Biomechanical analysis in freestyle snowboarding: application of a full-body inertial measurement system and a bilateral insole measurement system

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Several investigations show that 5–28% of all snowboarding injuries relate to the ankle joint complex. To reduce the risk of ankle injuries, the development of enhanced snowboard equipment is considered. Therefore, it is essential to understand the biomechanics in snowboarding. Scientific studies investigating the ankle joint complex in freestyle snowboarding, including inrun, flight phase, and landing, are so far not available. An auspicious method to determine relevant kinematical and kinetic parameters is based on the utilization of an inertial measurement suit in combination with a bilateral insole measurement system. This pilot study aims at the application of these two systems in freestyle snowboarding for data collection in a real snowboarding environment. The accuracy of the used measurement systems is assessed. The insole measurement system shows a root mean square error of 28% (±6.6%) in reference to a force plate. A maximum mean deviation of 4.8° (±0.3°) is found in the inertial measurement system compared to an optical video-based system. The on-snow data collection reveals valuable information and provides a better understanding of the biomechanics in freestyle snowboarding. Ranges of movement of the ankle joint complex and forces essential to perform snowboarding maneuvers are measured. In addition, combinations of joint angles and landing forces occurring during the landing phase of an aerial maneuver are found that have the potential to cause injuries. Critical values of 25° dorsiflexion and 8° external rotation in combination with a normal force of 3020 N are measured at the back leg.

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1. INTRODUCTION

Snowboarding is one of the premier alpine winter sports. With respect to the anatomic location of injuries, several investigations show that 5–28% of all injuries relate to the ankle joint complex [1–4]. Furthermore, correlations between the type of equipment used and the injury were found [2,3,5,6]. Thus, the development of enhanced snowboard equipment, to reduce the risk of equipment-related injuries, is considered in literature [2,5,6,7]. In a current research project at the University of Magdeburg in Germany, a new safety snowboard binding concept is in development, which in particular protects the snowboarder’s ankle joint. The usage of soft boots increases the risk of ankle injuries compared to hard boots [2,3,5,6]. Additionally, most snowboarders prefer the use of soft boots [3,6,8]. Following this, the aim of the research and development project is to develop of a soft boot-binding...
concept. The understanding of the biomechanics in snowboarding is crucial for this research project. It is essential to gain knowledge concerning specific biomechanical parameters, especially with regard to the ankle joint complex, to prevent equipment-related injuries.

The literature provides several studies investigating kinetics and kinematics in snowboarding. Corresponding to the determination of kinematical parameters of the ankle joint complex, Delorme et al. [8] analyzed this complex while on-slope snowboarding. McAlpine and Kersting [9] ascertained kinetic and kinematical values for the landing phase in freestyle snowboarding. However, scientific studies investigating kinematical parameters of the ankle joint complex in freestyle snowboarding, including turns, flight phases, jumps, and landings, are so far not available. A potential reason can be assigned to limitations of traditionally-used kinematical measurement systems, in particular, to the capture volume.

Today, as a result of the ongoing miniaturization of microelectromechanical systems, inertial measurement systems are used in a number of sports disciplines [10–13]. There are several studies showing the usage of such systems in the research of alpine winter sports [14–21]. Harding et al. [20,21] utilized inertial sensors in freestyle snowboarding for the determination of objective key performance variables; for example, air time and degree of rotation. The research of Brodie et al. [16,17] and Supej [18] demonstrate the application of an inertial measurement suit (IMS) for the determination of kinematical parameters in alpine skiing. It specifies advantages over optical methods in terms of capture volume, measurement preparation, and analysis time [18]. Thus, the application of an IMS is a potential method for the determination of kinematical parameters of the ankle joint complex in freestyle snowboarding.

Aside from kinematic parameters, kinetic parameters also need to be known. The knowledge of joint angles, as well as forces, is vital for the development of equipment. McAlpine and Kersting [9] measured ground reaction forces of jump landings in freestyle snowboarding by means of a snowboard-mounted force platform. The acquired loads reveal a potential injury risk. However, the mechanical characteristics (weight, standing height) of such a system can affect a snowboarder adversely. Aside from snowboard-mounted force platforms, the application of pressure-sensitive insoles is another possibility to measure ground reaction forces [14]. These systems are limited to the measurement of the normal force, which acts perpendicular to the boot sole. Due to the low weight and small size of these systems, the application of a bilateral insole measurement system is a potential method for the determination of kinetic parameters in freestyle snowboarding.

