previously reported to be the most efficient angular position [7,8]. The roll angle differed among athletes: Some participants kept the ski rotated around 50° (as **e** and **j**, Figure 5), while athlete **h** maintained relatively flat skis during the flight phase. A flat V-style has been shown to have better aerodynamic characteristics in comparison to a V-style where the skis are not so close to the body [32].

During the landing preparation (at the end of the flight phase, from 90% until the end of the flight time circa in Figures 4 and 5), subject **a** changed the pitch angle with rapid movements, while subjects **b**, **c**, and **d** prepared the landing in a smoother way, changing the ski pitch slower (Figure 4). The athletes demonstrated having generally asymmetrical ski movements, independently of the roll, pitch, or yaw angle. The asymmetry could be explained by the expertise of the athlete [7], but also by the inconstant lift and drag forces acting during the flight that, differently from wind tunnel testing, cannot be excluded during in-field tests [8].

Considering as criteria for judging the quality of the ski position technique the previously mentioned statement that the athlete should keep a stable and symmetrical position during the flight [5–7], none of the athletes of the study showed an outstanding ski position technique. This could be explained by the fact that the participants of the study, despite being elite athlete members of the German National Team, belonged to the Junior category, in which a technical maturity is still not reached.

The representations in Figures 4 and 5 are based on the normalization of ski movement data during the aerial phase of the ski jumping performance (from the end of the take-off until the landing impact). However, if the first flight and landing preparation time have a comparable duration among jumps of the same athletes, the flight phase has a different duration. This means that with a normalization to 100 samples, the data can be "stretched" or "compressed", and therefore, potentially influence the visual representation. However, for each athlete, the three t_{flight} were comparable in duration; on average, in fact, the difference among the jumps was of 0.10 s (3% of the average t_{flight}).

Finally, the analysis of the ski movement pattern is important during daily training of the athletes, and the use of inertial sensors could replace video cameras, providing reliable data without needing a lot of time for postprocessing or placing the cameras around the ski jumping hill.

4.2. Ski Movement during the Landing and Its Preparation Phases and Influence with the Kinetics

The pitch was the main ski movement to correlate with t_{flight} (Tables 2 and 3), confirming the role of this movement during the flight phase, given its relation with the angle of attack and the consequent influence on the aerodynamic forces. In particular, wider ranges of motion of the pitch corresponded to longer t_{flight} and consequently longer jumps. This means that the wider the difference between the ski pitch at landing and during the flight, the longer the jump length reached by the athlete. As a consequence, since the ski jumper needs to keep the skis flexed as long as possible in order to profit from the aerodynamic lift force [1], the athlete has to perform the landing preparation in a short time. No correlations were found between the pitch ROM and t_{flight} at $t_{0.16}$. This could be related to the fact that the athletes are close to the ground of the landing area at 0.16 s before the impact. Consequently, the angle of attack, controlled by the pitch movement, cannot influence the aerodynamic forces when the athlete is too close to the ground [1].

The magnitudes of the collected kinetic variables were comparable with the ones of previous publications [21,24,33] (Table 1). The correlation between the normal GRF_{max} and the ROM of the pitch before the landing (landing preparation) confirmed that the ski movements during this phase play an important role not only for the jumping performance, but also for safety, acting on the aerodynamic lift forces and their cushioning effect, reducing the impact forces [1] and, consequently, the injury risk [2] (Tables 2 and 3). In particular, wider ROM of the pitch corresponded to smaller normal GRF_{max} (and impulse), while the roll and yaw did not have any correlations with the kinetic variables.

Some of the collected kinetic variables correlated with certain kinematic variables differently among the ski jumping hills. For example, the impulse and normal GRF_{max} acting on the left side correlated with many kinematic variables collected in Oberhof (Table 1), but not in Ramsau-am-Dachstein (Table 2). This could be related to the fact that different athletes carried out the data collection on the two ski jumping hills. Consequently, their personal ski movement pattern could have influenced the kinetics in a different way. Therefore, a deeper analysis of the ski position pattern, as the one previously proposed, could give further information about the relation between ski movements and landing kinetics.

Focusing on the ski pitch between $t_{1.00}$ and $t_{landing}$ (Figure 6), it is possible to notice objectively how between 1.00 s and 0.56 s before the landing, the athletes kept a stable position. In fact, the average differences between the ski position of the left and right ski in the ranges $t_{1.00}$–$t_{0.76}$ and $t_{0.76}$–$t_{0.56}$ were of 1.0° ± 4.1° and 2.1° ± 2.6°, respectively. Moreover, no significant difference was found between the variations $t_{1.00}$–$t_{0.76}$ and $t_{0.76}$–$t_{0.56}$ (Figure 7). Therefore, due to the limited ranges of variation, it is possible to consider that the ski angular movements happening until 0.56 s before the landing are only adjustments for keeping the flying position stable. Therefore, in this phase, the athlete needs to adapt the ski movements to the aerodynamic changes he is subjected to. Between $t_{0.56}$ and $t_{0.36}$, and $t_{0.36}$–$t_{0.16}$, the pitch movements varied by 4.4° ± 3.2° and 8.2° ± 4.8°, respectively. In particular, the angular difference of 8.2° ± 4.8° between the pitch recorded at $t_{0.36}$ and $t_{0.16}$ could be considered remarkable and related to the start of the landing preparation, considering that the angular adjustments were too wide to be related only to adaptations to the aerodynamic changes. Therefore, in line with a previous publication [4], the start of the landing preparation can be considered to happen around 0.4 s before the landing, when major movements of the hip and ankle joints were detected [4].

Finally, it is important to keep in mind that we calculated the ski angular range of motion (ROM) between the landing impact t_s (set as reference) and specific timing before it. These timings (0.76 s, 0.56 s, 0.36 s, and 0.16 s) were chosen based on a previous publication [4]. It can be speculated that changing the timing during which the ROM of the ski movements was calculated would also change the possible correlations with impact kinetics. However, due to the variability of the ski pattern movement among athletes, defined timing before the landing was used instead of kinematic variables.

4.3. Limitations and Methodological Considerations

A remarkable aspect of the study was that it was conducted on a homogeneous group of elite athletes competing at International level with ages ranging between 16 and 19 years old. The tests were performed on behalf of a scientific support for the Ski Federation during training camps. Despite the small number of tested subjects (10), the group represented the totality of the German Junior National Team. Therefore, due to the limited number of athletes belonging to the team, including in the data collection a higher number of subjects with the same technical abilities and experience was not possible.

A limitation of the study was that the tests were carried out in two different locations, but where the ski jumping hills had a comparable size (both K-points set at 90 m) and comparable weather conditions (sunny, no wind). Moreover, two different subgroups of athletes belonging to the National Team performed the tests on the two ski jumping hills. The reason was that during the planned data collection performed within a training camp on the ski jumping hill of Oberhof, we could collect only six ski jumpers during the first day of measurements. During the second day, in fact, due to the rain and the wind, we could not carry out the tests with the remaining part of the team, because it was not possible to guarantee the same testing conditions. Therefore, we collected the data of the other four members of the National Team during the following training camp in Ramsau-am-Dachstein, on a ski jumping hill with a comparable size, always using the same combination of IMUs and force insoles. In this way, it was possible to provide the aforementioned biomechanical feedback to all the athletes of the National Team. For clarity, in the Discussion, we concentrated only on the biomechanical variables that were statistically significant on both the ski jumping hills.

Regarding the set-up, one of the main advantages was that it was not necessary to perform a calibration of the inertial sensors before doing the data collection. In fact, thanks to the algorithm proposed by Fang and colleagues [30], during the postprocessing, the raw data of the inertial sensors were reconstructed based on the design of the in-run of the ski jumping hill. The advantage of the post-initialization is very important, making the set-up easy to use, in case athletes and coaches would be interested in using the system on their own as feedback during training. In fact, not being professional researchers, they could introduce errors during the data collection. In addition, the combination of inertial sensors and force insoles can be considered relatively light (0.3 kg). Generally, the weight of the technological equipment used in the protocol is of significant importance when performing biomechanical research in sports, and it is essential in ski jumping, a sport in which the weight of the system equipment plus athlete is the main performance factor [34,35].

The low sampling rate of the loadsol insoles (100 Hz) could have affected the capability of measuring impact. However, publications related to this topic are discordant: Peebles and colleagues [26] highlighted under-/overestimation bias of the impact force peaks when using loadsol at 100 Hz. Other research groups did not report limitations related to the sample rate [25,27]. At the time of the data collection, loadsol insoles sampling at 200 Hz were still not available on the market. Anyway, for further studies, force insoles sampling at 200 Hz are recommendable to improve the accuracy.

A high number of external factors (such as wind and air pressure) generally interfere with the movement of the ski jumper. Consequently, we can speculate that each jump can be considered as a specific case, also when performed by the same athlete and even though the athletes belonged to an elite level. Therefore, performing statistics is very difficult in this kind of analysis, especially when dealing with the landing that is the phase at the end of the performance and, consequently, a resultant of the previous ones [32]. As a result, the statistics performed in this study, and generally in in-field ski jumping research, need to be evaluated carefully.

5. Conclusions

The pitch was the main ski movement influencing the magnitude of the normal ground reaction force (GRF_{max}) and the jump performance (t_{flight}) due to its relation with the angle of attack. As a result, in order to increase the jump length and reduce the impact forces, the athlete should keep the ski more flexed during the landing preparation phase. The pitch started to considerably vary between 0.36 s and 0.16 s before the landing impact, leading to the consideration that the landing preparation started around 0.36 s before the impact.

Despite the elite level of the athletes, each subject showed an individually unique ski movement pattern during the flight phase. The analysis of the ski position could permit improving the aerodynamics of the athlete during the flight, since previous publications gave suggestions on the best ski configuration to increase the performance [1,3,6,7,32,36,37]. However, a previous study performed in a wind tunnel showed how the aerodynamics of an isolated ski depend on the combination of the roll, pitch, and yaw angle [32]. Therefore, further studies should focus on analyzing the combination of the roll, pitch, and yaw movement during in-field performance.

According to the feelings of the jumpers, the set-up constituted by the force insoles and the IMUs resulted in not interfering with the performance. Therefore, under the practical point of view, the already proven advantages of the IMUs [15,17,18,20] and the force insoles [25–28], as well as the possible advantages of their combination shown in the present study, could provide a reliable and objective feedback for coaches and athletes for monitoring the kinetics and kinematics of the ski jumping performance. To confirm this, a report with graphs about ski pitch and roll movements and the kinetics during the whole performance were provided to athletes and coaches at the end of each day of data collection. Both athletes and coaches provided a positive feedback about the report.

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6.3 Validation of a New Inertial Measurement Unit System based on Different Dynamic Movements for Future In-Field Applications (Study III)

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Individual contribution

The author of this thesis is the main author of this paper. The doctoral candidate was the main responsible for the design and conceptualization of the study in agreement with Dr. Wolfgang Seiberl and Nadja Höschele, whose Master Thesis was based on part of the data collection of the present study. The author performed the data acquisition with Nadja Höschele in the Performance and Prevention Lab of the Technical University of Munich. The data analysis and interpretation was performed by the first author in agreement with Dr. Wolfgang Seiberl and Prof. Dr. Ansgar Schwirtz. The doctoral candidate wrote most of the manuscript indipendently, while co-authors critically contributed to the improvement of the content. All authors approved the final version of the manuscript before the submission. The doctoral candidate was mainly responsible for the submission process, replying to the reviewer's comments and changing/adding the manuscript in agreement with all coauthors.

Summary and main results

The purpose of this study was to validate the IMU-based system *aktos-t* (hardware, software, biomechanical model), testing its feasibility for future in-infield data collection.

In the study, 14 subjects wore 16 IMUs and a set of 39 reflective markers, in order to compare the IMU-based system's outcomes with the ones of the optoelectronic motion capture system Vicon, while performing different tasks (repetitive movements, walking and jumping). A set up of an optoelectronic system consisted of a certain number of infrared cameras that detect the position of reflective markers positioned on reference points on the body of the subject. The positions of the markers are then used to reconstruct the subject's movements by means of a related software using specific biomechanical model.

To test the accuracy and precision of the IMU-based system, different statistical methods were used to compare the outcomes of the two systems. The accuracy and precision were considered acceptable when: root mean square error (RMSE) < 10° [87], coefficient of repeatability (CR) < 10° [88,89] and bias < 5° [90]. The accuracy of pelvis, hip and knee joints ranged between acceptable (RMSE < 5°) and tolerable (RMSE < 10°) in walking, while the upper limb joints showed inaccuracy (RMSE > 10°) and imprecision (CR > 10°) during the repetitive movement test. Jump impact appeared not to influence the IMU outcomes ($p > .05$), an important aspect when the system is used in sport that required high dynamic movements and impacts as volleyball and SkiJ. The main sources of error could be related to the IMU-alignment during the reference pose performed before starting the data collection.

The results showed that the accuracy of *aktos-t* varies according to the task performed. The study provides to researchers the means to judge if the analysed IMU-based system is sufficiently accurate for their in-field applications.

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Validation of a New Inertial Measurement Unit System based on Different Dynamic Movements for Future In-Field Applications

Using inertial measurement units (IMUs) in monitoring and analysing sport movements has become popular in sports research since it avoids the laboratory limitation. However, the accuracy of modern IMU-systems (hardware combined with software) needs to be validated using gold-standard systems as baseline. In this study, we investigated the feasibility of the aktos-t IMU-system for in-field biomechanical research by comparing its outputs in various tasks (repetitive movements, gait and jumping) undertaken by 14 participants, with those of an optoelectronic system. The results showed that the accuracy of aktos-t varies according to the task performed. The accuracy of pelvis, hip and knee joints ranged between acceptable (root mean squared error (RMSE) < 5°) and tolerable (RMSE < 10°) in gait, while the upper limb joints showed inaccuracy (RMSE > 10°) and imprecision (coefficient of repeatability > 10°) during the repetitive movement test. Jump impact appeared not to influence the IMU outcomes ($p > 0.05$). The main sources of error could be related to the IMU-alignment during the reference T-pose. Finally, the study provides researchers the means for evaluating the accuracy of aktos-t (hardware, software and biomechanical model) as sufficiently precise for its application in their in-field investigations.

Keywords: motion capture; IMU; outdoor measurements; in-field feedback; jump

Introduction

In-field biomechanical analyses are important providing useful feedback for both researchers and athletes (Camomilla, Bergamini, Fantozzi, &Vannozzi, 2018). Field tests prevent performance limitations of a laboratory setup (Godwin, Agnew, & Stevenson, 2009), especially for sports that are difficult to simulate indoors (i.e. ski jumping or alpine skiing). For the majority of kinematic measurements, typically also for gait analysis, marker-based indoor motion capture systems are used (Tunca, Pehlivan, Nagme, Arnrich, Salur, & Ersoy, 2017), and can be considered the gold standard (Van der Kruk, & Rejne, 2018).

Inertial measurement units (IMUs) offer a practical solution for outdoor measurements without any capture volume limitation (Camomilla et al., 2018; Dellaserra, Gao, & Ransdell, 2014; Tao, Liu, Zheng, & Feng, 2012). However, their components (accelerometer, gyroscope, and magnetometer) present problems, such as the gyroscope drift (Godwin et al., 2009; Mundt et al., 2017). Different algorithms of sensor fusion have been developed in order to reduce the disadvantages posed by the components (Tao et al., 2012). Consequently, each commercial system (composed of hardware and software) available on the market has its own sensor fusion algorithm and biomechanical model to handle the raw data. Therefore, the accuracy and precision of each IMU-system needs to be evaluated. No matter at what step of data acquisition or processing errors originated, the resulting inaccuracy of estimated joint angles could lead the researchers and clinicians to a wrong evaluation and interpretation of the human movement, leading to incorrect feedback or treatment to the participant. Therefore, IMU accuracy and precision are commonly validated by comparing the outcomes to a gold standard optoelectronic system (Camomilla et al., 2018; Mundt et al., 2017; Robert-Lachaine, Mecheri, Larue, & Plamondon, 2017; Tulipani, Boocock, Lomond, El-Gohary, Reid, & Henry, 2018).

The aktos-t system (myolution GmbH, Ratingen, Germany) is a setup composed of its software and of 16 waterproof IMUs, connected wirelessly to a receiver. The software directly post-processes the outcomes based on a full body biomechanical model. To the best of our knowledge, the aktos-t is one of the few IMU-systems able to record and store the data on sensor memory, without being limited to the connection area with the receiver. Using this data logging feature, all the sensor characteristics, like e.g. the sample rate, are maintained. As a result, aktos-t can be used to analyse complex sports requiring movements of the upper and lower limbs and performed in wide field or in the water (i.e. cross-country skiing, ski jumping, swimming…). However, before using aktos-t in in-field applications, the quality of the kinematic measurement should be guaranteed and therefore, its accuracy and precision need to be validated.

In previous validations of different IMU-systems, various task-specific movements have been assessed including walking on stairs (Mundt et al., 2017), moving boxes (Robert-Lachaine et al., 2017), touching the nose with the finger (El-Gohary & McNames, 2012) or arm sweeping (Godwin et al., 2009). Highly dynamic movements, such as jumps, have rarely been included, despite it is of interest how sensors deal with e.g. fast acceleration or landing impacts. Therefore, the IMUs need to be evaluated for the use in dynamic sports (Teufl, Miezal, Taetz, Fröhlich, & Bleser, 2019). However, it is already known that the performance of an IMU-system depends on the motion tasks (Robert-Lachaine et al., 2017) and the participant's anthropometry (Leardini, Chari, Della Croce, & Cappozzo, 2005). As a result, a validation should include simple and complex movements of the limbs of different participants. In addition, particular attention needs to be given to the sensor placement on the segment, due to the interferences on the quality of the measurement, of soft tissue and joint movements (Liu, Inoue, & Shibata, 2009).

