BIOMECHANICAL PERFORMANCE DIAGNOSTICS: CONCEPTS AND APPLICATIONS IN SKI-JUMPING

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This paper presents an overview regarding the evaluation of existing biomechanical measurement methods and their practicability in biomechanical performance diagnostics (BPD) in ski-jumping. Depending on the purpose of the BPD different biomechanical measurement systems have been developed and applied. Force plates as well as pressure insoles are used to assess the kinetics during hill jumps and dry land exercises. Based on an inverse dynamics approach, ground reaction forces can be calculated during take-off using the kinematic information in conjunction with the body segment parameters. Inertial measurement units provide the opportunity to determine the orientation of the skis during flight. Easy handling, low interference with the athlete and the ability to give immediate feedback are the requirements for a measurement system in order to enable an effective BPD setting.

KEYWORDS: measurement system, practicability, training.

INTRODUCTION: Ski-jumping is a competitive sport which attracts large numbers of spectators. The entire ski-jumping sequence comprises several phases: in-run, take-off, early flight phase, stable flight phase, landing preparation and landing. The sport poses high demands on the technical and the physical abilities of the athletes. During in-run the athlete has to gain a high velocity as this is one of the main contributors to large jumping distances (Schmölzer & Müller, 2005). The prerequisites for achieving high in-run velocities are: (i) Very good gliding abilities, (ii) an aerodynamically advantageous position as well as (iii) very well adjusted material (especially grinding and waxing of the skis). The consecutive take-off is performed under fairly challenging conditions. It has to be executed within 250 - 300 ms, at in-run velocities of more than 100 km/h. During this phase, the jumper must produce a high vertical release velocity while maintaining the horizontal velocity by keeping the upper body in a crouched position. High knee and hip angular velocities are required to achieve high vertical release velocities and therefore require high performance of the neuromuscular system of the knee and hip extensors (Schwameder & Müller, 1995). Additionally, a forward rotated angular momentum has to be generated during early flight in order to compensate for the backward rotated angular momentum caused by the aerodynamic forces during this phase. After take-off the jumper has to get into a stable flight position as quickly as possible by elevating the ski tips and leaning the body forward. The stable flight phase has gained increasing importance in the achievement of large jumping distances over the last years (Kim et al., 2016; Kyeoongtae et al., 2016). The jumper is required to optimize the lift to drag ratio during this phase by fine-tuning his body position relative to the skis as well as the orientation of the skis in space (pitch, yaw and role angle, respectively). Landing has to be performed in the demanded "Telemark-landing" (lunge position), required to achieve a high level of performance points. This is a challenging and also dangerous task, especially in cases of very long jumping distances above the K-line. In order to be able to perform ski-jumping at the elite level, many years of high quality training regimes are required. To control the training progress, biomechanical performance diagnostics (BPD) are frequently conducted. These BPD can be arranged on five different levels (Schwameder, 2012).

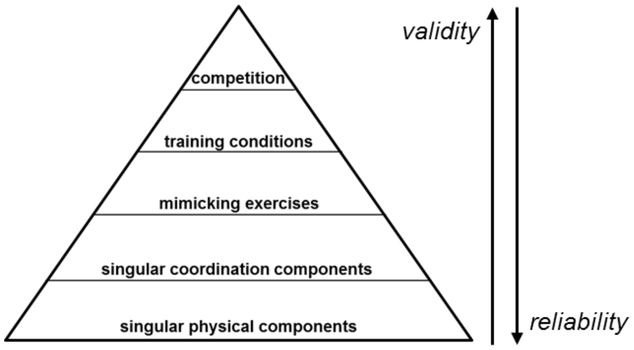

Figure 1: Different levels of performance diagnostics in ski-jumping *(Schwameder, 2012)*

The degree of validity and reliability of the BPD depends on the level, where the BPD is executed. The highest degree of validity is achieved when the BPD is performed during competition (level 5), but requires a measurement system without an interference with the jumper. BPD on level 4 offers the opportunity to obtain kinematic and kinetic data during real hill jumps without being constrained to measurement systems, which do not interfere with the jumper. In general, BPD on the levels 4 and 5 come along with high organizational and financial demands (e.g. force plates installed in the take-off table). Therefore, BPD are also performed in dry land settings resulting in lower level of validity, however, higher level of reliability due to the facilitated test standardization. Level 3 comprises mimicking exercises, which are used to imitate the hill situation (imitation jumps). On level 2, singular coordination components like squat jumps or counter movement jumps are assessed. Isometric strength tests, for instance, can be classified in level 1 representing the evaluation of the quality of singular physical components. Depending on the level and the BPD purpose (e.g. focus on a certain phase or a certain parameter like the vertical release velocity), different biomechanical measurement methods can be applied. The purpose of this overview was to present selected measurement systems, which can be used for BPD in ski-jumping. Furthermore, these systems are evaluated regarding their practicability in daily training practice in order to bridge the gap between science and coaching.