The accuracies of the IMS and the insole measurement system have to be known in order to draw conclusion from the measured parameters for the current research and development project. Thus, the aim of this study is divided into three parts: (i) to assess the accuracy of a commercially-available IMS system in a field-based setting; (ii) to assess the accuracy of a bilateral insole measurement system against a laboratory-based force plate; and (iii) to collect and analyze data with these systems during the ‘on-snow’ performance of one freestyle snowboarding maneuver in order to provide important biomechanical information necessary for the development of enhanced snowboarding equipment.

2. METHOD

2.1 Evaluation of the IMS in a Field-Based Setting

The accuracy of an IMS depends on the specific application and the sensor fusion algorithm used by the system [22]. A quantitative validation of a full-body IMS with respect to the achievable measurement accuracy for application in a real snowboarding environment is not yet available. Due to the severe conditions in snowboarding, an evaluation in a laboratory is not sufficient. On that account, the determination of the measurement accuracy was conducted in a real snowboarding environment. Given the common application of optical video-based systems for kinematic analyses in snowboarding and alpine skiing, it was chosen as reference system for evaluation. For that purpose, a snowboarder equipped with a full body IMS (Moven, Xsens Technologies, Enschede, The Netherlands [23]) performed a test run on a well-prepared slope (Figure 1a). The system consists of 16 sensor units and two transmission units. The sensor units include gyroscopes, accelerometers, as well as magnet field sensors [24], which are placed in a suit worn by the snowboarder. The sensor units

Figure 1. Setup for the determination of the accuracy of the IMS using a traditionally used optical camera based system and a differential GPS system (a) and the computed 3-D model (b).
were fixed to the boots, lower legs, upper legs, pelvis, shoulders, head, upper arms, forearms, and hands of the test person. The sample rate was 120 Hz. Based on the measured sensor data, the software (Moven Studio 2.1, Xsens Technologies, the Netherlands) computed a 3-D model of the snowboarder (Figure 1b). A second-order, low-pass filter was used with cutoff frequencies of 10 Hz (pelvis) and 20 Hz (other segments). According to the disadvantages of the IMS for the application in skiing [18], a differential GPS (DGPS) system (GPS1200, Leica Geosystems, Heerbrugg, Switzerland) was additionally employed to determine the absolute position of the snowboarder in space (Figure 1a). The system measured the trajectory of the snowboarder with a sample rate of 20 Hz. The calculated accuracy of the measured data is 1–4 cm (LGO software, Leica Geosystems, Germany). Due to the weight and size of the DGPS system, the evaluation was conducted on a prepared slope to ensure the safety of the snowboarder. A video-based kinematical analysis was carried out in order to determine the accuracy of the IMS. For this purpose, one turn of the test run was filmed by three synchronized cameras (50 Hz). The capture volume of the video-based system was limited to 1.5 m of the turn. Passive markers were placed at anatomical landmarks of the snowboarder (Figure 1a). The markers were manually digitized in the lab using Simi Motion software (Simi Reality Motion Systems, Unterschleißheim, Germany). Subsequently, the software computed 3-D coordinates of the markers and a 3-D model of the snowboarder. The data were filtered using a moving average filter (n = 3). The analysis of the ankle joint complex was limited owing to poor visibility of the snowboard boot markers. For this reason, the knee angle was chosen as the parameter and used for the evaluation. To determine the accuracy of this setting, the distance between two markers placed at the knee and hip was measured and compared to the computed data. A maximum error of 3 cm was found. The DGPS data and the data of the optical system were interpolated to a frequency of 120 Hz. The GPS data were linked to the data of the IMS. The manufacturer’s sensor fusion algorithm (Moven Studio 2.1, Xsens Technologies, the Netherlands) calculated the sensor kinematics of each sensor unit and translated the kinematics to segment kinematics of a 3-D model (Figure 1b). The detection of contact points with the surroundings and supplementary information from the DGPS system were used to correct the computed model [25]. Knee angles of the computed 3-D model of the snowboarder were subsequently calculated. To quantify the results, the mean deviations between the data of the optical video-based measurement system, the IMS, as well as the combined usage of the IMS and a DGPS system were computed.