The aim of the present study was to evaluate the aktos-t system compared to a gold-standard optoelectronic system during repetitive movements, gait and jumping. We were interested in the accuracy and precision of aktos-t for the measurements of the major joint kinematics of upper and lower body. A final goal was to provide limits of agreement for the use in in-field biomechanical performance analysis. Based on literature on a comparable system (Robert-Lachaine et al., 2017), we hypothesised that the aktos-t system is accurate for major joints of the lower limb, but more inaccurate for upper body joints with high complexity, as the shoulder (El-Gohary & McNames, 2012; Nordin & Frankel, 2001).

Methods

Participants

Fourteen healthy participants (7 males, 7 females; 29 ± 5 years; 1.73 ± 0.09 m; 67.4 ± 11.3 kg) voluntarily carried out the protocol. All experiments were conducted according to the Declaration of Helsinki. The protocol used in the study obtained the Ethical approval from a designed Commission of the Faculty of Sport and Health Sciences of the Technical University of Munich.

Setup

The protocol required the use of the IMU-system aktos-t (hardware, software and biomechanical model) and of the optoelectronic system Vicon (Vicon Motion Systems, Oxford, UK) consisting of 10 infrared cameras sampling at 200 Hz, and synchronised by an electronic trigger. Each tri-axial IMU had a sampling rate of 143 Hz and a sensing range of ±16 g for the accelerometer, ±2,000°/s for the gyroscope and ±1 mT for the magnetometer (myolution aktos-t, Technical data, 2018). Before starting the recording, the IMUs were precisely aligned to allow the 'static calibration' (Appendix A).

Prior to the start of the protocol, the participant's anthropometrics were assessed and 39 reflective markers were placed on each participant, according to the positioning of the Plug-in-Gait (P-i-G) model (Vicon Motion Systems). The 16 IMUs were positioned using a double-sided tape, far from soft tissues and joints to avoid artefacts (Liu et al., 2009), on the feet, shanks, thighs, pelvis, C7 vertebra, chest, forearms, upper arms, hands and head (Figure 1). Moreover, the 'Reference-by-Global' of aktos-t was performed, to align each IMU to the body segment where it is located (Appendix A).

Figure 1. Set up on a subject, where it is possible to notice the markers and the inertial sensors positioned on the body.

Procedure

The protocol was divided into three parts: isolated joint motion, gait, and jumping (Figure 2). Firstly, the participants carried out five repetitive movements of six joints (ankle, knee, hip, wrist, elbow and shoulder) of their right-side. The repetitions were performed at a pace of 40 BPM per cycle, given by an external acoustic source. The participants performed the following movements: Shoulder and hip flexion/extension and abduction/adduction, elbow flexion/extension, wrist ulnar deviation and flexion/extension, knee flexion/extension and ankle dorsi-/plantarflexion and internal/external rotation. Secondly, participants walked five times a 7-m distance on plane ground at self-paced speed. Finally, three squat jumps were executed on a force plate (Kistler Instrumente AG, Winterthur, Switzerland; 1 kHz sample rate). Before the start of each trial, the 'drift correction' was performed (Appendix A).

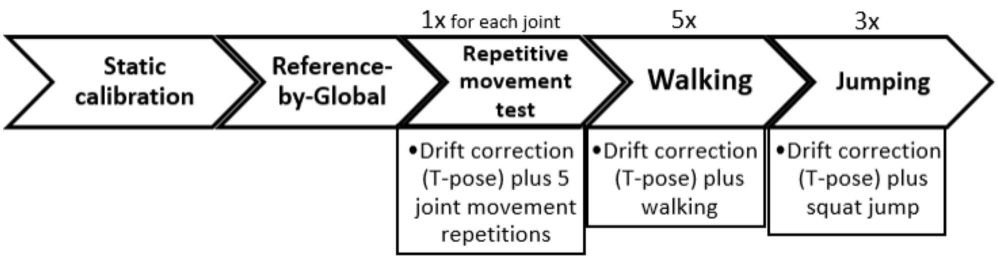

Figure 2. Timeline of the protocol with the number *n* of repetitions (*n*x) for the different trials of the repetitive movements, gait and jumping.

Data Processing

The data were processed using the software Vicon Nexus 2.7 and iSen 3.08 (STT Systems, San Sebastián, Spain) for the optoelectronic and IMU-system, respectively. The Vicon data were processed using a 10 Hz low-pass-filtered (Woltring with Mean Squared Error setting), whereas the aktos-t data were internally low-pass filtered by the manufacturer software (10 Hz, 2^{nd} order Butterworth filter before it was exported). The algorithm of iSen 3.08 is based on sensor fusion of the accelerometers and the gyroscopes, without considering the magnetometers. Data post-processing was conducted via self-written codes in Matlab 2017a (MathWorks Inc., Natick, MA, USA).

The offset between the respective joint angles measured by the two systems was evaluated in order to quantify its influence on the recorded data. In more detail, the flexion/extension values of the six evaluated joints were measured during the T-pose in three trials per participant. The offset between the systems then was defined as the initial difference of the measured joint angle during this static posture.

The minimum (min) and maximum (max) joint angles, and range of motion (ROM, difference between max and min joint angles) of three repetitions for each participant were considered in the analysis of the repetitive movement test. For the gait and jumping trials, the recordings of the left body side were analysed assuming that there were no differences between the sides. In the gait test, for each participant, five gait cycles were included into the analysis. The start and the end of one cycle was defined as heel foot contact and subsequent heel foot contact of the same foot, respectively (Perry & Burnfield, 1992). The cycles were normalised on 100 samples, averaged and subsequently analysed. The variables min, max and ROM of the ankle plantar-/dorsiflexion, knee and hip flexion/extension and pelvis rotation, tilt and obliquity of each averaged cycle were defined. Only the flexion/extension of the lower limb joints were examined, being the most evaluated and relied on in gait analysis (Kadaba, Ramakrishnan, & Wootten, 1990; McGinley, Baker, Wolfe, & Morris, 2009). Due to differences in the used reference system axis directions, some corrections were performed for the movements of the pelvis: The reverse of the rotation outcomes was applied, with the vertical axis positive facing up for Vicon and down for aktos-t. Moreover, depending on the walking direction of the participant, the IMU-based lateral axis resulted in either a positive or a negative rotation; therefore, the tilt angle was offset at ±180°, which was subsequently corrected during the post-processing.

Finally, one out of three squat jumps of each participant was used for the analysis of the IMUs' accuracy after impact. The jump followed by the most stable post-impact T-pose, in terms of steady position kept for more than one second, during the analysed period, was taken into consideration in the calculation. The pre- and post-impact differences between the data collected by the two systems for the hip, knee and ankle angles in the sagittal plane were then compared.

Statistical Analysis

Prior to the statistical analysis, the data set was tested for normality using the Shapiro–Wilk test. All data are presented as mean and standard deviation (SD) and, when not normally distributed, also median and interquartile range are reported. To quantify the accuracy, the joint angles of the repetitive movements and the gait tests were evaluated with Spearman's and Pearson's correlations, depending on the normality test of the data sets. When the data set recorded by one or both the motion capture systems was not normally distributed, Spearman's correlation between the two data sets was calculated. The accuracy was also evaluated using the root mean square error (RMSE), defined as the SD of the difference between the value collected by Vicon and the IMUs' values. Moreover, the limits of agreement method (Bland & Altman, 1986) was applied using an open-source code (Klein, 2010). In this method, the bias was defined as the mean difference between the two systems. The coefficient of repeatability (CR) is a measure of precision and defined as 1.96 times the SD of the differences between the two measurements, while the bias divided by the mean of the values recorded by the systems defined the bias in percentage (Bland & Altman, 1986). To the gait analysis, also a one-dimensional statistical parametric mapping (1D-SPM) was applied to statistically answer the hypothesis of whether the joints' angular movements measured by the two systems differ during a gait cycle (Pataky, 1982; Friston, Holmes, Worsley, Poline, Frith, & Frackowiak, 1995). The analysis was performed using the open-source code for two-tailed paired t-tests (Pataky, 2016). When the SPM trajectory crossed the critical threshold, a statistical difference between the two system outcomes was present. For the jump test, a parametric Student's t-test was performed to verify whether the systems' bias after the impact was significantly different from the one recorded before the jump. The criterion for statistical significance was set at $p \leq 0.05$. SPSS Statistics Version 20.0 (IBM Corp., Armonk, NY, USA) was used to performed the statistical analysis.

Accuracy and Precision Interpretation

The accuracy of the results was interpreted with different RMSE parameters as follows (McGinley et al., 2009):

- RMSE ≤ 2°: *good accuracy*, within the natural variation of an individual's kinematic parameters.
- 2° < RMSE ≤ 5°: *acceptable accuracy*.
- 5° < RMSE ≤ 10°: *tolerable accuracy*, requires consideration in the interpretation.
- RMSE > 10°: *unbearable accuracy*.

We considered CR *not precise* when > 10° (El-Zayat et al., 2013; Schiefer et al., 2014). The bias was evaluated *acceptable* for biomechanical research when < 5°, a scale used by examiners to rate the ROM (Schiefer, Kraus, Ellegast, & Ochsmann, 2015).

Results

The average offsets for the two systems during the reference T-pose were 6.2 ± 3.2° for the ankle, 1.2 ± 4.7° for the knee, −0.4 ± 5.6° for the hip, 12.5 ± 10.8° for the wrist, 20.2 ± 6.6° for the elbow and −4.8 ± 4.8° for the shoulder.

Repetitive Movement Test

The difference between the outcomes of the two systems depended on the analysed joint (Table 1). Generally, the hip movement indicated minor differences (RMSE: 4.9–7.3°; minimum bias: −0.7°; CR: 6.5–13.5°) (Table 1). On the other hand, the wrist and ankle joint movements showed the largest differences (Table 1), for instance the maximum RMSE was 34.5° for the ankle max internal/external rotation.

The offsets recorded during the T-pose correlated with the differences between the two systems for the max and min flexion/extension angles of four out of six analysed joints. In particular, significant correlations were found for knee (max: $r = -0.708$, $p = 0.005$; min: $r = -0.931$, $p < 0.001$), ankle (max: $r = -0.570$, $p = 0.033$), hip (max: $r = -0.751$, $p = 0.002$; min: $r = -0.613$, $p = 0.020$), and elbow (max: $r = -0.587$, $p = 0.027$; min: $r = -0.614$, $p = 0.020$).

Table 1. Repetitive movement test. Mean (standard deviation) of minimum (min), maximum (max) and range of motion (ROM) values recorded by Vicon and aktos-t. Statistics show root mean square error (RMSE), bias ± coefficient of repeatability (CR), bias in percentage and the correlation (*r*) between systems. The [median (interquartile ranges)] were reported when the data set was not normally distributed. When the data set recorded by one or both the systems was not normally distributed, the Spearman's correlation between the two data sets was calculated. Acceptable RMSE (<5°), bias (<5°) and CR (<10°) are highlighted in bold.

			Vicon [°]	aktos-t [°]	RMSE [°]	Bias ± CR [°] ([%])	*r*
Shoulder	Flexion/ Extension	min [1]	−52.9 (14.2) [-55.4 (13.9)]	−36.8 (12.6) [-42.1 (10.1)]	18.0	−16.2 ± 16.0 (−36.1)	0.572* [2]
		max [1]	70.6 (4.6)	94.6 (14.5) [92.6 (8.3)]	27.0	−24.0 ± 25.5 (−29.1)	0.224 [2]

		ROM	123.5 (16.2)	131.3 (20.5	14.6	−7.8 ± 25.0 (−6.1)	0.782**
	Abduction/ Adduction	min [1]	7.0 (5.1)	9.4 (8.1) [12.1 (15.1)]	9.5	−2.4 ± 18.7 (−29.3)	0.068 [2]
		max [1]	96.4 (11.5) [94.7 (7.9)]	105.7 (12.1) [101.8 (21.7)]	12.6	−9.3 ± 17.4 (−9.2)	0.796** [2]
		ROM	89.4 (11.7)	96.3 (8.6)	10.9	−7.0 ± 17.1 (−7.5)	0.671**
Elbow	Flexion/ Extension	min [1]	20.5 (5.4) [19.1 (5.4)]	−2.0 (10.9) [-4.2 (11.3)]	25.8	22.5 ± 25.8 (243.2)	-0.308 [2]
		max [1]	140.6 (8.8) [142.9 (10.6)]	140.2 (13.7)	13.0	**0.4** ± 26.5 (0.3)	0.436 [2]
		ROM	120.0 (9.5)	142.2 (17.1)	27.1	−22.1 ± 32.0 (−16.9)	0.655*
Wrist	Flexion/ Extension	min	−39.1 (16.3)	−58.7 (11.8)	20.4	19.6 ± 19.0 (40.1)	0.806***
		max	65.2 (10.3)	64.4 (15.7)	17.4	**0.8** ± 17.4 (1.2)	0.846***
		ROM	104.3 (21.2)	123.1 (18.6)	17.6	−18.8 ± 20.3 (−16.5)	0.872***
	Ulnar deviation	min	−18.0 (18.9)	−25.6 (10.9)	21.7	7.6 ± 38.5 (34.7)	0.217
		max	21.1 (16.4)	26.0 (7.9)	8.6	**−4.8** ± 34.0 (−20.4)	0.114
		ROM	39.1 (8.4)	51.6 (12.2)	21.2	−12.4 ± 25.3 (−27.3)	0.260
Hip	Flexion/ Extension	min	−14.6 (7.6)	−8.9 (4.9)	7.3	−5.7 ± **9.4** (−48.5)	0.788***
		max	68.4 (8.3)	70.3 (8.4)	5.8	**−1.9** ± 11.0 (−2.7)	0.774**
		ROM	83.0 (10.4)	79.2 (9.5)	**4.9**	**3.7 ± 6.5** (4.6)	0.951***
	Abduction/ Adduction	min	−7.8 (4.2)	−10.3 (5.2)	5.1	**2.5 ± 8.9** (27.6)	0.552*
		max	39.2 (5.5)	37.4 (4.8)	6.9	**1.8** ± 13.5 (4.7)	0.117
		ROM	47.1 (6.2)	47.8 (7.9)	**4.9**	**−0.7 ± 9.9** (−1.5)	0.770**
Knee	Flexion/ Extension	min	5.0 (6.3)	3.9 (5.1)	5.3	**1.0** ± 10.5 (22.5)	0.575*
		max	119.6 (7.7)	115.1 (6.7)	8.1	**4.5** ± 13.7 (3.8)	0.531
		ROM	114.6 (8.4)	111.2 (6.8)	5.7	**3.4 ± 9.1** (3.0)	0.834***
Ankle	Dorsi-Flexion	min	−35.7 (8.9)	−42.1 (6.6)	11.0	6.4 ± 18.2 (16.5)	0.316
		max	29.4 (8.1)	24.6 (6.8)	8.6	**4.8** ± 14.5 (17.8)	0.519
		ROM	65.1 (12.8)	66.7 (7.4)	13.1	**−1.6** ± 26.5 (−2.4)	0.193
	Internal/ External Rotation	min	−2.8 (14.0)	−7.5 (4.5)	15.6	**4.7** ± 30.1 (−91.3)	−0.155
		max	48.8 (12.6)	17.5 (4.9)	34.5	31.3 ± 29.6 (94.4)	−0.369
		ROM	53.4 (4.7)	24.2 (4.3)	15.6	29.2 ± 11.0 (37.6)	0.217

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

[1] Data set not normally distributed. [2] Spearman's correlation.

Gait Analysis

All the considered ROMs, except for the pelvis tilt, showed high correlations between the two systems (Table 2). The ankle ROM showed the strongest bias (10.3 ± 10.1°).

Table 2. Gait analysis. Mean (standard deviation) of the minimum (min), maximum (max) and range of motion (ROM) values for hip, knee flexion/extension, ankle dorsiflexion and pelvis tilt, rotation and obliquity recorded by Vicon and aktos-t. Statistics show root mean square error (RMSE), bias ± coefficient of repeatability (CR), bias in percentage and Pearson's correlation (*r*) between systems. The [median (interquartile ranges)] were reported when the data set was not normally distributed. When the data set recorded by one or both the systems was not normally distributed, the Spearman's correlation between the two data sets was calculated. Acceptable RMSE (<5°), bias (<5°) and CR (<10°) are highlighted in bold.