LEVELS 4 & 5: Force plates installed in the take-off table are used to assess the kinetics of the take-off during hill jumps. This system does not interfere with the athletes and can be used during competition (Pauli et al., 2016; Virmavirta & Komi, 1993). The measurement requires relatively little effort once a hill is instrumented with force plates. Therefore, this method is well suited for BPD in daily training. By using this system, however, only the last few meters of the in-run phase as well as the take-off, can be recorded. Pressure insoles represent another kinetic measurement system. The main advantage of pressure insoles is the ability to measure the entire jumping sequence and therefore the yielding of kinetic information across all phases of the jump (Schwameder & Müller, 1995). Due to the simple handling of modern pressure insole systems they can easily be implemented into daily training practice, delivering immediate feedback via mobile applications. Although measuring forces over the entire sequence, the obtained kinetic information is restricted to the measurement of the force components perpendicular to the surface. Recently, a new measurement system (JH-SJ) has been developed and validated. This system consists of two separated force plates mounted under the front part and the rear part of the ski binding for each ski. Each component measures the forces in vertical direction (compression and tension; latter is specifically interesting for the rear part during the flight phase) and horizontal (anterior-posterior) direction. This system is mainly designed for research purposes, but can be used to detect intra- and inter-individual differences in a BPD setting due to its high accuracy and precision. Kaps, Schwameder and Engstler (1997) used an inverse dynamics approach to calculate the vertical ground reaction forces based on the kinematic data. This method avoids the need of an expensive kinetic measurement system and yields synchronized kinetics and body kinematics. However, the accuracy of the calculated ground reaction forces needs to be further refined if this approach is to be suitable for BPD purposes. Inertial measurement units have been used to detect the pitch, roll and yaw angles of the skis during flight (Petrat & Bessone, 2017). Information about the ski orientation during flight can then be used by the coaches and athletes to optimize the flight position and to evaluate different material setups (e.g. binding systems). The low expanse as well as the low interference with the athlete during measurements using such a system enables the application during daily training. The processing of the raw data, however, is often a time-consuming procedure, which doesn´t allow for immediate feedback to the athletes, hence being the limiting factor of this method.

LEVEL 3: Due to the high organizational demand of the hill jumps, only a few trials can be performed within one training session. Therefore, ski-jumpers use imitation jumps to mimic the hill situation. BPD on imitation jumps can be performed in a controlled lab setting, enabling the use of a great variety of measurement systems (3D kinetics and kinematics, EMG, etc.). Due to different boundary conditions (in-run speed, aerodynamics, friction, etc.) between the imitation jumps and the hill jumps, however, differences concerning selected biomechanical parameters exist (Virmavirta & Komi, 2001). Consequently, the degree of validity of BPD on this level is decreased. In order to get closer to the real hill situation, coaches and athletes try to alter these boundary conditions. This results in a great variety of different imitation jump types and is therefore challenging for implementation as a uniform diagnostics tool applied to a large variety of different imitation jump types, especially when synchronized kinetics and body kinematics are required. Fritz, Kröll, Lindorfer and Schwameder (2018) evaluated the feasibility of an inverse dynamics approach for BPD purposes on this level. Due to the high accuracy of the calculated forces (F_{ID}) compared with the measured ground reaction forces (F_{PL}), the above authors concluded that this approach could be used as a uniform diagnostics tool if further development work is undertaken (especially implementation into an automated video setting). Such a video based tool would increase the quality and flexibility of BPD on this level substantially by providing synchronized kinetic and kinematic information using only a single measurement system.

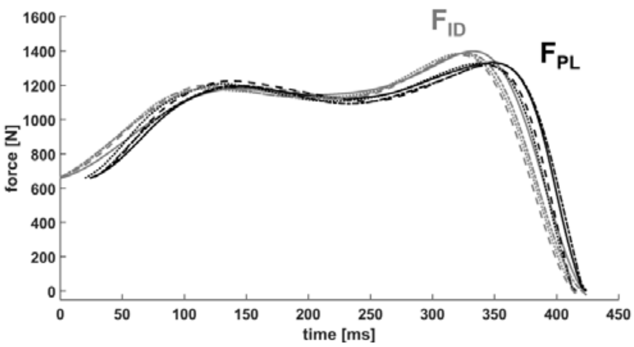

Figure 2: F_{ID} and F_{PL} of four imitation jumps for one representative jumper *(Fritz et al., 2018)*

LEVELS 1 & 2: To set the stage for a successful take-off, the ski-jumpers spend a lot of time in performing dry land exercises to enhance the strength of the lower limbs (e.g. barbell squats, loaded jumps, etc.). The progress in strength development is monitored by BPD on the level 1 using e.g. isometric strength tests at different knee angles and level 2 using loaded and unloaded squat jumps or counter movement jumps on a force plate (Schwameder, Müller, Raschner & Brunner, 1997). An attempt has been made by Fritz, Lindinger and Schwameder (2016) to evaluate the importance of the BPD on the lower two levels by correlating parameters from a typical BPD at levels 1 and 2 with complex ski-jumping performance (SJP). Peak rate of force development, as well as jump height during squat jumps, show significant correlations to SJP. Further, significant correlations between the parameters from the isometric strength test and the squat jumps have also been shown. This emphasizes the importance of high performance at BPD on the lowest two levels of the research pyramid (Fig. 1). BPD on these two levels can be easily implemented into the daily training practice, because they can be performed in a very standardized setting at little measurement effort.

CONCLUSION: Various biomechanical measurement systems exist, which can be used for BPD purposes in daily ski-jumping practice. Considering the advantages and disadvantages of the specific measurement systems, their selection for BPD depends on (1) the level of application (1-5), (2) the phase (e.g. take-off) and (3) the selected parameters (e.g. vertical release velocity during take-off) of interest. In general, it is desirable to select measurement systems, which do not interfere with the jumper or at least reduce the interference to a minimum. Considering this aspect, the rapid development of measurement systems (especially light-weight wearable sensors) opens up promising opportunities for BPD in ski-jumping.

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