2.2 Evaluation of the Bilateral Insole Measurement System in a Laboratory

The bilateral insole measurement system (T&T Medilogic, Schönefeld, Germany [26]) consists of two insoles, two amplifiers, a wireless data transmission unit, and a data logger. Each insole includes 64 pressure sensors and was inserted in the athlete’s snowboard boot. The accuracy of the system was tested in a laboratory environment using a force plate (Kistler, Winterthur, Switzerland) as the reference system. For that purpose, 10 trials with 10 consecutive squats of a test person equipped with snowboard boots, bindings, and a board similar to the equipment used in the field test were analyzed using both systems simultaneously. Furthermore, the clamping force of the binding system was measured by the insole measurement system. The weight of the snowboard equipment was metered by the force plate. All data were captured at a sampling frequency of 120 Hz. The mean force values for each trial were calculated. Subsequently, the root mean square error (RMSE) of the bilateral insole measurement system was computed.

2.3 Data Collection in Freestyle Snowboarding

The investigation was carried out during the winter of 2007/2008 in Kappl (Austria). An experienced recreational snowboarder (n = 1, male, 28 years, 73 kg, snowboarding for 16 years) performed a single test run (360° indie grab) in a prepared snowboard park (Figure 2). The size of the park jump was approximately 8 m. The IMS (Moven, Xsens Technologies, the Netherlands) was used to measure kinematical parameters at a sample rate of 120 Hz. The set-up time, including the calibration procedure, was approx. 15 min. Additionally, the pressure distribution on the plantar surface was measured applying the bilateral insole measurement system (T&T Medilogic, Germany) with 120 Hz. The total weight of the complete measurement equipment was approximately 2.2 kg. The measured data were sent wirelessly to data loggers placed beside the track. Data synchronization was established by a distinctive movement of the snowboarder. The test run was additionally filmed. The ankle joint axes were simplified as a set of three orthogonal axes. To determine the angle of the ankle joint, the joint rotation of the foot with respect to the shank was calculated using the orientations of the segments given by the IMS. The normal force (forefoot and heel) was calculated from the pressure distribution data. The IMS and the insole measurement system provided the necessary data right after the test run. The calculation of the joint orientation and the normal force using these data took approx. 10 min.

Figure 2. Snowboarder performing the aerial maneuver (360° with an indie grab).
3. RESULTS

3.1 Evaluation of the Full-Body IMS

The accuracy of the full-body IMS is moderate with regard to the optical video-based system. The results of the inertial measurement exhibit slightly different knee angles, especially for the left leg (Figure 3). The mean deviation between both systems for the left leg and the right leg are 4.8° (±0.3°) and 3.1° (±1.7°), respectively. At the same time, high correlation coefficients (left knee angle $r = 0.96$; right knee angle $r = 0.77$) are observed. No differences in the measured angles between the IMS and the combined usage with a DGPS system are found. Thus, the IMS can be used solely to measure joint angles. With respect to the calculation of the absolute position in space of the snowboarder, the IMS shows a drawback. By solely using the IMS, the determination of the snowboarder’s position is not possible. Therefore, additional systems, such as DGPS, must be utilized [18].

3.2 Evaluation of the Bilateral Insole Measurement System

The accuracy of the bilateral insole measurement system is limited. The result of the measurements represents a mean RMSE of 28% (±6.6%) for 10 trials (Figure 4). The test person reported no adverse effects.

3.3 Data Collection in Freestyle Snowboarding

The measurement results reveal ranges of movement and normal forces for all phases of the performed freestyle snowboarding test run (Figure 5). Internal rotations of 2–11° for the front leg and up to 15° external rotation for the back leg are measured in the inrun phase. In the initiation phase of the jump, the snowboarder pushes off actively. Thus, an increased normal force of 930 N (1.2 body weight, front leg) and 1080 N (1.35 body weight, back leg) is detected. Furthermore, an increased plantar flexion of 12° of both legs, an internal rotation of 41° (front leg) and an external rotation of 32° (back leg) are measured, which is caused by the rotation of the upper body around the longitudinal axis. Due to the performed aerial maneuver, comparatively high peak values, in particular for the front leg, are identified (Table 1). At the end of the flight phase, the snowboarder is in a neutral position to ensure a safe landing (Table 1). Throughout the landing phase, the snowboarder leans towards the tail of the snowboard. Thus, an increased inversion of 25° is measured for the front leg. In contrast, the back leg shows an eversion of 15°. In addition, an increased normal force of 3020 (3.8 body weight) is detected at the back leg compared to the 920 (1.2 body weight) measured at the front leg (Figure 5).