			Vicon [°]	aktos-t [°]	RMSE [°]	Bias ± CR [°] ([%])	*r*
Hip	Flexion/ Extension	Min	−15.5 (7.5)	−8.3 (6.4)	9.8	−7.2 ± 13.6 (−60.5)	0.512
		Max	30.5 (7.5)	32.1 (5.0)	6.7	**−1.6** ± 13.2 (−5.1)	0.476
		ROM	46.0 (3.4)	40.4 (4.0)	6.1	5.6 ± **5.2** (13.0)	0.757**
Knee	Flexion/ Extension	Min	1.0 (5.5)	0.6 (3.7)	5.3	**0.3** ± 10.8 (37.5)	0.332
		Max	62.2 (4.9)	68.1 (4.0)	9.1	−5.9 ± 14.0 (−9.1)	−0.292
		ROM	61.2 (3.5)	67.4 (4.7)	6.8	−6.2 ± **5.7** (−9.6)	0.795**
Ankle	Dorsi-Flexion	Min	−15.8 (4.7)	−19.2 (6.6)	6.6	**3.4** ± 11.4 (19.4)	0.514
		Max	16.7 (4.7)	23.6 (5.9)	10.1	−6.9 ± 14.9 (−34.2)	-0.011
		ROM	32.5 (6.3)	42.8 (7.7)	11.4	−10.3 ± 10.1 (−27.4)	0.750**
Pelvis	Obliquity	Min	−4.0 (4.9)	−4.8 (1.6)	**4.3**	**0.8 ± 8.6** (18.2)	0.550*
		max [1]	5.0 (3.4) [4.2 (1.3)]	6.0 (1.9)	**3.7**	**−0.9 ± 7.2** (−16.4)	0.138 [2]
		ROM	9.1 (2.9)	10.7 (1.9)	**2.4**	**−1.7 ± 3.6** (−17.2)	0.816**
	Rotation	min	−5.4 (2.7)	−5.9 (3.4)	**2.4**	**0.5 ± 5.2** (8.8)	0.312
		max	4.9 (2.3)	5.7 (3.1)	**2.6**	**−0.8 ± 4.6** (−15.1)	0.036
		ROM	10.4 (3.7)	11.7 (4.7)	**2.9**	**−1.3 ± 5.2** (−11.8)	0.834**
	Tilt	min	2.7 (3.9)	0.3 (4.7)	6.2	**2.4** ± 11.5 (160)	0.122
		max	6.6 (3.9)	4.8 (4.8)	6.2	**1.8** ± 12.1 (31.6)	0.053
		ROM [1]	3.8 (1.8) [3.4 (1.4)]	4.5 (1.3)	**2.5**	**−0.7 ± 4.9** (−16.9)	−0.011 [2]

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

[1] Data set not normally distributed. [2] Spearman's correlation.

The 1D-SPM analyses showed no significant differences between the systems for the pelvis movements, while the ankle, knee and hip flexion/extension patterns differed mainly around 50–70% of the gait cycle (Figure 3). In detail, the flexion/extension significantly differed at 49.6–83.6% of the cycle for the hip, at 47.6–71.5% for the knee, and at 6.5–37.7% and 54.3–59.6% for the ankle.

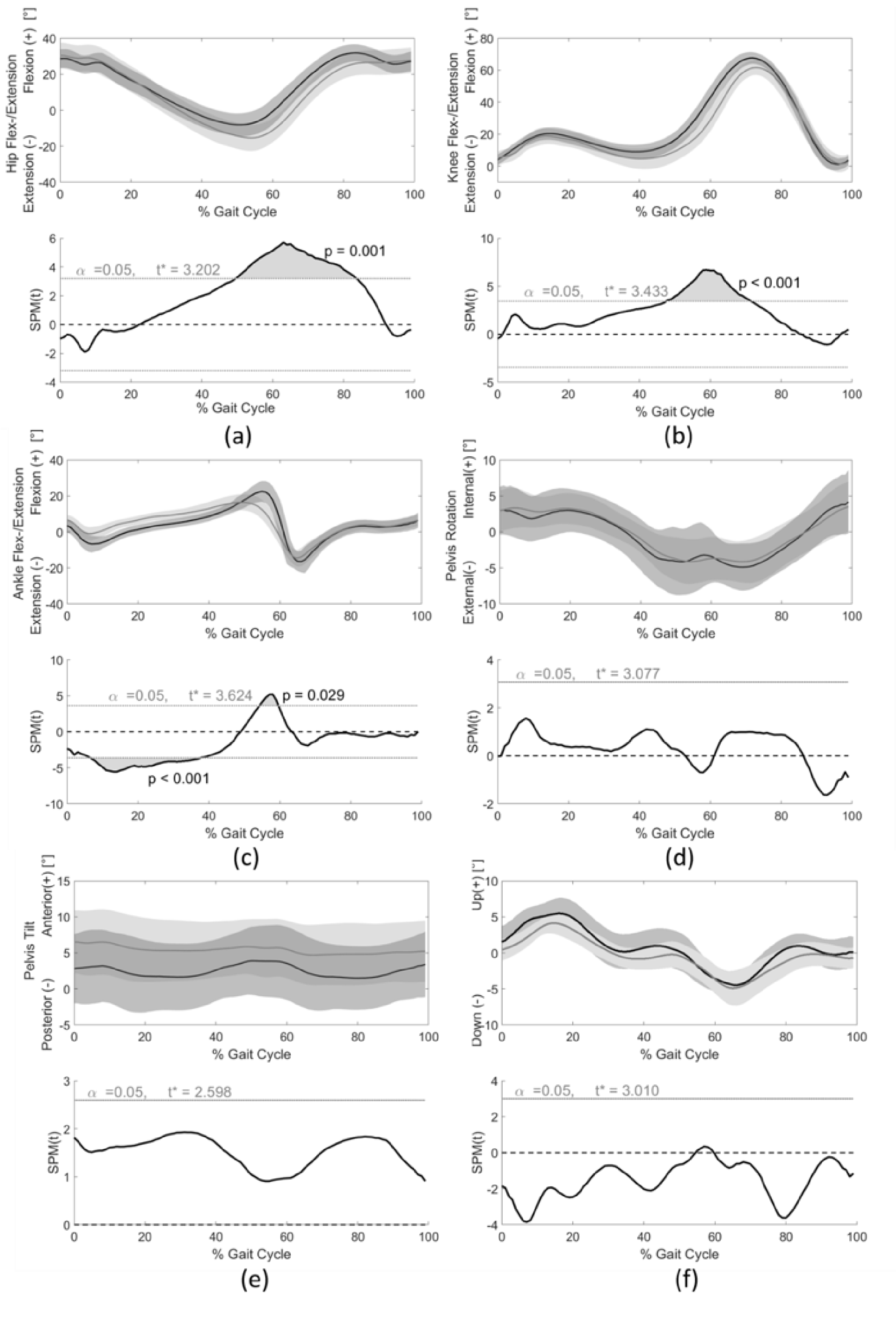

Figure 3. (a) Hip, (b) knee and (c) ankle flexion/extension and pelvis (d) rotation, (e) tilt and (f) obliquity movements (aktos-t in dark grey, Vicon in light grey) and respective 1D-SPM analyses during a normalised gait cycle (n=14). When the SPM trajectory exceeds the threshold (grey line in SPM graphs), significant differences ($p < 0.05$) between the outcomes of the two systems occur (indicated by the grey area).

Squat Jump Test

No statistical differences ($p > 0.05$) were found between the squat jump pre- and post-impact outcomes (with impact of 5.4 ± 2.8 times body weight). The recorded differences were 0.3 ± 1.5° ($p = 0.461$), −0.2 ± 1.5° ($p = 0.712$) and −0.2 ± 1.7° ($p = 0.627$) for the ankle, knee and hip angles, respectively.

Discussion and Implications

In this study, we evaluated the performance of the IMU-system aktos-t against an optoelectronic system during different tasks in order to provide limits of agreement for the use in in-field biomechanical performance analysis. aktos-t was found inaccurate for the ankle, wrist and shoulder joints, but could provide acceptable measurements for pelvis, hip and knee. The main source of error could be related to the IMU-alignment during the reference T-pose. Moreover, aktos-t appeared to be unaffected by jump impact. The main limitation of the study was to use two different biomechanical models in the analysis. Previous work showed that the validation and thorough description of errors between systems are highly affected by the incorporated biomechanical models used in the respective software (Godwin et al., 2009; Mundt et al., 2017; Robert-Lachaine et al., 2017). Moreover, while the current study represents the first validation of the IMU-based system aktos-t and provides useful information about its accuracy, further studies are needed. This work is based on a small sample size and higher numbers of participants in future work can help to identify accuracy and precision from a wider range of anthropometric differences.

Repetitive Movement Test

The majority of the upper body's variables were *not acceptabl*e, *not precise* and had *unbearable accuracy* for biomechanical use (Table 1). On the other hand, all the knee and hip joint variables showed at least *tolerable accuracy.* Similar to previous validations of other IMUs (Robert-Lachaine et al., 2017), none of the variables met the condition of *good accuracy*. In particular, the majority of the ankle and upper limb joints variables were *unbearable accurate*. Errors in the ankle internal/external rotation were expected since the markers and IMUs were positioned on the shoe instead of on the foot, with consequent relative movements caused by the stretch of the footwear fabric. The markers, in fact, defined the embedded axis around which the coordinate system of the joint is created and the angles are estimated. In case of relative movements, for flexion/extension, the error is small; however, the effect increases significantly for rotation and abduction/adduction of the analysed joint (Kadaba et al., 2016). As a result, the ROMs are more accurate than the max and min values, since not based on absolute values. The knee and hip ROMs were *precise* and *acceptable* and the hip ROM at least *tolerable* according to the RMSE (Table 1).

A few variables of the upper limb joints (shoulder abduction/adduction min, wrist ulnar deviation and flexion/extension max, and elbow flexion/extension max) showed a bias < 5°. Some data set of the shoulder flexion/extension and abduction/adduction, and of the elbow flexion/extension were not normally distributed (Table 1). Therefore, an evaluation of the CR cannot be done. However, irrespective of CR, the RMSE showed unbearable accuracy and, consequently, the system can be considered inaccurate for measuring the shoulder and elbow variables. Due to the shoulder's complexity (Nordin & Frankel, 2001), the different models applied by the two systems could influence the angle detection more than for the other joints, as happening for the high absolute bias (max: 24.0°) and RMSE (max: 27.0°). Our results and their interpretation are in accordance with a previous validation of another IMU-system, where a shoulder maximum bias of 26.3° and RMSE of 40.2° were reported (Robert-Lachaine et al., 2017). During the shoulder movement, the thoracic and lumbar spine also contribute to ROM (Nordin & Frankel, 2001). As a result, optoelectronic marker placement is affected by soft-tissue artefacts due to muscle contraction and skin sliding (Charbonnier, Chagué, Kolo, Chow, & Lädermann, 2014). This implies that even the gold-standard measurement might not be able to accurately reflect anatomical joint angular movement. Thus, in this case a validation to the gold-standard needs to be handled with caution. For the wrist and the ankle, the higher RMSE and bias in repetitive movement tests could be explained by the higher acceleration of the hand and the foot, respectively (Robert-Lachaine et al., 2017). Moreover, the space on the dorsal part of the hand was limited. Since the marker already occupied part of it, the IMU was placed partially on the carpal bones, eventually too close to the joint with consequent artefacts (Liu et al., 2009).

Finally, as highlighted by the significant correlations, errors in the absolute values were related to the offset that was already existent during the static T-pose reference. This error has been demonstrated also in a previous publication involving different IMU and optoelectronic systems (Al-Amri, Nicholas, Button, Sparkes, & Sheeran, 2018). In our study, for instance, the offset of the elbow (20.2 ± 6.3°) correlated with the flexion/extension angular differences between the two systems for the min and the max during the repetitive movement test (Table 1). The T-pose kept by the participant during the 'Reference-by-Global' affected all subsequent measurements, since all joint angles were calculated with reference to this pose, resulting in an offset present in all trials (Appendix A). Moreover, if the 'drift correction' T-pose was not comparable to the reference pose, the outcomes would have been affected, as demonstrated in another IMU-system (Mundt et al., 2017). In fact, the algorithm would have corrected the drift by aligning the IMUs incorrectly. In this regard, the authors suggest replacing the T-pose with an anatomical reference pose (i.e. standing erect with the arms hanging down and the hand palm facing forward), allowing a more repeatable and stable pose of the arms. Where possible, the reference pose should be repeated with the participant's back against a wall in order to have the spine and limbs properly aligned, and a more repeatable posture.

Gait Analysis

The ROM of the analysed joints, except the pelvis tilt, showed a joint motion comparable to those in previous publications (Kadaba et al., 1990; Winter, 1991; Bonnefoy-Mazure & Armand, 2015; Al-Amri et al., 2018) (Table 2). The pelvis tilt showed a slightly wider overall ROM and lower min and max angles during the gait cycle compared to the literature (Perry & Burnfield, 1992; Winter, 1991; Bonnefoy-Mazure & Armand, 2015; Al-Amri et al., 2018). Since both systems recorded comparable values, this difference of the tilt measurements to the previously published data might be related to our participant samples.

The ROMs of all the measured joint angles were *precise* and showed from *acceptable* to *tolerable accuracy* (RMSE = 2.4–9.8°), with exception of max and ROM ankle dorsiflexion (RMSE = 10.1°; RMSE = 11.4°, respectively). The detection of pelvis rotation and obliquity were the most accurate, since all the variables had acceptable *accuracy* and *precision*, while the bias was *acceptable* for all tilt variables.

The shapes of the gait angular movements (Figure 3) were comparable with those in previous publications (Kadaba et al., 1990; Winter, 1991; Nordin & Frankel, 2001; Bonnefoy-Mazure & Armand, 2015; Al-Amri et al., 2018), with the exception of the ankle dorsiflexion recorded by the IMUs. In comparison to the optoelectronic data of this and of previous studies (Winter, 1991; Bonnefoy-Mazure & Armand, 2015; Al-Amri et al., 2018), the ankle dorsiflexion presented a higher peak and a less smooth trend at the end of the stance phase (at about 50–60% of the gait cycle). Specifically, 1D-SPM highlighted differences in the ankle dorsiflexion between 54.3 and 59.6% of the gait cycle (Figure 3), when the foot is just about to leave the ground (Nordin & Frankel, 2001). The error could be related to the sensor placement on the metatarsal part of the foot and to the relative movement of the footwear fabric discussed in the previous section. Although both system models consider the foot as a single rigid body, the IMUs were more exposed to the actual non-rigidity of the foot segment (e.g. due to metatarsal phalangeal joints). Therefore, ankle angular comparisons between the two systems might be possible only when the foot is considered the most rigid, such as during the swing phase. In our experiments, 1D-SPM did not reveal ankle dorsiflexion differences during the swing phase (60–100% of the gait cycle), while showing differences during the stance (6.5–37.7%). In this phase, the possible cause of the error might again be the sensor placement and may not be a result of the ground contact impact (Mayagoitia, Nene, & Veltin, 2002), since 1D-SPM showed no statistical difference during the initial contact (0%). However, previous studies using different IMU-systems showed that the gait speed can influence the measured outcomes, since the algorithm cannot properly filter the acceleration as a consequence of higher impacts (Mundt et al., 2017; Al-Amri et al., 2018). Therefore, future work should validate the aktos-t system at different gait velocities. The 1D-SPM analyses highlighted differences between 50 and 70% of the gait cycle for the knee and between 50 and 84% for hip flexion/extension. This coincides with the double support at the end of the stance and the initial part of the swing phase for both joints (until the mid-swing for the hip) (Nordin & Frankel, 2001). One reason for the difference between the two systems in this part of the gait might also be related to the biomechanical model P-i-G that was used in the supposed 'gold standard' method. It is criticised in that P-i-G uses an anatomical instead on a functional joint centre, what might result in erroneous outcomes especially for wide ROMs (Besier, Strunieks, Alderson, & Lloyd, 2003). Thus, especially the knee and hip movement in sagittal plane can be affected by the misalignment of the joint centre. Therefore, it is hard to state if the difference between IMUs and marker-based systems also reflect the difference to the real joint movement.

Squat Jump Test

For the use in in-field sport scenarios, IMUs need to handle impacts. The results of aktos-T showed no statistical difference between the values recorded pre and post impacts that were up to five times body weight. Consequently, besides outcomes concerning accuracy and precision presented in the earlier sections, the IMUs can provide acceptable pre/post impact outcomes when used in sports that impose ground reaction forces at or below this magnitude.

Conclusion

Our findings showed that the aktos-t system can provide acceptable measurements, especially for pelvis, hip and knee joints, having at minimum *tolerable accuracy* (RMSE < 10°). The accuracy of aktos-t varied with the performed task and the analysed joint. aktos-t accuracy can be considered sufficient for providing ROM feedback to athletes during in-field trainings, where a controlled setup as in the laboratory is difficult to reproduce. Moreover, we demonstrated how the offset, recorded during the reference T-pose, influenced the minimum and maximum absolute joint angles. This can be considered one of the major sources of error during the use of aktos-t and needs careful attention in order to achieve the best possible measurements.

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Disclosure statement

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Appendix A

Static calibration

The 'static calibration' is a manufacturer requirement for creating a reference system and zeroing the IMUs. In this procedure, the IMUs are placed on a flat surface (table), all facing the same direction with x-, y-, and z-axis aligned.

Reference-by-Global

In the 'Reference-by-Global' settings, the participant is asked to perform a so-called T-pose. This means standing upright with the feet close to each other and the arms outstretched, forming in this way a T-shape with the body. In this procedure, each IMU is anatomically aligned to the body segment where it is located. In detail, a time-independent rotation matrix is created, specifying how the sensor's axis is to be rotated to match the segment axis as expected during a proper T-pose. The T-pose kept during the 'Reference-by-Global' is the pose, where all joint angles are set to zero. Being the reference pose of the data collection, all subsequently recorded joint angles are expressed in relation to this 'Reference-by-Global' T-pose.

Drift correction

For the software option called 'drift correction', the T-pose was repeated and the software realigned the IMU based on the Reference-by-Global T-pose. The purpose of this procedure is to correct the occurring drift of the IMU sensors that is known to be one of the limitations of IMU-systems (Mundt et al., 2017).

6.4 Ground reaction forces and kinematics of ski jump landing measured with wearable sensors (Study IV)

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Individual contribution

The author of this thesis is the main author of the paper. The doctoral candidate was responsible for the design and conceptualization of the study in agreement with Johannes Petrat and Prof. Dr. Ansgar Schwirtz. The author performed the data acquisition with Johannes Petrat on three different SkiJ hills (Oberstdorf, Oberhof and Ramsau am Dachstein) during summers 2017 and 2018. The data analysis and interpretation was performed by the first author in agreement with Prof. Dr. Ansgar Schwirtz. The doctoral candidate wrote most of the manuscript indipendently, while co-authors critically contributed to the improvement of the content. All authors approved the final version of the manuscript before the submission. The doctoral candidate was responsible for the submission process, replying to the reviewer's comments and changing/adding the manuscript in agreement with all coauthors.

The doctoral candidate presented the set up and some preliminary results of the second part of Study IV during the International Congress of Science and Skiing, hold in Vuokatti (FIN) in March 2019.

Summary and main results

The study was twofolded. The purpose of the first part of the study was to use the *loadsol* wireless force insoles (described in 2.2.2) to detect the magnitude of the maximal GRF (GRF_{max}) and other kinetic variables during the impact. In the second part, one of the athletes was equipped with wireless insoles and a set of 11 *aktos-t* IMUs positioned on the skis, feet, shanks, thighs, pelvis, C7 vertebra and chest (Figure 12b; additional markers were added on the upper body, but not used in the analysis). With the outcomes of this combination was possible to introduce the IMU-based system *aktos-t* for SkiJ biomechanical analysis, and to detect possible correlations between the kinematics of the lower body during the impact and the kinetics.

In the first part of the study, 22 male ski jumpers competing at International level were tested while wearing wireless force during summer training conditions on the SkiJ hills of Oberhof (GER), Oberstdorf (GER) (Figure 13b), and Ramsau am Dachstein (AUT).

The total recorded jumps were 101 with the athletes landing using telemark or parallel leg landing according to the athletes' experience, external conditions and jump length. Besides the kinetic variables of GRF_{max}, I and $t_{landing}$, the symmetry index SI was calculated based on previous publications [91,92]. The IMUs *aktos-t* positioned on the lower body and trunk of the ski jumper permitted to detect not only the kinematics of the landing and its preparation, but also the kinematics of the whole performance. The connected software iSen 3.08 (STT System, San Sebastian, Spain) allowed to obtain a representation of the outcomes with a skeleton model (Figure 14).

Figure 14. Visual representation in the software iSen of the outcomes of the IMUs *aktos-t*, recorded during the landing impact (telemark position).

The primary finding was that to longer t_{flight} corresponded higher normal GRF_{max} and I (GRF_{max}: left side: $r = .481$; right side: $r = .469$; I: left side: $r = .552$; right side: $r = .538$; all $p < .001$), due to the highest speed reached and due to the incline of the SkiJ hill that becomes flatter the longer the jump lengths are. Moreover, the normal GRF_{max} and I were not symmetrically distributed between the two feet, independently from the landing technique. For example, the normal GRF_{max} was asymmetric (SI > 15% [91,92]) in 81% of the parallel leg landing cases and in 50% of the telemark ones.

Under the biomechanical point of view, correlations between the hip, knee and ankle angles and the kinetic variables were found, in particular, the kinetic variables of one side correlated with the kinematic variables of the opposite one. For instance, the absolute values of the back leg and front leg hip flexion kept at t_s correlated with the back leg $t_{landing}$ ($r = -.783$, $p = .013$; $r = -.789$, $p = .011$; respectively; $n = 9$). The front leg GRF_{max} correlated with the front leg knee rotation, front leg hip flexion and back leg hip rotation (*r* = .689, *p* = .040; *r* = -.670, *p* = .048; *r* = .820, *p* = .007; respectively).

Additional results related to the kinematics collected by means of the IMUs are reported in this section (Figure 15). The kinematic patterns are comparable with previous researches [8,42], in which the definition of flexion/extension is the opposite of the one we used (full flexion/extension was defined as 180°/0° in the present study, but 0°/180° in [8,42]). In the last part of the stable flight phase (between 1.00 and 0.50 s before the impact), the hip and knee angles of the two sides are comparable, while the trunk is almost fully extended which widens the cross-sectional area and improves the aerodynamics. During landing preparation, the kinematic variables changed compared with those of the stable flight. From around 0.50 s before the landing impact, the athlete progressively flexes his hip, knee and trunk and extends the ankle to assume the position described in the FIS competition rules [1]. Then 0.10 s before the impact, the trunk, hip and knee flexion angles were steady, while the athlete prepared to absorb the impact. After the impact, as required by the FIS regulations [1], the jumper flexed the trunk and the lower limb joints asymmetrically, first, to perform the telemark landing, and then to maintain the balance after the impact. As in the study of Greimel and colleagues [8], the hip joint of the back leg extended more than the front one, and the back knee became more flexed. In contrast, the athlete kept a wider angle for the rear ankle in comparison to the front one.

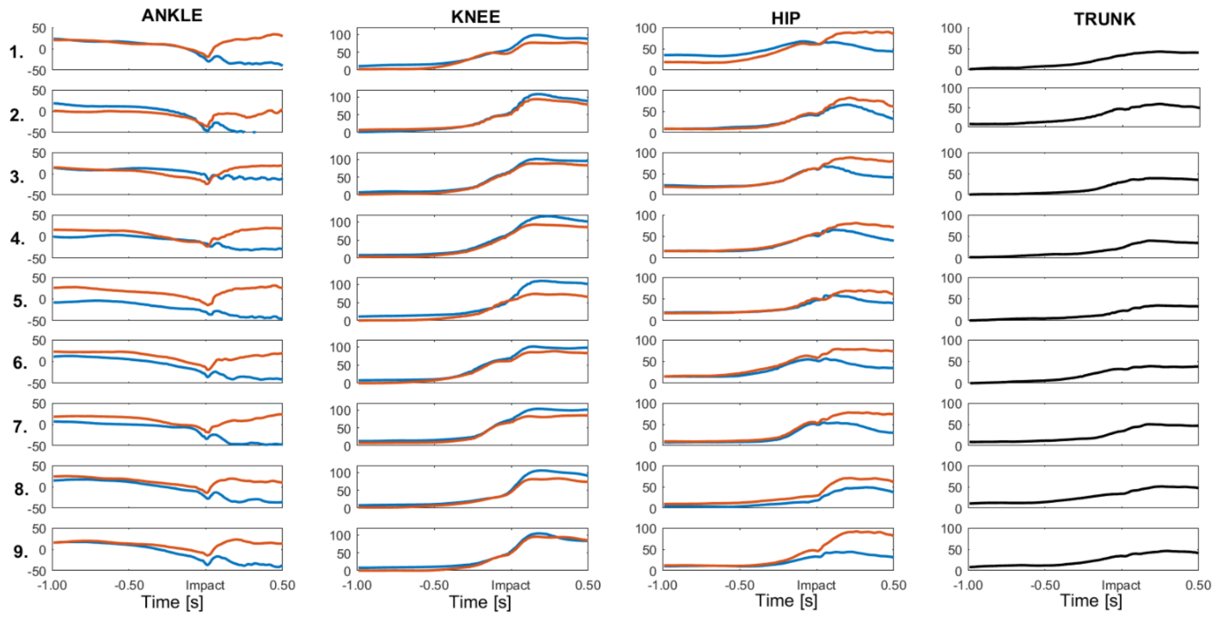

Figure 15. Flexion/extension angles of 9 jumps of one subject performing on the SkiJ hill. The angles represented are the one of ankle, knee, hip and trunk joints. The data are

reported from 1.00 s before the landing impact until 0.5 s after it. The blue line represents the flexion/extension of the left side joints, the blue line the right ones, while the black line the one of the trunk.

sensors

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Article

Ground Reaction Forces and Kinematics of Ski Jump Landing Using Wearable Sensors

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Abstract: In the past, technological issues limited research focused on ski jump landing. Today, thanks to the development of wearable sensors, it is possible to analyze the biomechanics of athletes without interfering with their movements. The aims of this study were twofold. Firstly, the quantification of the kinetic magnitude during landing is performed using wireless force insoles while 22 athletes jumped during summer training on the hill. In the second part, the insoles were combined with inertial motion units (IMUs) to determine the possible correlation between kinematics and kinetics during landing. The maximal normal ground reaction force (GRF_{max}) ranged between 1.1 and 5.3 body weight per foot independently when landing using the telemark or parallel leg technique. The GRF_{max} and impulse were correlated with flying time ($p < 0.001$). The hip flexions/extensions and the knee and hip rotations of the telemark front leg correlated with GRF_{max} ($r = 0.689$, $p = 0.040$; $r = -0.670$, $p = 0.048$; $r = 0.820$, $p = 0.007$; respectively). The force insoles and their combination with IMUs resulted in promising setups to analyze landing biomechanics and to provide in-field feedback to the athletes, being quick to place and light, without limiting movement.

Keywords: landing; injury prevention; kinematics; kinetics; performance; winter sport; force insoles; inertial sensors; impact

1. Introduction

Among ski jumping phases, landing has never been deeply scientifically investigated, being considered of minor interest both by researchers [1] and athletes [2]. However, landing and its preparation are important for performance and safety [1,3–7]. In fact, the athlete has to land using the telemark technique (step position) rather than with a parallel leg landing (squat position) in order to gain technical points from the judges for their overall performance score [8]. Concerning the safety aspect, in ski jumping, as in all jumping sports [9–12], injuries are frequent (around 21 for every 100 athletes) and involve the knee joint in 25 % of cases [13]. In particular, in jumping, a high ground reaction force (GRF) has been indicated as one of the main factors in non-contact anterior cruciate ligament (ACL) rupture [14], but also for other knee injuries [15,16]. In addition, when landing on an inclined surface, as in the case of the landing area of the ski jumping hill, the GRF and lower body kinematics vary [17]. Besides the landing height and the "heel first" landing strategy, GRF has been demonstrated to correlate with ankle, knee, hip and trunk flexion angles with the possibility of inducing knee injuries, as well as ACL rupture [15,18,19]. For example, subjects with ACL rupture had higher hip flexion during landing impact (50.1° versus 25.8°) [18]. Generally, the hip movement absorbs the upper body weight, while the ankle and knee joints absorb the GRF [19]. Besides the knee injury factor, we can speculate that a high GRF could influence balance during landing, with a possible consequent fall. Therefore, the quantification of the magnitude of the GRF, as well as the determination of the kinematics of the lower body during ski jump landing, could play an important role in injury prevention, providing feedback to the athletes and technical indications to coaches to optimize the landing gesture.

Besides the disinterest, one of the main reasons for the limited number of studies into landing was the difficulty of performing kinetic and kinematic analyses on the ski jumping hill, due to certain technical problems [1]: force insoles have the disadvantage of limiting the athlete movements due to the cables that connect the insoles with the receiver [4,20–22], while custom-made force-measuring bindings are relatively unsafe and need to be validated [23]. On the other hand, the integration of a force plate in the ski jumping hill table permits the measurement of the GRF only at take-off [24–27]. However, the development of wireless connections over the last years has permitted an evolution also in the sensors normally used during biomechanical studies. The introduction of wireless force insoles, connected by Bluetooth to a receiver or with an embedded battery and memory, could permit the performance of kinetic analyses of different sports, such as cross-country skiing and running [28,29], without interfering with athlete's movements.

Concerning the kinematic analysis, inertial motion units (IMUs), with their easy-to-use, accurate and wide recording volume characteristics, overcome the problems related to the inaccuracy and the long post-processing and positioning time of the video camera set-ups [30].The IMUs have already shown their potential in ski jumping when positioned on the body [31–33] or only on the skis [34,35]. However, no studies have investigated the landing kinematics with the sensors positioned on the lower limbs, rather concentrating on the overall jump performance [31–33].

To the best of our knowledge, no studies have specifically investigated the impact force during ski jump landing and among different landing techniques. Our investigation is divided into two studies. The goal of the first study is to detect and quantify the magnitude of the force during telemark and parallel leg landing by means of loadsol wireless insoles (Novel GmbH, Munich, Germany). Secondly, an explorative study adding IMUs to the insole set up was performed in order to consider the possible correlations between kinematics and kinetics during landing.

The hypotheses were that longer jumps are correlated with higher impact forces, and that these forces are not equally distributed between both feet during parallel leg landing. Moreover, we hypothesized that the kinematics of the lower limbs influence the impact kinetics. Increasing the understanding of the landing biomechanics of ski jumping by means of wearable sensors could provide information on how the athlete should move in order to reduce the ground reaction force and, consequently, the possibility of injury. After determining this, a non-invasive set-up for landing analysis could be useful, not only for biomechanical research, but also for providing case-specific feedback to the athlete while training on the ski jumping hill.

2. Materials and Methods

The investigation is divided into two parts. In Study I, loadsol wireless insoles were used to detect the kinetics during ski jump landing in order to quantify the distribution, magnitude and impulse of the GRF among different subjects, different ski jumping hills and different landing techniques. In Study II, one subject was tested combining inertial sensors with the force insoles in order to detect possible correlations between kinetic and kinematic variables and to introduce a possible sensor combination to be utilized in further studies.

2.1. Study I

Twenty-two male ski jumpers and Nordic combiners (age: 17 ± 1 years old; weight: 65 ± 7 kg) competing at the National and International Junior level performing on the ski jumping hills HS100 in Oberhof (Germany), HS106 in Oberstdorf (Germany) and HS98 in Ramsau-am-Dachstein (Austria) during summer training conditions were studied. The total number of recorded jumps was 101: 37 in Oberhof, 38 in Oberstdorf and 26 in Ramsau-am-Dachstein. The athletes performed telemark or parallel leg landings, depending on their jump length and expertise. The participants were verbally informed in full about the nature of the study, signed a participation form and were allowed to withdraw at any point without giving a reason. The authors received the ethical agreement to the protocol of the study from the Dean of the Faculty of Sport and Health Science of the Technical University of Munich.

The athletes jumped wearing loadsol plantar force insoles, sampling at 100 Hz and were able to stop automatically after a certain time. The insoles were connected via Bluetooth to the app loadsol installed on an iPod (Apple, Cupertino, CA, USA), which worked as receiver and data logger and which was positioned on the arm of the athlete with a smartphone running case. The force insoles detected the fore/rear foot and overall normal ground reaction force; i.e., the force between the plantar side of the foot and the shoe [36] (Figure 1). The insoles have been previously validated [29,37–39]. Before each jump, the system was calibrated with the athlete's body weight (BW) measured before the training using a body scale and including ski boots, helmet, gloves and ski suit. At the end of each jump, the athlete had to verbally report the kind of landing technique he performed.

Figure 1. Detecting area division of the fore and rear foot part in loadsol force insole (adapted from [36]).

The recorded overall, rear and fore foot normal GRF were normalized on the BW and used as outcomes from the loadsol app, where the values are rounded in steps of 5 N. The maximum ground reaction force (GRF_{max}) was the maximal GRF measured under each foot during the landing impact, while the impulse I (1) was calculated as

$$I = \int_{t_s}^{t_f} \mathrm{GRF}dt \quad (1)$$

as reported in [23]. The start of the landing impact (t_s) was defined as the first increase of normal GRF; i.e., when GRF was higher than 0.5 BW (Figure 2). The end of the landing (t_f) coincided with the minimum of the signal after the second normal GRF peak after touchdown, corresponding with the end of the eccentric phase [23]. The difference between t_f and t_s defined the landing time ($t_{landing}$).

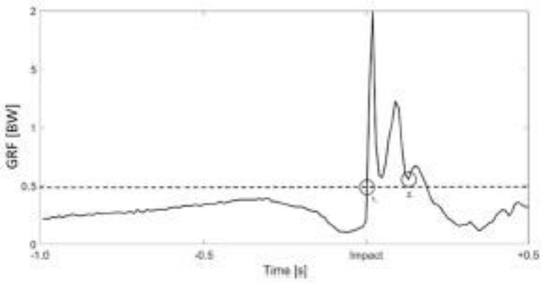

Figure 2. An example of the normal ground reaction force (GRF) (black line) from 1.0 s before the impact until 0.5 s after it. The dashed line represents 0.5 body weight (BW), used as threshold for the start of the landing (1.), while the end of the landing (2.) was defined as the minimum GRF after the second peak.

The symmetry index (SI) (2) of the normal GRF_{max} and I between the two sides (indicated as variables x_L and x_R in (2)) was calculated according to [40] as

$$SI = \frac{|x_L - x_R|}{0.5 * (x_L + x_R)} * 100 \quad (2)$$

A value of 0% indicates perfect symmetry, while a value equal or higher than 15% has been indicated to be a relevant asymmetry between the sides [41,42]. Finally, the distribution of the impulse between the front and rear foot was calculated as the ratio between I of the rear foot and the overall I, shown as percentage.

The duration of the flight phase (t_{flight}) was considered to be the time between the end of take-off and t_s, calculated for both feet and consequently averaged. The end of the take-off was considered when the normal GRF was smaller than 0.5 BW. Considering the wind condition to be stable during the entire data collection, we assumed that a longer t_{flight} corresponded to a longer jump.

The data processing was conducted using custom-written Matlab 2017a (Mathworks Inc., Natwick, MA, USA) codes.