4. DISCUSSION

4.1 Evaluation of the Full-Body IMS

It is important to consider that the presented accuracy of the IMS is determined in reference to an optical video-based system. Given the common application of such systems for kinematic analyses, it is chosen as reference system. A reason for the found deviations can be a systematic error, as both systems resulted in high correlations of the knee angle data. This might be caused by the misalignment of the optical system’s marker and the calibration procedure of the IMS. As a consequence of the poor visibility of the optical boot markers in the capture volume of the cameras, the knee angles instead of the ankle joint angles are validated. However, the determination of both joint angles is based on equal sensors and the same algorithms of the IMS. Due to soft snow conditions, no strong vibrations potentially influencing the measurements are observed. In addition, the validity of the ankle joint angle data is confirmed by agreement between the calculated 3-D model and the video data, as performed by...
Therefore, it is assumed that the rotations of the ankle joint have the same measurement accuracy as the knee angle data. On account of the recommended combination of an IMS, and for example, a GPS system [18], a DGPS system is used additionally. Unfortunately, the DGPS system affects the snowboarder adversely. Therefore, the evaluation study is not conducted in the snowboarding park, but on-slope to ensure the safety of the subject and the measurement equipment. However, the results show that additional data have no influence on the posture of the calculated 3-D model of the IMS. Joint angles can be determined by using the IMS solely. However, it is important to keep in mind that the accuracy of the IMS depends on the conditions while snowboarding [18,22]. Thus, the accuracy of the data might vary in the different phases of a run, particularly in the landing phase. Considering these facts, further studies have to be conducted to evaluate the IMS, in particular for the landing phase and the ankle joint complex. If only joint angles are of interest, an evaluation can be conducted in a snowboard park without any additional systems (e.g. DGPS).

### 4.2 Evaluation of the Bilateral Insole Measurement System

The arrangement of the sensor elements in the insole, as well as the mechanical characteristics of the snowboard boot, can be considered as potential influencing factors. Due to the comparable high RMSE, the data of the insole measurement system are only used to determine the phases of the test run and to estimate acting loads. Nevertheless, the application of the system in the current research and development project for data collection in freestyle snowboarding is considered to be useful. In particular, the lack of any adverse effects is beneficial.

### 4.3 Data Collection in Freestyle Snowboarding

The measurement results reveal a potential injury risk in the landing phase. Boon et al. [27] found a 20° dorsiflexion, 10° inversion, and 0°–20° external rotation with an applied axial load of 2200–8900 N, which was required to produce fractures in nine out of 10 specimens. In addition,
5. CONCLUSION

This pilot study illustrates the application of an IMS in combination with a bilateral insole measurement system for biomechanical analyses in freestyle snowboarding.

The main advantage of this set up is the measurement of kinetic and kinematic data without limitations with regard to a restricted capture volume. However, it is important to realize that the accuracy, in particular of the kinetic data measured by the bilateral insole measurement system, is limited. Referring to the athlete the adverse effects caused by the weight and the mechanical characteristics of the IMS, as well as the insole measurement system, are almost negligible. Thus, the application of an IMS in combination with an insole measurement system in freestyle snowboarding is considered to be beneficial. The systems can provide useful information to improve the understanding of the biomechanics in freestyle snowboarding. The measured data reveal ankle joint angles and loads, which have the potential to cause injuries.

In the context of the current research and development project, the measured data provide valuable information. The knowledge of the estimated acting loads and the range of movement of joints will be implemented in the current design process. This is a vital source of information for the definition of the requirement list. The measurement results are going to be integrated in the requirement list for the development of the new safety snowboard binding concept. Further studies are planned to collect data with a higher sample of test runs and snowboarders.

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