2.2. *Study II*

One of the participants of Study I during the data collection on the ski jumping hill of Oberstdorf was additionally equipped with 11 inertial sensors aktos-t (myolution GmbH, Ratingen, Germany). The sensors were sampled at 143 Hz and were positioned on the skis, feet, shanks, thighs, pelvis, C7 vertebra and chest, placed under the ski suit and attached using medical tape. The procedure of calibration, drift correction and the use of inertial sensors is described in Appendix A. In total, nine jumps were collected using the combination IMUs and force insoles with the athlete always landing with telemark.

Three video cameras were added around the landing area to record the jump length. A light barrier at the take-off table, normally used during official competition, detected the take-off speed.

The kinematic data were firstly processed using the software iSen 3.08 (STT System, San Sebastian, Spain), which applied a low pass filter (Butterworth, second order, 10 Hz) to the raw data. Subsequently, a post-processing was performed using Matlab 2017a; if the hip, knee and trunk flexions/extensions showed negative values during the flight phase (i.e. not physiological extension) due to the offset created during the T-pose reference position [43], the angles were adjusted. In particular, the absolute value of the recorded minimum negative joint angle during the flight phase was considered as offset and added to the overall outcome. The flexion/extension, abduction/adduction and rotation of the knee and hip, the ankle dorsiflexion and abduction/adduction, and the orientation of the trunk (flexion, abduction and rotation) were analyzed at t_s after having post-synchronized the data based on the comparison of t_{flight} recorded by the insoles (calculated as explained in Study I) with the one recorded by the IMUs. The minimum ankle dorsiflexion after take-off was used to define the end of the take-off, while the end of the flight was defined as the first maximum ankle extension before the impact.

2.3. *Statistical Analysis*

Due to the high number of variables interfering with the movement and the different kinds of landing technique, each ski jump was considered as a specific case, even when performed by the same athlete. The mean and standard deviation (SD) are reported in order to show the magnitude of the detected variables in Study I. To determine the relationships between the kinematic and kinetic variables in Study I and II, Pearson correlations were calculated. The statistical analysis was performed using IBM SPSS Statistics (IBM Corp., Armonk, NY, USA). The criterion for statistical significance was set at $p < 0.05$.

3. Results

3.1. Study I

Of the 101 collected jumps, 56 were reported as telemark and 27 as parallel leg landing; the other 28 were not possible to classify, since the athlete reported to have not performed a distinct telemark or parallel leg landing. The average normal GRF_{max} per foot was 2.7 ± 0.9 BW (range: 1.1–5.3 BW; $n = 101$), respectively, of 2.6 ± 0.8 BW and 2.7 ± 0.9 BW ($n = 56$) for the telemark front and rear leg (max: 5.2 BW) and 2.7 ± 1.0 BW ($n = 27$) during parallel leg landing (max: 5.3 BW). The overall $t_{landing}$ was 0.19 ± 0.05 s for both sides, while t_{flight} was 3.32 ± 0.29 s. The normal GRF_{max} and I correlated with t_{flight} (both $p < 0.001$), as reported in Table 1.

Table 1. Correlations between the impulse and normal GRF_{max} of the left and right leg, and $t_{landing}$ and t_{flight} for the 101 collected jumps.

	t_{flight}	$t_{landing}$
F_{max}	left: $r = 0.481$ ***; right: $r = 0.469$ ***	
I	left: $r = 0.552$ ***; right: $r = 0.538$ ***	right: $r = -0.263$ **

** $p < 0.01$; *** $p < 0.001$

The SI indexes are reported in Table 2. The normal GRF_{max} during parallel leg landing was asymmetric (> 15% as according to [41,42]) in 81% of the cases, while I was asymmetric in 50% of the cases. During telemark landing, the normal GRF_{max} was asymmetric in 62% of the collected landings, while I in 68% of the cases.

Table 2. Symmetry index (SI) of the normal GRF_{max} and impulse (I), and I distribution on the rear part of the foot during parallel leg and telemark landing (for the front (fl) and back (bl) positioned leg).

	Parallel Leg	Telemark
Number of jumps	26	56
GRF_{max} SI between sides [%]	24 ± 13	26 ± 21
I SI between sides [%]	15 ± 8	24 ± 17
I distribution on the rear foot [%]	56 ± 19	bl: 52 ± 25 ($n = 55$); fl: 48 ± 17

The normal GRF_{max} distribution on the front (fl) and the back (bl) positioned leg in the telemark landing varied among the jumps and the t_{flight} (Figure 3).

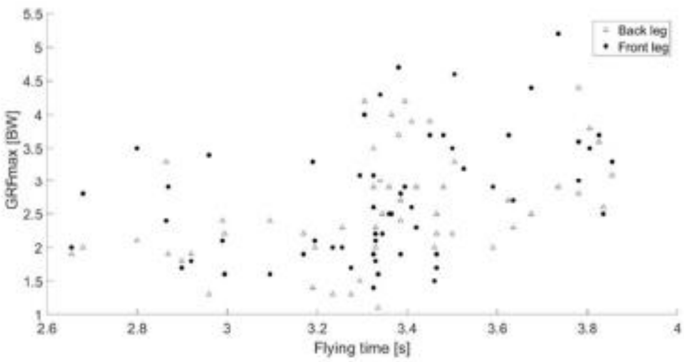

Figure 3. Normal GRF_{max} acting on the rear and front leg during telemark in relation to the flying time for 56 jumps.

Greater impulses correlated with greater normal GRF_{max} (left: $r = 0.781$; right: $r = 0.776$, both $p < 0.001$; $n = 101$). In Table 3, the correlations of the normal GRF_{max} and I with $t_{landing}$ are shown in relation to the ski jumping hill where the data were collected.

Table 3. Correlations between t_{flight}, and normal GRF_{max} and impulse (I) acting on the left and right foot, in relation to the jumping hills where the data were collected. The landing area incline characterized the jumping hills [44].

	Ramsau am D.	Oberstdorf	Oberhof
Incline of the landing area	36°	35.5°	35°
GRF_{max} (left)	$r = 0.517; p = 0.007$	$r = 0.363; p = 0.025$	$r = 0.597; p < 0.001$
GRF_{max} (right)	$r = 0.637; p < 0.001$	$r = 0.400; p = 0.013$	$r = 0.545; p < 0.001$
I (left)	$r = 0.342; p = 0.095$	$r = 0.554; p < 0.001$	$r = 0.651; p < 0.001$
I (right)	$r = 0.448; p = 0.022$	$r = 0.695; p < 0.001$	$r = 0.465; p = 0.004$

3.2. *Study II*

During the nine jumps, the athlete equipped with IMUs and insoles always landed using telemark. The kinematic variables during landing impact were correlated with the opposite kinetic variable; for example, bl ankle flexion was correlated with the impulse of fl ($r = -0.708$, $p = 0.033$). The absolute values of the bl and fl hip flexion kept at t_s were correlated with the bl $t_{landing}$ ($r = -0.783$, $p = 0.013$; $r = -0.789$, $p = 0.011$; respectively; $n = 9$). The fl GRF_{max} correlated with the fl knee rotation, fl hip flexion and bl hip rotation ($r = 0.689$, $p = 0.040$; $r = -0.670$, $p = 0.048$; $r = 0.820$, $p = 0.007$; respectively). No correlations were found between ankle dorsiflexion and torso angular movements and kinetic variables ($p > 0.05$).

The jump length recorded with the video cameras correlated with t_{flight} ($r = 0.960$, $p < 0.001$). The take-off speed (85.7 ± 0.7 km/h) did not correlate with any of the kinetic variables.

Values for t_{flight} calculated using the IMUs and using the insoles had an average difference of approximately 0.02 ± 0.02 s.

4. Discussion

In the study, wearable sensors were used to biomechanically analyze the ski jump landings. The main goal of the study was to determine the impact force and its distribution during different ski jump landing techniques by means of wireless plantar force insoles. Moreover, the detection of possible correlation between kinetics and kinematics during impact landing thanks to the introduction of the combination of IMUs and insoles was the goal of the explorative investigation of *Study II*. As assumed, the jump length was strongly correlated with t_{flight} ($r = 0.960$, $p < 0.001$). The post-synchronization for individuating t_s can be considered acceptable. The difference between the t_{flight} calculated using the IMUs and the force insoles was 0.02 ± 0.02 s, corresponding to 0.6% of the average t_{flight}. Therefore, the calculation could be considered comparable. Not surprisingly, the primary finding was that a longer t_{flight} corresponded to a higher normal GRF_{max} due to the highest speed being reached and due to the flatter incline of the jumping hill [4]. Moreover, the normal GRF_{max} and the impulse were not symmetrically distributed between the two feet, independently from the landing technique. Finally, correlations between the hip and knee angles and the kinetic variables were found.

4.1. *Study I*

The outcomes of the force insoles during the entire performance (Figure 2) were comparable with those in previous publications [1,21,35]. The normal GRF_{max} and the impulse were correlated with t_{flight} (Table 1). The range of the normal GRF_{max} per foot varied widely and, considering that the athletes landed with high speed, the magnitudes unexpectedly resulted to be relatively low in comparison to previous publications dealing with drop and countermovement jumps, which found a GRF_{max} per foot of 2.0 BW [45,46]. The reasons for the low magnitude could be related to technological, material and set-up problems. Firstly, previous publications disagreed about how the low sampling rate of the loadsol insoles could affect the capability of measuring impact: the groups of Burns [29] and of Seiberl [38] did not mention a limitation of the detection related to the low sampling rate, while the group of Peebles [37] stated that underestimation and overestimation biases of the impact force peaks were detected in single hop and stop jumps when using loadsol at 100 Hz (−0.46 BW, 0.36 BW, respectively) and at 200 Hz (0.37 BW, 0.35 BW, respectively). However, a difference of circa 0.4 BW would still represent a small contribution to the collected normal GRF_{max}. Secondly, the ski jump boots are stiffer and with a more angulated shape in comparison, for example, to running shoes. When the athlete flexes his ankle during landing, he leans forward, with the shank pushing on the front part of the boot, carrying part of his BW. Therefore, in the data collection, part of the impact force could have been bypassed by the boot frame. Lastly, as reported by the insoles' specifications [36], the collected impact represents only the normal component relative to the insoles' surface. The overall GRF acting on the athlete is influenced by the incline (~35°) and, in particular, by the cosine of the incline (~0.82); therefore, the GRF collected by the insoles represents only circa 80% of the overall ground reaction force (Figure 4). Related to this, the correlations between kinetics and t_{flight} are more significant on the ski jumping hill of Oberhof (Table 3), where the incline of the landing area is the smallest (35°) and the cosine is therefore higher. This means that longer jumps on ski jumping hills with flatter landing areas lead to higher GRF.

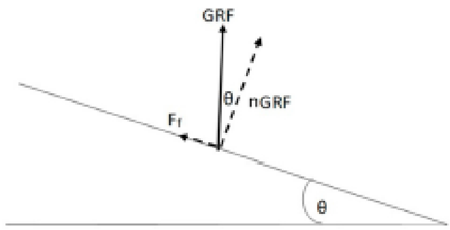

Figure 4. Overall GRF and its components (nGRF, normal GRF; F_f: friction) related to the incline θ of the landing area.

The distribution of the normal GRF_{max} between the front and the back leg in telemark seemed to be case-specific (Figure 3). The overview of parallel leg and telemark landing SIs showed that the GRF_{max} and I are not equally distributed between the feet in both landing techniques in the majority of the collected jumps, although technically required by the International Ski Federation rules [8]. This could be explainable by a wider ski positioning leading to a one-side load with the possibility of ski edging [5] or by a possible different placement of the centre of mass during touchdown [46]. It can be assumed that the kinematics of the athlete play a role in the kinetic distribution and on the kinetics in general, as previously demonstrated [19]. To confirm this, thanks to the addition of the IMUs to the insoles' set up in *Study II*, it has been possible to observe how the kinetic and kinematic variables were correlated. In some cases, due to the asymmetry of the telemark position, a kinetic variable of one side was correlated with a kinematic variable of the opposite side, as happened for the front leg hip flexion with the back leg $t_{landing}$. However, an asymmetric position is not recommendable since it has been related to higher peak ACL forces in a simulation of jump landing in alpine skiing [47], as well as in studies on preventing ACL injuries [11,48].

The BW distribution between the front and the rear part of the foot seemed to be case-specific. Knowing this force distribution could be an important feedback for reducing injuries, since it has been shown how the 'heels first' landing technique results in higher vertical ground reaction force and smaller knee valgus and contraction in comparison to the 'toes first' approach when landing from a jump [15,19,49].

4.2. Study II

During the landing, athletes cannot modify the impulse acting on the force, since it is related to their body mass and velocity. However, the athlete can increase the $t_{landing}$ acting on the hip, knee and ankle amplitudes, as occurs in gymnastics [49]. Respective to the joint movements of the subject analyzed in *Study II*, hip flexions/extensions, and knee and hip rotations of the telemark front leg were the movements that were mainly correlated with the normal GRF_{max}. In the specific analysed case, in order to reduce the impulse, the athlete should try to land without rotating his front knee and hip joints, since the internal rotation of the knee is a risk factor for non-contact ACL injuries [49]. Moreover, in order to increase $t_{landing}$, the analyzed athlete should keep the hips more extended at t_s. However, since the lower body kinematics during landing vary according to gender and performance level, in normal jumping as well as in ski jumping [7,19,50], our findings might not be applicable to other athletes. Nonetheless, the study is the first to combine data from force insoles and IMUs positioned on the lower body and trunk, and it could provide perspectives for future research in the field. In general, an inertial sensor-based feedback has been shown to reduce the risk factors for ACL during drop jumps [51]. This application could also be effective for ski jump landing, giving suggestions to athletes about how they would need to perform in order to reduce the impact kinetics.

4.3. Limitations

Regarding the limitations of the studies, as previously mentioned, the low sample rate of the force insoles could have influenced the collected outcomes [35]. Therefore, during further studies, a higher sampling rate (200 Hz) of the loadsol insoles would be recommendable. The main limitation of *Study II* was the focus on only one subject. Due to the influence of the kinematics on the kinetics [9], further studies should be performed using a combination of inertial sensors and force insoles as proposed in the explorative investigation of *Study II*. In fact, a higher number of subjects would better describe the biomechanics of the landing, which vary among athletes according to gender, expertise and age [7]. Finally, a consideration for future research is that the researchers should pay particular attention when the athlete is getting dressed in their ski jumping suit, after having positioned the sensors on the skin. In fact, the suit could press on and move the sensors, resulting in incorrect outcomes.

5. Conclusions

The use of wireless force insoles to quantify the kinetic variables in ski jump landing could play an important role for injury prevention in this sport. The present study focused on the kinetics during landing impact in ski jumping, involving elite athletes during summer training and using wearable sensors. The combination of inertial sensors and force insoles did not interfere with the performance and resulted in non-invasive measurement according to the feeling of the jumpers. Therefore, from a practical point of view, the use of these wearable sensors during daily training could be effective for athletes, giving specific feedback on how they should move in order to reduce their vertical ground reaction force and impulse.

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Appendix A

The inertial sensors aktos-t (myolution GmbH, Ratingen, Germany) used in *Study II* can be activated using a laptop and a receiver or by means of a remote control. In this last case, the sensors can store the collected data in their memory. The outcomes can be downloaded at the end of the data collection using the software iSen 3.08 (STT System, San Sebastian, Spain) and consequently analysed.

After having placed the sensors on the body of the athlete, a reference T-pose (posture with straight back, head looking forward and arms stretched to each side, forming a T-shape) needs to be performed [43]. The pose is performed before starting the data collection with the sensors connected by Bluetooth with a receiver and is required by the software iSen 3.08 to anatomically align each IMU to the body segment on which it is located [43]. This pose is the reference posture, where all joint angles are set to zero; therefore, all subsequent angles are recorded relative to it. During the data collection of *Study II*, the ski jumper found difficulties in keeping a steady T-pose with the leg fully extended while wearing the ski boots, since they are characterized by a specific stiffness and shape. Therefore, the athlete kept the T-pose position with the tips of the foot on a wooden bar. This stratagem was used to permit the athletes to have their knee and hip normally extended and in a normal standing position. The angle of the ankle was calculated with and without the bar in order to detect the difference between the two configurations. The difference was then considered during the data processing.

After the IMU calibration, the configuration of the sensor placement can be saved on the memory of the sensor. After this, the sensors can be switched on and off using the remote control. On the ski jumping hill, the sensors were switched on by an experimenter with the remote control while the athlete was preparing himself on the stairs beside the in-run. Before each jump, a T-pose was repeated with the tips of the ski boots on a wooden bar. This T-pose is required by the software iSen 3.08 to correct the drift accumulated during the data collection. After the jump, the sensors were switched off using a second remote control by an experimenter placed at the end of the landing area, with the athlete steady.

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7. Discussion and research perspectives

In this chapter, the main results of the reported studies will be shortly discussed (7.1), the limitations and methodological considerations will be summarized (7.2) and considerations about future research related to the main findings will be proposed (7.3). An extensive interpretation and discussion of the studies can be found in the original manuscripts of the scientific papers. As a reminder to the reader, each study is referred in the text by its Roman numerals and, when necessary, by keywords in parenthesis, as follows:

I. Bessone, et al. (2018). Analysis of landing in ski jumping by means of inertial sensors and force insoles. (pilot)

II. Bessone, et al. (2019). Ski position during the flight and landing preparation phases in ski jumping detected with inertial sensors. (IMUs on ski)

III. Bessone, et al. (2019). Validation of a new inertial measurement unit system based on different dynamic movements for future in-field applications. (validation)

IV. Bessone, et al. (2019). Ground reaction forces and kinematics of ski jump landing measured with wearable sensors. (IMUs on body and GRF)

7.1 Discussion of the main findings

Study I, II and IV permitted to increase the understanding of SkiJ landing biomechanics and demonstrated how the use of wearable sensors allow to perform in-field biomechanical analysis of SkiJ landing. Based on the data collected with IMUs and wireless force insoles, correlations between the ski's and athlete's body kinematics, and the impact kinetics were notable. The presence of a correlation between kinematics and kinetics in SkiJ is in line with previous publications involving normal jumps [11,84,91,92].

The results of Study III showed that the accuracy of the IMU-based system *aktos-t*, in comparison with the outcomes of the optoelectronic system, varies according to the task performed, with a higher accuracy for the pelvis, knee and hip joints (RMSE < 10°), and a lower for the upper body joints (RMSE > 10°).

7.1.1. In-field biomechanical analysis of SkiJ landing

The main focus of Study II (IMUs on ski) and IV (IMUs on body and GRF) was on the investigation of possible correlations between the kinetics and the kinematics of the athlete and of the skis in order to reduce the GRF magnitude, one of the main reason of knee injuries in jumping sport [11-13].

Longer t_{flight} resulted in higher normal GRF_{max} and I, having found from low ($0.30 < r < 0.49$) to high ($0.70 < r < 0.90$) correlations between t_{flight}, and GRF_{max} and I (Study I, II and IV) [93]. Being the jump length very highly correlated with t_{flight} ($r = 0.960$, $p < 0.001$) [93], longer jumps resulted also in higher normal GRF_{max} and I (Study IV). One of the main reasons is because the longer the jump, the flatter the landing area is [86]. As a consequence, the normal GRF, influenced by the cosine of the incline, becomes greater the flatter the landing surface is. This means that the smaller is the angle of the landing area, the greater is its cosine and, therefore, the greater is the normal GRF. As a result, the design of the landing area can play an important role in the reduction of the GRF during the impact. Despite the relation between jump performance and kinetics, the jump length remains the main goal of this sport. However, it is evident that during the process of optimization of the trajectory and of the technique, as well as during the design of the SkiJ hill, the GRF acting on the athlete during landing needs to be considered. In this regards, computer simulations should be employed. In fact, simulations based on biomechanical model can furnish valid outcomes, without risks for the athletes, and with the possibility of changing the initial conditions and the external factors acting on the system athlete plus skis. On behalf of the project SkOPTing of which the current thesis is part (see *Introduction*), simulations to detect the optimal trajectory related with the lowest GRF were performed [94,95]. In Figure 16, for instance, the simulation of the trajectory shows how the jump length and GRF for an average athlete are related when jumping on the SkiJ hill of Oberstdorf. It is notable how for a jump length over 80 m, the GRF increases drastically.

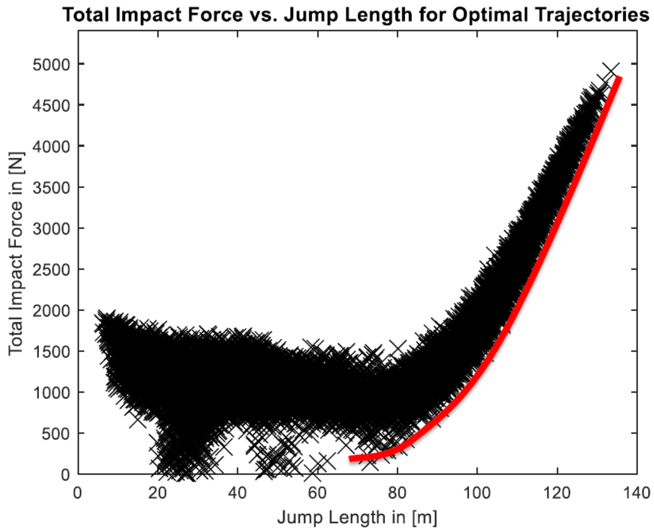

Figure 16. Estimation (red line) of a multi-criterial optimization for the maximum jump length and minimum impact force on the SkiJ hill of Oberstdorf [96].

The pitch was the main ski movement correlating with t_{flight} and the normal GRF_{max} magnitude. The importance of the pitch during the landing preparation for lengthening the ski braking action [6], was strengthened by the positive correlations between pitch ROM and normal GRF_{max} magnitude ($r \geq 0.50$, moderate correlation [93], Study II, IMUs on ski). Moreover, the wider the difference between the pitch at t_S and during the flight is, the longer the jump ($r \geq 0.50$, moderate correlation [93], Study II), since a wider angle of attack permits to better exploit the aerodynamic forces [6,7]. However, the pitch position at 0.16 s before the landing did not correlate with GRF_{max} ($p > 0.05$, Study II). This means that, when the athlete is approaching the ground, the ski position does not influence the GRF. In fact, since the athlete is too close to the landing area, the aerodynamic forces cannot act. Wider ranges of pitch motion in the last phase of the landing preparation corresponded to longer t_{flight}. This means that the ski jumpers, firstly, need to keep the skis as long as possible flexed in order to exploit the aerodynamic forces, and then, they need to fast move the skis for preparing the impact. In Study II, major differences in the pitch were recorded between 0.36 s and 0.16 s, leading to the consideration that the start of the landing preparation happens around 0.4 s, as stated by Greimel and colleagues [8]. Finally, the ROM of roll and yaw during the landing preparation did not influence any of the kinetic variables (Study II).

GRF_{max} magnitude, its symmetry and the symmetry of I between the feet varied widely among jumps, indistinctly between telemark and parallel leg landing (Study IV, IMUs on body and GRF). GRF_{max} (range: 1.1 – 5.3 BW) resulted to be higher than in a previous publication [5]. Moreover, based on the outcomes of Study IV, it cannot be stated that one of the two techniques (telemark and parallel leg position) leads to a lower GRF in comparison to the other. This means that other variables as, for example, the landing speed and the jump length, are influencing the GRF. However, according to Hochmuth [6], the telemark landing with its step position gives more balance and permits to reduce the impact. Considering that the athletes landed with high speeds, the average magnitudes resulted to be unexpectedly relatively low (2.6 ± 0.8 BW), in comparison to drop and countermovement jumps [90,91]. The reasons for the low magnitude could be related to technological (sample rate), material (SkiJ boots' stiffness) and set-up (incline of the landing area) problems and will be later reported in 7.2.4. The SI of GRF_{max} and the SI of I were not equally distributed between the feet in both landing techniques in the majority of the collected jumps, although technically required by the FIS rules [1]. This behaviour is explainable with a possible ski edging [6] or a different placement of the centre of mass during touchdown [97] that could influence the balance of the athlete, leading to a possible fall. Moreover, the BW distribution between the front and the rear part of the foot seemed to be case-specific among subjects (Study IV). Since the 'heels first' landing technique has been shown to lead to higher GRF than the 'toes first' during landing, giving the feedback about the front/rear distribution could be an important feedback for the athletes [11,91,92,98].

The hip, knee and ankle angles correlated with the kinetic variables in the explorative study combining IMUs on the athlete's body and wireless force insoles (Study IV). In the case study, the GRF_{max} of the front positioned leg moderate correlated with the knee rotation and hip flexion of the same leg (r = 0.689, p = 0.040; r = -0.670, p = 0.048, respectively) and highly correlated with the hip rotation of the back positioned leg (r = 0.820, p = 0.007) [93]. Therefore, based on this explorative study, it might be speculated that the kinematics of the lower body during the landing impact as well as while approaching it, is influencing the kinetics of the impact itself, as in normal jumps [11,84,91,92,99]. In particular, the athlete during the landing impact could reduce the impulse I acting on the kinematics of the lower body. In fact, I is calculated as the integral of GRF over $t_{landing}$. The GRF acting on the athlete cannot be reduced during the landing impact, however, $t_{landing}$ can be modified acting on the kinematics of the lower body. For instance, based on the data collected of Study IV, it can be suggested to the participant athlete to focus on the hip flexions for lengthening $t_{landing}$ showing a high correlations between the variables (*r* = -.783, *p* = .013; *r* = -.789, *p* = .011; respectively for the back and front hip flexions) [93].

7.1.2. Use of IMUs for determining the ski jumping performance

Before discussing the advantages and disadvantages of the use of IMUs in SkiJ, it is important to remind the reader that, in the studies composing this dissertation, two different IMU-based systems were utilized. Study I (pilot) and II (IMUs on skis) were performed with the sensors from MSR Solutions, while Study III (validation) and IV (IMUs on body and GRF) with the *aktot-t* system from myolution GmbH. Two different systems were employed to better exploit their characteristics: The IMUs of Study I and II could be used standalone without a pre-calibration and with a fast placement; the IMUs of Study IV were associated to a biomechanical model and could provide the lower body kinematics.

The hardware of the sensors used in Study I and II have not been validated. However, the IMUs were not associated to a biomechanical model, in which a higher number of errors can be introduced due to the sensors' placement and the model itself. On the contrary, the post processing of the IMUs placed on the skis, have been specifically validated by Fang [85], on behalf of the collaboration project SkOPTing, described in the *Introduction*.

Besides the previously discussed relation between ski movement kinematics and kinetics during landing (Study II, IMUs on skis), the IMUs placed on the skis showed the curves of the ski angles from the take-off until the landing. The ski movements were distinctive among the participants (Study II), owning their personal movement patterns depending on the expertise [76], but at the same time, they were in line with the technical considerations proposed by the FIS technical regulations [1]. Considering as criteria for judging the quality of the ski position technique that the athlete should keep a stable and symmetrical position during the flight [1,78,100], it was remarked that none of the athletes of the study showed an outstanding ski position technique, probably since still belonging to the Junior category.

The IMUs placed on the lower body permitted to detect the biomechanics of the athlete during the landing impact (Study IV), as well as of the landing preparation, as showed by the unpublished data reported in section 6.3, demonstrating how IMUs could constitute important technologies for the biomechanical analysis of this phase.

However, some limitations of the use of IMUs in SkiJ need to be considered and will be discussed in 7.2.3.

Due to the importance of the ski movement pattern, athletes and coaches were particularly interested in obtaining outcomes after the tests on the SkiJ. In fact, coaches evaluate athletes' technique based on visual observations and, in some cases, by recording the flight phase with a video camera. However, the quality and accuracy of the videos is low [47], restricted to the flight phase and without a quantitative feedback of the kinematic variables. Consequently, the use of IMUs could replace video cameras, providing reliable data without time lost for post processing and for placing the cameras around the SkiJ hill. In this regard, after the data collection of Study I and II, a report with the ski movement pattern of the collected jumps was provided to each athlete, in order to strengthen the collaboration between scientists and sportsmen. Despite the demonstrated utility of IMUs for monitoring the SkiJ performance, some distinctions and considerations about the two different utilized systems are necessary. In fact if, from one side, the employment of IMUs placed on skis would be easy to perform during daily trainings, on the other side, the use of the IMUs placed on the whole body could be performed only occasionally. The reasons are the following ones:

- positioning time and precision: the time necessary to position the IMUs on the whole body is longer than the placement of only two IMUs on the skis. This means that the already low number of jumps performed by the athletes during a training session (from four to six), would be further reduced, since part of the training time would be used for placing and attaching the sensors on the athlete. Moreover, due to the high precision necessary in the IMUs' placement on the whole body, a professional needs to perform the data collection in order to avoid positioning errors, while the IMUs on the skis can be easily placed and fixed behind the bindings by not professionals, after being correctly instructed.
- calibration and in-field use: the two IMUs positioned on the skis do not need any calibration, while the IMUs placed on the lower body do at the start of each trial, with a possible introduction of errors and time loss. Both the systems need to be activated by a coach or a professional before the start of each jump.
- data processing and feedback: for both systems a live feedback is not possible, and the outcomes of both the IMU-based systems' raw data need always to be post-processed at the end of the training. However, after being correctly instructed, the coaches can perform the data processing for both the systems.

- cost: due to the consistent different price of the two IMU-based systems (approximately 1000 € for two IMUs to be placed on the skis versus 25000 € for the *aktos-t* IMUs/software/model), a lower number of IMU-based system (as *aktos-t*) can be owned and therefore, a minor number of athletes can be tested simultaneously.

7.1.3. Use of wireless force insoles for determining the ski jumping kinetics

As previously discussed, the force insoles permitted to analyze the kinetics of the landing. Although the focus of the studies of the dissertation was on this phase, the utilized force insoles *loadsol* permitted to collect the normal GRF during the entire SkiJ performance (Figure 17), providing an important feedback without interfering with the safety of the athletes. The outcomes were in lines with the ones of Schwameder and Müller [5] (Figure 17) and it is possible to notice how the normal GRF at the beginning of the in-run is around 0.5 BW, since divided between the two feet and since the total GRF is decomposed on an incline in the normal and the parallel components. At the end of the in-run, due to the centrifugal force created by the change of radius of the SkiJ hill, the normal GRF is increasing. Being the take-off table a flat surface, the GRF recorded in this phase is relatively constant. During the flight phase, the GRF is smaller than the BW since the athlete is leaning in the air and part of the total BW is “taken” by the trunk surface. Interestingly, since the insoles are placed in the boots directly connected to the skis, a relation between the movement of the skis recorded by the IMUs and the GRF recorded by the insoles was noticed in Study I (pilot). In fact, acting on the skis and in relation to the wind, the air pressure beneath the skis is varying and, as a consequence, also the pressure recorded by the insoles. During the landing preparation, the normal GRF acting on the skis is increasing, since the aerodynamic forces are increasing in relation to the ski pitch movement performed to reduce the speed. Finally, the peak of the landing impact is visible, while during the outrun, the outcomes of the force insoles show spikes as reaction to the friction between the ski and the synthetic grass of the landing area (Figure 17).

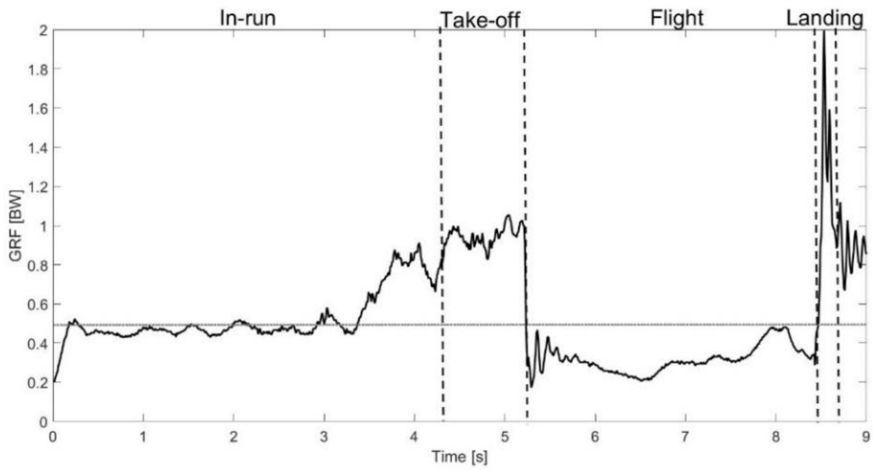

Figure 17. Vertical ground reaction force (GRF) collected by one insole from the start of the SkiJ performance until the out-run after the landing impact. The vertical lines indicate the start/end of the different phases.

Athletes and coaches during the tests have been particularly interested in knowing the outcomes of the force insoles during the performance. Therefore, to each athlete a report for all the collected jumps was provided with the overall GRF of the left and the right side (Figure 18a – 18b) and of the front and back GRF distribution from the in-run until the landing (Figure 18c – 18d). Moreover, the report provided also the GRF distribution (in percentage) on the front foot during the take-off for the two sides (Figure 19), since considered by coaches, and scientists [101], an important aspect of the performance. Figure 18 reports the three different kinetic outcomes of two jumps of two different athletes (called X and Y) provided at the end of the data collection. It is notable how subject X (Figure 18a) showed an asymmetry of the BW distribution during the in-run, while subject Y (Figure 18b) had a comparable BW distribution. Therefore, in this case, a feedback to subject X was given to optimize his in-run BW distribution. Figure 18c and 19d showed the distributions of GRF between front and rear foot during the entire performance. At the end of the in-run, due to the centrifugal force caused by the radius of the SkiJ hill [101], the distribution of GRF remained constant on the rear part, while increased on the front foot. In addition, it is notable how the GRF of subject Y (Figure 18f) during the take-off was more distributed on the front part in comparison to subject X (Figure 18e). Consequently, a feedback about the BW distribution between the front and the rear part of the foot was given to subject X. Generally, it is recommendable to concentrate the BW on the front part of the foot, in order to optimize the angular momentum at the take-off [101].

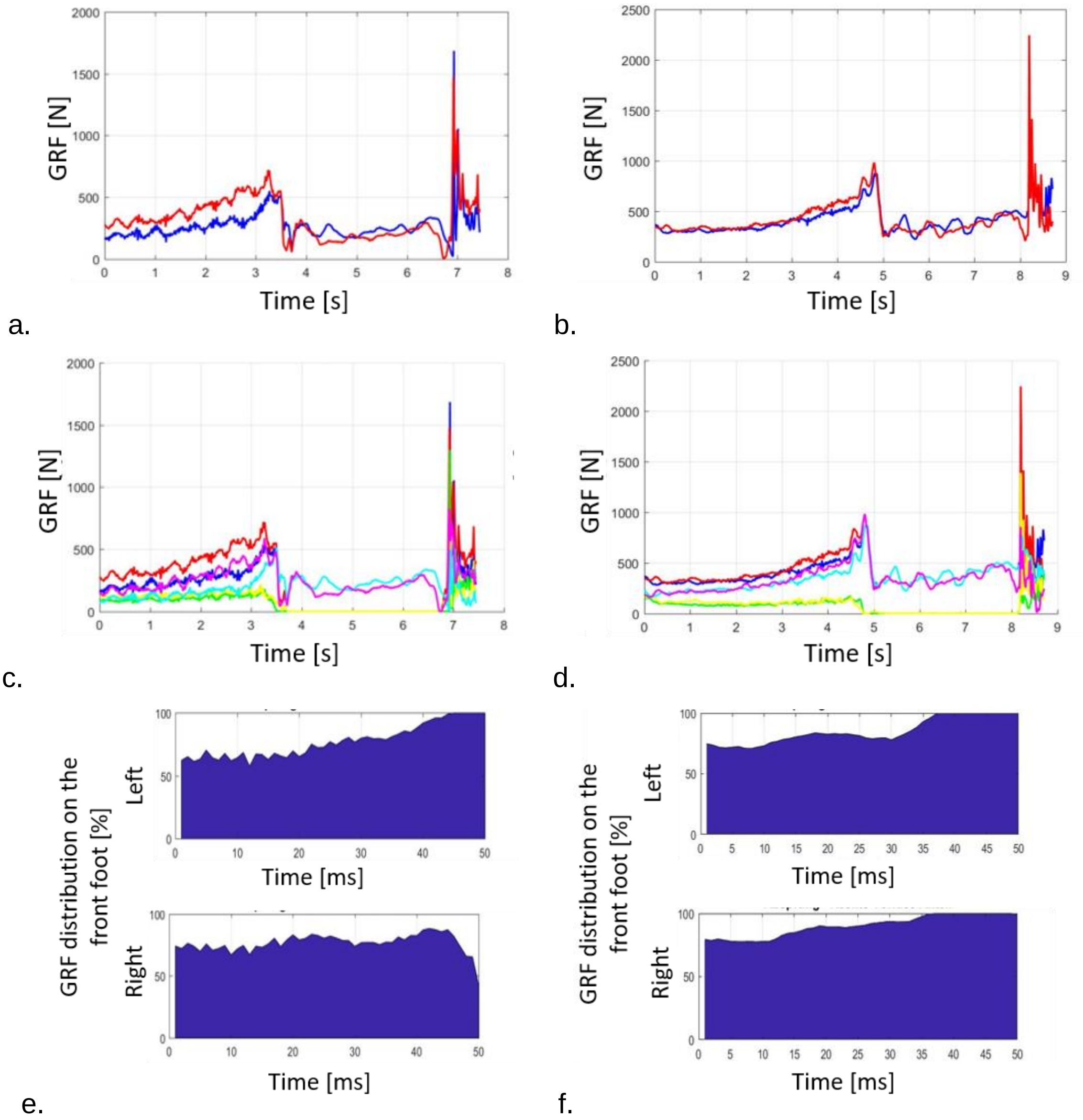

Figure 18. Overall (a.-b.) vertical ground reaction force (GRF) and its distribution (c.-d.) over time for two different subjects (X. (18a and 18c) and Y. (18b and 18d)) collected for the left (blue) and the right (red) sides from the in-run to the landing. The green line represents the rear GRF of the left foot, the yellow of the right, the light blue the front GRF of the left foot, the magenta of the right (c.-d.). Ground reaction force (GRF) distribution (in %) on the front foot during the take-off for the two sides for two different subjects (X. (1fe) and Y (18f)).

Finally, under the practical point of view, the use of the wireless force insoles is simple and also not professionals can properly use them with a high accuracy. The insoles provide the kinetics of the whole performance, even if the athletes and coaches are interested especially in the kinetics of the take-off phase rather than the one of the landing. However, only few SkiJ hills are equipped with embedded force plates at the take-off table, that always need a person in charge responsible for their use. Therefore, having wearable sensors that can be used easily in different locations could be considered an interesting solution for kinetic feedback during training camps, also because the insoles can be employed, during other kind of trainings, as for example, simulation jumps. Another advantage of the wireless force insoles is that after each jump, an immediate feedback of the kinetics can be dispensed, simply looking at the plot visualized on the screen of the wearable receiver (as the iPod).

7.1.4. Considerations about the validated IMU-based system

Being the focus of the present thesis on the landing biomechanics, the outcomes of the IMU validation (Study III) will be only briefly discussed in this section. The accuracy of the *aktos-t* (as hardware, software and biomechanical model) was tested by comparing with a gold standard optoelectronic system (Vicon), in order to permit its use in consequent studies, as Study IV. The *aktos-t* accuracy was found to be, at least, tolerable for the pelvis, knee and hip joints (RMSE < 10° [87]), in comparison to the upper body joints that resulted to be inaccurate (RMSE > 10° [87]) and imprecise (CR > 10° [88,89]). In general, the *aktos-t* accuracy can be considered sufficient for providing ROM feedback to athletes during in-field trainings. The IMU-based system appeared to be unaffected by jump impact and, as a consequence, it can be used in in-field scenarios, also in sports requiring high dynamic movements. In addition, particular attention needs to be given to the placement of the IMU on the foot, due to the artefacts related to the shoes' fabric, as well as to the Reference pose kept by the athlete at the beginning of the data collection.

The results of Study III are of particular importance when considering the use of the IMU-based system in SkiJ. Thanks to the findings of Study III, the outcomes of Study IV collected on the SkiJ hill could be considered valid, since only the lower body kinematics was considered in the study. Moreover, Study III provided the tools for other researchers to judge the *aktos-t* as sufficiently accurate for their studies.

7.2 Limitations and methodological considerations

7.2.1. Sample and study design

Elite athletes, competing at National and International level, were analyzed in the studies of the thesis based on in-field data collection (I, II and IV). The goal was to guarantee the same level of expertise and technique, even though as in all sports, personal technical adaptations are present among ski jumpers and cannot be excluded.

The SkiJ German Junior National Team is usually composed by no more than ten athletes. In Study I, II and IV, the whole SkiJ Junior National team was tested, and in Study IV also the whole Nordic Combined Junior National Team was involved. Therefore, the same technical abilities and experiences were guaranteed in the studies, and a higher number of subjects with comparable characteristics was not possible to have. Important to highlight is the fact that the level of the tested subjects was very high (elite), competing at International level. Regarding the sample size, to the best of our knowledge, its calculation has never been performed in previous publications about SkiJ. When calculating the sample size of our tested group, using the software G*Power [102], the sample should have been composed of 13 athletes. In the calculation, α was considered equal to 0.05, while 1-β was 0.95 and effect size of 0.70, since high correlations among the kinetic and kinematic variables were expected (Figure 19). Therefore, we can consider the number of tested subjects, for example in Study II (10), reasonable "close" to the suggested from the power analysis in order to perform correlations.

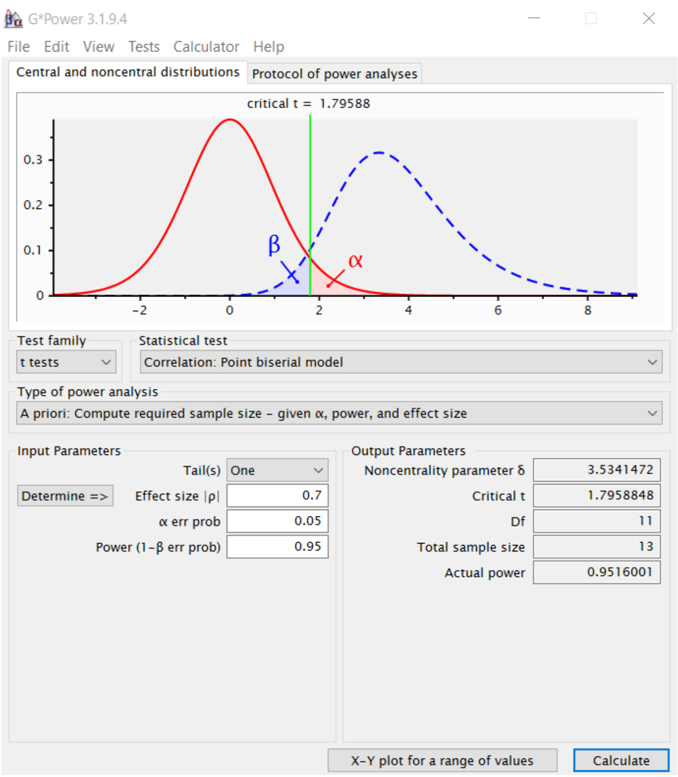

Figure 19. Outcomes of the software G*power for what concerns the calculation of the sample group of ski jumpers [102].

SkiJ is characterized by a low number of repetitions: The athletes usually performed between four and six jumps per training (circa 2 hours) [2]. Although our set ups in Study I, II and IV were fast to place, a calibration of the force insoles was necessary at the beginning of each jump, and therefore, some minutes of the training session were lost, resulting in a lower number of collected jumps.

The studies (I, II and IV) were performed on different SkiJ hills (Oberhof, Oberstdorf and Ramsau-am-Dachstein), but with a comparable size (K-point set at 90 m) [88] and with comparable weather conditions (sunny, no wind). The weather conditions on the SkiJ hill are changing suddenly, especially the wind. Therefore, also the same jumper during the same training session has to face external changes and needs, as consequence, to adapt his/her technique. In general, being SkiJ an outdoor sports, guaranteeing the same external conditions to all the athletes is not possible. Consequently, especially phases as the early flight, the flight and the landing preparation are particularly affected by wind and sudden air pressure changes.

Finally, the focus of our studies was the detection of correlations between kinetics and kinematics during the SkiJ landing, without distinctions between telemark and parallel leg landings. However, the analysis of the biomechanics should specifically distinct between these two techniques. Among the presented studies, different approaches were used. In the methodical Study I, only telemark landing was analyzed. In Study II, no distinctions between telemark and parallel leg techniques were performed. In Study IV, the kinetic analysis was divided between the two landing techniques, while the explorative study with IMUs on the lower body and force insoles was performed only on telemark.

7.2.2. Variable definition

In Study II and IV, in order to quantify the jump performance, we assumed t_{flight} related to the jump length since a very high correlation ($r = 0.960$, $p < 0.0010$, [93]) was found between the jump lengths recorded by video cameras and t_{flight} (Study IV). Evaluating the jump performance using t_{flight}, permits to avoid the use of video cameras in the set up. However, t_{flight} depends on the flying trajectory and air pressure, consequently, slightly differences could be present between jump length and t_{flight}.

In Study II and IV, in order to permit comparisons between the publications, the start t_s and end t_f of the landing impact was defined as reported by Groh and colleagues [48] (t_s was defined when the BW recorded by the insoles overcome the threshold of

0.5 BW; t_f coincided with the minimum of the signal after the second normal GRF_{max} after touchdown). The definitions are based on unpublished data performed by Fritz and Schwameder [103], who compared the kinetic outcomes collected by mens of custom made force bindings during the landing impact on the SkiJ hill with the outcomes recorded on a force plate during indoor imitation jump. Therefore, some considerations regarding $t_{landing}$ and I related to $t_{landing}$ can be done: The threshold of 0.5 BW per foot proposed in [48], for example, can be judged too high for SkiJ landing impact, while it can be considered biomechanically acceptable when landing on a flat surface. In fact, considering that the SkiJ landing is performed on an incline area, the normal GRF is a smaller component of the overall GRF, since related to the cosine of the incline, as afterwards explained in 7.2.4. Moreover, despite the imitation take-off performed indoor is comparable with the one performed on the hill [34-36], it can be assumed that the same cannot be valid for landing, since its timing and speed are different. In addition, the movement is stopped during indoor test, while it is executed while gliding during in-field performance. Therefore, the timing of the knee eccentric phase utilized to define t_f could be different.

In Study II, always to permit comparisons between the publications, specific timing before the landing (0.76 s, 0.56 s, 0.36 s and 0.16 s) were utilized to calculate the ski angular ROM [8]. It can be assumed that changing the timing during which the ROM of the ski movements was calculated, would also change the possible correlations with impact kinetics. On the other hand, choosing a common specific movement (as closing the skis from a V to a parallel shape), that the athletes are doing during the landing preparation was not possible, independently if of the lower/upper body or of the skis. In fact, as showed in Study II, the ski movements' pattern utilized by the athletes, is different among subjects.

7.2.3. Reference pose of the IMU-based system in laboratory and ski jumping hill tests

In the validation (Study III), two different biomechanical models were utilized in the analysis (the one of the optoelectronic system Vicon and the one of *aktos-t*). As previously demonstrated for different IMU-based systems [74,104,105], the use of two different models for the validation can limit the outcomes of the validation itself. Therefore, further validation studies should employ the same model in order to avoid errors related to the biomechanical model's definition.

The T-pose kept by the subject during the Reference-by-Global (described in 6.2 – Study III), affected all subsequent records, being all joint angles calculated with reference to this pose, resulting in an offset present in all trials, as showed in [105] for different IMU and optoelectronic systems. Moreover, if the 'drift correction' T-pose (described in 6.2 – Study III) had not properly been repeated at the start of the trials, the outcomes would have changed, as happening in another IMU-based system [74]. As a matter of fact, the algorithm would have corrected the drift by aligning the sensors referring to a wrong pose. In this regard, the authors suggest to replace the T-pose with the anatomical reference pose (i.e. standing erect facing forward with the arms hanging down and the hand palm facing forward), allowing a more repeatable and stable pose of the arms. When possible, the reference pose should be repeated with the subject's back against a wall in order to have the spine and limbs properly aligned, and a more repeatable movement.

For what concerns the use of the *aktos-t* IMU-based system during in-field data collections, considerations regarding the Reference-by-Global and drift correction T-pose need to be done. Due to the suit and the ski boots, the athlete had a limitation of the movements, in particular of the extension of the arms, knees and hips and had a fixed dorsiflexion of the ankle. As a result, these limitations affected the athlete in performing the Reference-by-Global and drift correction T-pose. Therefore, in the explorative test of Study IV, the Reference-by-Global T-pose was performed without the suit and with the ski boots, with the tips of the feet on a wooden bar. This stratagem was used to permit the athlete to have knee and hip normally extended as in a normal standing position. The angle of the ankle was calculated with and without the bar in order to detect the difference between the two configurations. The difference was then considered during the data processing. During the drift correction pose performed before each jump, the T-pose was also repeated with the tips of the SkiJ boots on a wooden bar. However, the athlete wore the SkiJ suit and a correct arm position was not possible to keep due to the tightness of the suit. During further in-field tests on the SkiJ hill, it is recommendable to replace the T-pose with the abovementioned anatomical reference pose and with the tips of the feet on a wooden bar. Finally, particular attention needs to be given when the athlete is wearing the SkiJ suit, since the compression applied by the suit and/or the movement made while wearing it, could cause a possible sensors' misplacement.

7.2.4. Force insoles during in-field ski jumping analysis

For the studies of this thesis, the *loadsol* insoles were considered to be the optimal solution. In fact, these wearable sensors are light, not invasive, and easy to use. Moreover, there was the possibility of showing an immediate feedback to the athletes during the training, thanks to the screen of the iPod to which the insoles were wireless connected. However, previous studies observed an underestimation bias when comparing in-shoe pressure insoles with force plates' outcomes due to the material of the shoes [68,69]. Moreover, during landing, underestimation and overestimation bias of the impact force peaks were detected in single hop and stop jumps when using *loadsol* at 100 Hz (-0.46 BW, 0.36 BW, respectively) and 200 Hz (0.37 BW, 0.35 BW, respectively) [66].

An indoor evaluation showed that part of the GRF is bypassed by the boot frame. In the test, the outcomes of the force insoles *loadosol* placed in the SkiJ boots were compared with the ones of a force plate (Kistler, Winterthur, CH, 1000Hz) while standing in a static position. The comparison showed that only the 94% of the total GRF is collected by the force insoles. However, since the frame of the SkiJ cannot be changed, regarding the "bypassed" BW problem all the force insoles are affected. Using a force-measuring binding system would overcome the problem, but as mentioned in (2.2), this kind of system needs to be validated, and its weight could affect the safety and performance of the athlete.

Lastly, a limitation of the *loadsol* insoles is that the collected impact represents only the normal component relative to the insoles' surface. Therefore, the mediolateral and forward/backward direction of the GRF is not recorded, leading to an essential loss of information, especially when considering the outcomes for injury prevention.

7.2.5. Statistics

Considering the external factors acting on the performance of the athlete, we could consider each jump as a standalone case, also when comparing jumps performed by the same athlete during the same training; in particular, when dealing with landing, that is the last phase of the performance and consequently, the more influenced by external factors and by the biomechanics of the previous phases. Therefore, the correlations have been calculated considering the overall number of collected jumps on the SkiJ hill has standalone cases.

7.3. Research perspectives

The presented results, their related discussions and limitations permit to provide suggestions for future researches on the topic of SkiJ landing biomechanics. In particular, the doctoral candidate suggest five main research focuses:

1. **Kinematic analysis.** IMUs were employed to detect the ROM of skis (Study I and II) and of the lower body joints (Study IV). However, further researches should focus also on the speed and the acceleration of the limbs and of the skis, with an extensive biomechanical analysis of the entire kinematics of telemark and parallel leg landings by means of IMUs. As a results, comparing telemark and parallel leg landings performed in equal conditions and with a comparable jump length, it would be possible to biomechanically indicate which of the two positions is recommendable, being safer than the other. In addition, the center of mass position during the landing should be investigated, being an important variable in term of balance and stability. Finally, combining kinetic and kinematic data as well as inverse dynamics, the direction of the forces and of the momenta acting on the joints can be estimated, giving additional information in regards of preventing injuries.
2. **Equipment development.** The ski boots and bindings play an important role in the injury prevention of alpine skiing [106,107]. As happening for alpine skiing's equipment, also for the ones of SkiJ, mechanical laboratory tests and simulations should be performed to design safer materials. In fact, the actual SkiJ bindings permit a good control of the skis during the flight phase, but drastically reduce the ROM of the ankle joint during landing, with consequent unsafe movements' adaptations while performing the telemark. Moreover, the bindings rarely release during landing including a ski rotation, causing the twist of the knee, for instance. At the same time, the SkiJ boots are stiff and shaped, reducing the angular ROM of the ankle. As a result for injury prevention reasons, future research should focus on the design of the equipment, in particular on the angular movement's freedom of the boots, on a safe releasing of the binding when a rotation of the ski is happening while landing and on bindings that permit a wider ROM during the telemark landing.
3. **Wind tunnel test.** Wind tunnel tests showed how the V-style during the landing preparation can increase the braking action and the jump length [7]. But, at the same time, the ski aerodynamics changes related to the ski positioning itself, as

combination of roll, pitch and yaw [108,109]. Therefore, further wind tunnel tests are recommendable to increase the understanding of the ski aerodynamics (and the system ski plus athlete) while approaching the landing impact.

4. **Landing biomechanics of female ski jumpers.** As mentioned in the *Introduction*, the totality of the SkiJ studies involved male athletes. However, women are generally more prone to ACL rupture and knee injuries in general, due to anthropometrics, hormones, and neuromuscular activation [110,111]. Moreover, always for physical characteristics, female ski jumpers might perform the landing with different timings and movements. As a consequence, biomechanical analysis of the landing is recommendable to be performed also on female athletes in order to reduce the injury risk.
5. **Computer simulations.** Further computer simulations of the SkiJ landing, as the one performed for alpine skiing by Heinrich and colleagues [71] and the one performed on behalf of the project SkOPTing, will permit to optimize the movements and the technique during the landing preparation and the impact itself, increasing the number of repetitions and without interfering with the safety of the athletes. In addition, computer simulations could also provide indications for designing new SkiJ hills, and especially their landing area, showed to influence the GRF_{max} (Study IV). Always regarding the landing area, the questionnaire reported in the *Rationale for the thesis and aims*, highlighted how, according to the athletes, some improvements can be already done on the existing SkiJ hill to improve the safety. As an example, increasing the visibility of the landing area (adding lights and/or increasing the contrast with the snow), as well as a better grooming could enhance the safety of SkiJ landing.

8. Conclusion and implications

This thesis focuses on the biomechanical analysis of SkiJ landing by means of wearable sensors. Employing IMUs and wireless force insoles, it was possible to increase the understandings of landing biomechanics, quantifying the GRF magnitude and defining its correlations with the kinematics of the athlete, while overcoming the invasive characteristics and recording volume limitations of the previous utilized technologies. The conclusion of the thesis, based on the reported results, will be presented in this section.

It can be generally concluded that the kinematics and the kinetics of the SkiJ athletes during the landing are directly connected (Figure 20). Therefore, in order to reduce the GRF magnitude, the athletes should focus on their kinematics before the landing.

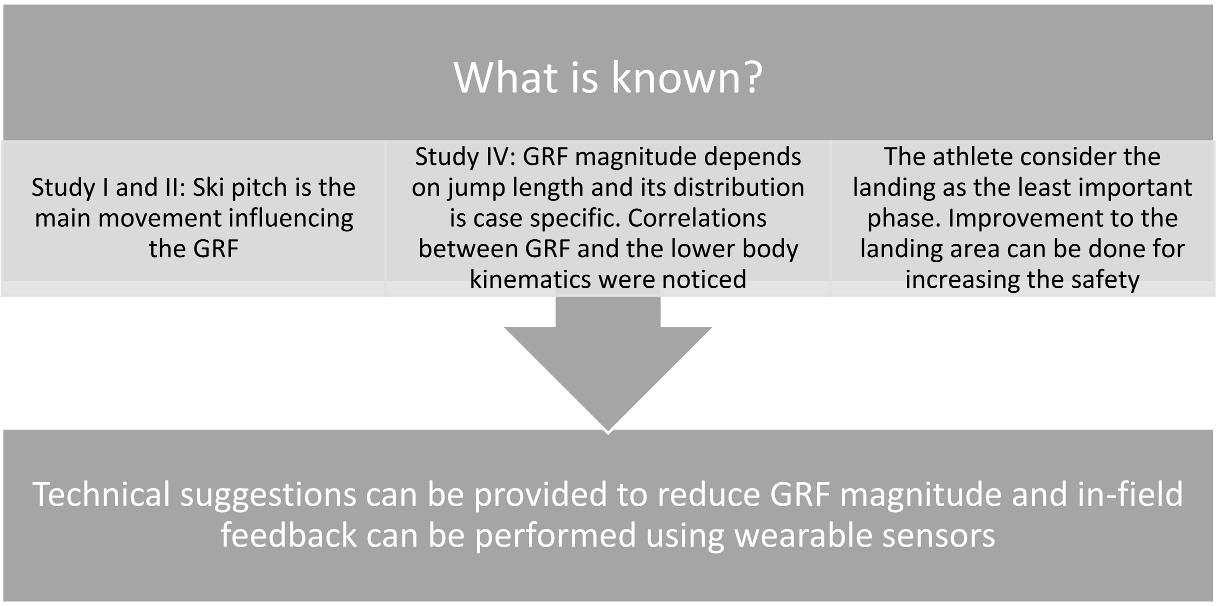

Figure 20. Answered questions with the outcomes of the thesis regarding the landing phase in SkiJ (based on Figure 10).

8.1 Technical suggestions for reducing the GRF magnitude

Based on the results of the thesis, technical suggestions can be given to coaches and athletes in order to reduce GRF_{max}, one of the main cause of knee injuries [11-13].

During the landing preparation, the pitch resulted to be the ski movement that most influences the GRF_{max} and the SkiJ performance. As a result, the athlete should keep the skis more flexed during this phase in order to increase the angle of attack [6,7]. Moreover, at the same time, the pitch is not influencing the GRF_{max} when too close to the ground. Therefore, athletes need to find a compromise between the exploitation of the aerodynamics for increasing the jump distance and, then, for reducing the speed. Consequently, the landing preparation phase with its braking action needs to be prepared around 0.2 and 0.4 s before the impact.

The outcomes of the studies do not highlight differences between the GRF acting on the athlete while landing using telemark or parallel leg landing. Therefore, for what concerns only the kinetic aspect, no recommendations can be given regarding the best position to land with.

During the landing impact, the kinematics of the athlete cannot modify the GRF. However, the ski jumper can reduce I, increasing the $t_{landing}$, by acting on the lower body kinematics, as occurs for example in gymnastics [98]. Based on preliminary results, and on considerations about the landing biomechanics of general jumps, we can speculate that the athletes should land with more extended hips, in order to bump the trunk inertia during the impact. Moreover, the athletes should try to land without internally rotating the front hip and knee joints, since the internal rotation of the knee is a risk factor for non-contact ACL injuries [97].

Due to the subjectivity of the flying and of the landing techniques, as well as due to the different physical and physiological characteristics among the ski jumpers, it is recommendable to perform, for each of them, tests combining IMUs and wireless force insoles. In this way, for each athlete, the position and technique that are optimizing the most the landing, while reducing the GRF magnitude, can be found.

8.2 IMUs and wireless force insoles for ski jumping biomechanical analysis and in-field feedback

The present thesis is based on in-field data collection that successfully employed wearable technologies. The IMUs and wireless force insoles used in the studies permitted to overcome the main limitations that reduced the past number of publications in SkiJ biomechanics, i.e., the recording volume constrains and the movement's impediment caused by cables and weight of the equipment. According to the feelings of the tested ski jumpers, the set-up constituted by the force insoles and the IMUs did not interfere with their performance. Therefore, it can be recommended to use the described methods for further biomechanical analysis as well as for providing in-field technical feedback to the athletes. The use of the wireless force insoles and their combination with IMUs placed on skis can be considered a promising tool for providing feedback to the athletes during trainings. In addition, the data collection can be performed also by the coaches, after being instructed. On the other hand, it can be suggested to employ the IMUs placed on the whole body only for biomechanical research or for giving occasionally feedback to the athletes.

The studies of the current thesis provide additional evidence of the advantages of using wearable sensors for monitoring and testing sports, considered the new frontier for in-field biomechanical analysis. Especially for sports as SkiJ, for which laboratory testing cannot replace the in-field performance, the possibility of monitoring the kinematics and kinetics of the athletes during the trainings, could increase the effectiveness of the feedback of the coaches as well as the relationship between coach and athlete for what concerns the technical aspects. Despite the performance and technique are further augmented during the competitive setting in comparison to the normal trainings, in SkiJ the use of wearable sensors could be considered applicable only during trainings. In fact, even if the sensors are not limiting the movements of the athletes and are light, the weight of these technologies can still be considered reducing the performance of the athlete, being the weight a performance factor in this sport [23,24].

To conclude, future investigations in the field of the biomechanical analysis of SkiJ landing need to find a compromise between improving the performance and reducing the injury risk. In this regards, different approaches need to be considered: orthopedically-traumatic, anatomically-biomechanical, kinematic, energetic, skiing load related, muscular, neuromuscular, skiing technical [112] as well as external factors, such as the conditions of the slope, and intrinsic aspects (i.e. pre-existing damage) [111]. These different aspects have been highlighted for knee injuries' prevention in alpine skiing [112], but they can be extended to ski jumping too.

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List of abbreviations

ACL	Anterior Cruciate Ligament
BW	Body Weight
CR	Coefficient of Repeatability
EMG	Electromyography
FIS	International Ski Federation
GA	Gastrocnemius
GL	Gluteus
GRF	Ground Reaction Force
GRF_{max}	Maximal Ground Reaction Force (Figure A)
I	Impulse
IMU	Inertial Motion Units
RMSE	Root Mean Square Error
SI	Symmetry Index
SkiJ	Ski Jumping
TA	Tibialis Anterior
t_{flight}	Flight time from the end of the take-off until the landing impact
t_s	Start of the landing impact, defined when the BW recorded by the insoles overcome the threshold of 0.5 BW (Figure A 1.)
t_f	Start of the landing impact, coincided with the minimum of the signal after the second normal GRF peak after touchdown, corresponding with the end of the eccentric phase (Figure A 2.)
$t_{landing}$	Landing time calculated between t_s and t_f
♂	Male
♀	Female

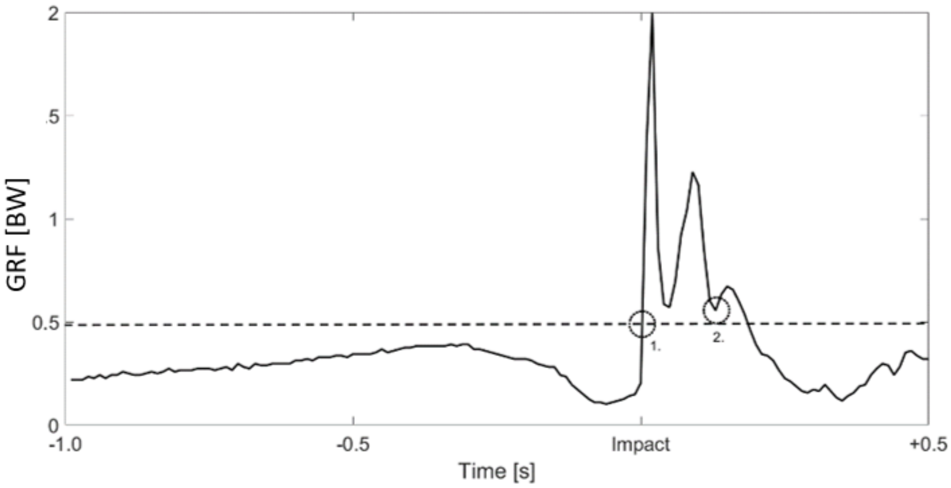

Figure A. An example of the normal ground reaction force (GRF) from 1.0 s before the landing impact until 0.5 s after it. The dashed line represents 0.5 body weight, used as threshold for the start of the landing (1.), while (2.) shows the end of the landing.

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Appendix

Eidesstattliche Erklärung

Anhang I

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich die bei der promotionsführenden Einrichtung
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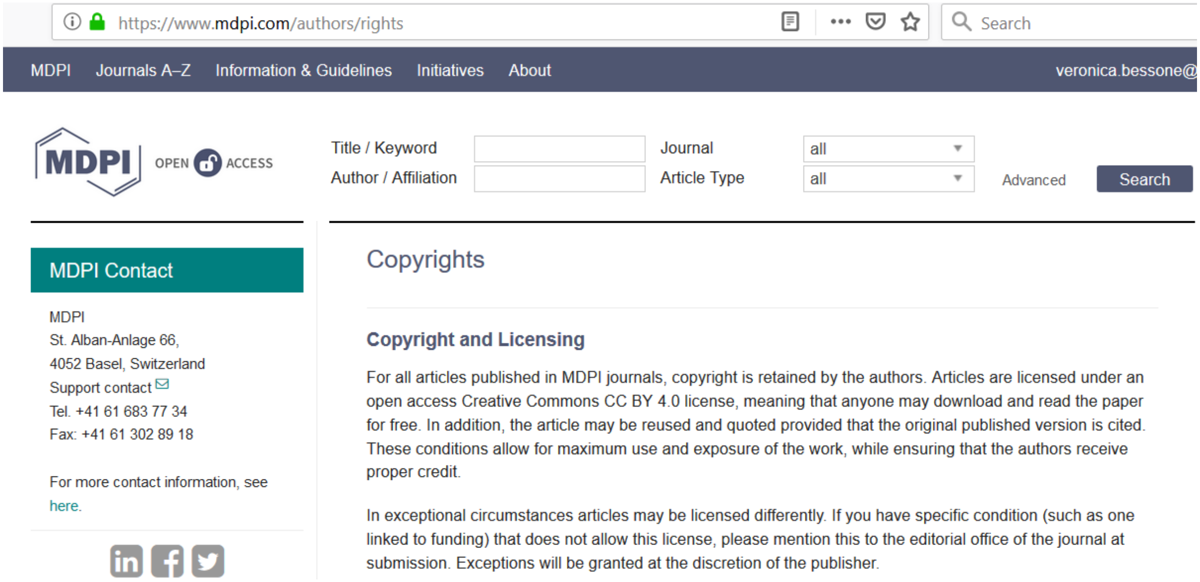
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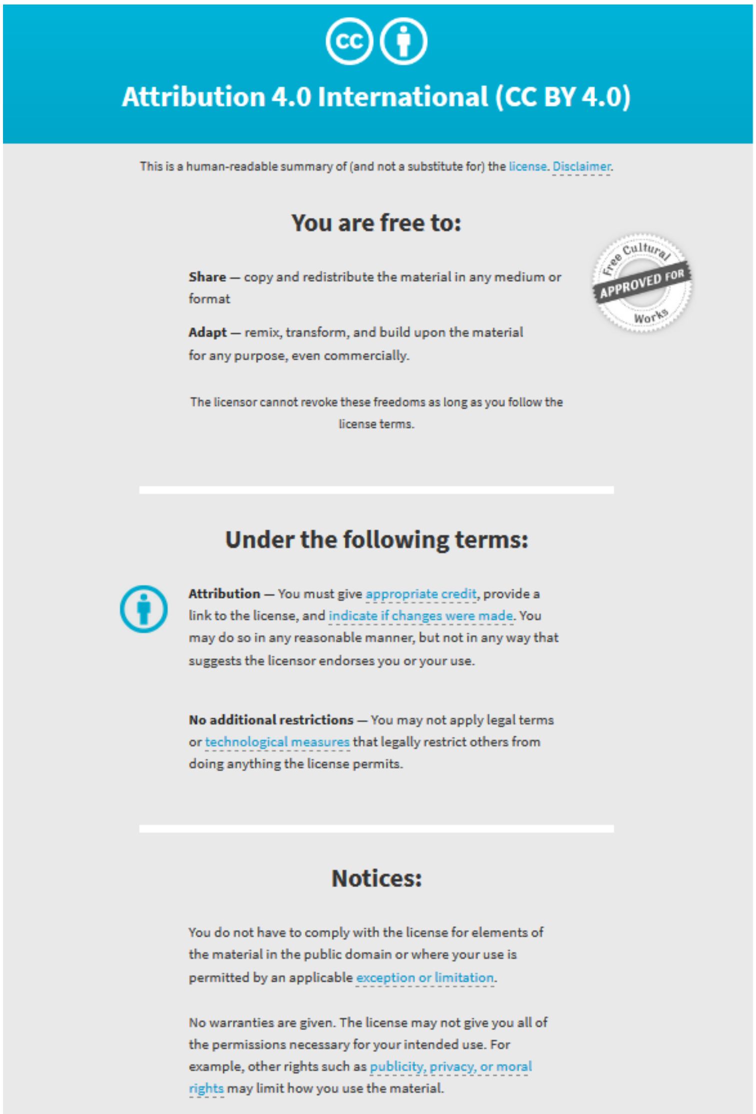
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