ESTIMATION OF GROUND REACTION FORCES FROM KINEMATICS IN SKI-JUMPING IMITATION JUMPS

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The purpose of the study was to determine the accuracy and the precision of calculated forces based on inverse dynamics during imitation jumps by comparing the results with force plate data. Ten ski-jumpers performed four imitation jumps on a force plate. Additionally, the vertical ground reactions forces were calculated based on an inverse dynamics (ID) approach using kinematic data from a motion capture system. The average accuracy and precision was found to be 60 N and ± 20 N for the peak vertical force, respectively, and -0.3 cm and ±1.6 cm, respectively, for the average jump height. The ID approach is assessed to be feasible for the estimation of vertical ground reaction forces exclusively from kinematic data with sufficient accuracy and precision so it can be used for the development of a universal diagnostics tool for ski-jumping imitation jumps.

KEYWORDS: inverse dynamics, performance diagnostics, accuracy, precision

INTRODUCTION: Performance diagnostics in ski-jumping is essential for training control and performance enhancement. Due to the special circumstances only a low number of hill jumps can be performed during on-site training sessions. Therefore, imitation jumps in terms of dryland training are frequently performed for specific coordination and skill training (Schwameder, 2012). Based on the different boundary conditions between imitation jumps from a static position and hill jumps (friction, in-run speed, initial load, aerodynamics) substantial differences concerning biomechanical parameters exist (Müller et al., 2000; Schwameder, 2008; Virmavirta & Komi, 2001a, 2001b, 2001c). Therefore, this type of imitation jumps cannot entirely display the actual hill jump performance.

For optimizing the imitation jumps regarding a more valid and reliable exercise for performance diagnostics, coaches and athletes try to change the boundary conditions for getting closer to hill jumps. Changes of boundary conditions, however, induce a large number of different imitation jump types. Hence, the combination of different demands within one single diagnostics tool is challenging. Such a tool should be simple in usage, should be applicable to different imitation jump types and should provide kinematic and kinetic data. In biomechanical research several measurement systems could fulfill these demands, but most of them are either very expensive or not feasible in practical training. This is specifically true for force measuring systems. The most frequently used measurement and feedback systems are video collections providing qualitative and quantitative information of hill and imitation jumps kinematics. The general idea of the presented project is to use the kinematics obtained from video tapings in hill jumps, imitation jumps and other dryland exercises for estimating specific kinetics and performance related parameters based on an inverse dynamics (ID) approach.

This study presents the first part of the project by checking the principle feasibility of the methodological approach (ID). More specifically, the aim of the present study was to validate the ID approach by determining the accuracy and the precision of peak force and jump height values obtained from the calculated forces during imitation jumps in relation to the vertical ground reaction forces measured with a force plate.

METHODS: The body was modeled with 14 rigid segments (hands, forearms, upper arms, head+neck, torso+pelvis, thighs, shanks and feet) connected with hinge joints. The forces at each joint were calculated iteratively using a top down approach from the hand segment downwards to the foot segment (Yeadon & King, 2008). The sum of the forces on the distal part of the foot segments represents the ground reaction forces. This approach has already been applied in various activities of daily living (Fluit et al., 2014).

Ten junior ski-jumpers (age: 17±1 yrs, mass: 63±5 kg, height: 180±4 cm) participated in this study by performing 4 imitation jumps from a static squat position. Vertical ground reaction

forces were measured using two force plates (AMTI, 250 Hz, measured forces = F_{PL}) and served as reference for the accuracy and the precision evaluation of the calculated vertical ground reactions forces using the inverse dynamics approach (F_{ID}).
The kinematics of the jumpers was recorded with ten infrared cameras (Vicon, 250 Hz) and a full body marker set. The position and orientation of each segment was calculated using the 6-DOF pose estimation algorithm (Visual 3D, C-Motion, Inc.). The centers of mass (CoM) and the masses of each segment were determined according to the model of De Leva (1996). The trajectories of the CoM were low-pass filtered (Butterworth, cut-off: 6 Hz). Acceleration was calculated using numerical double differentiation. The vertical accelerations and the masses of the segments served as input to the inverse dynamics model for calculating the resulting ground reaction forces (F_{ID}). Two ski-jumping specific performance diagnostics parameters served for evaluating the accuracy (mean difference) and the precision (standard deviation of the differences) of F_{ID}: F_{peak} ($\Delta F_{peak}=F_{peak\text{-}ID}-F_{peak\text{-}PL}$) and jump height ΔH ($=H_{ID}-H_{PL}$). Latter was computed using the impulse calculation, the total body mass and the relation of kinetic and potential energy of CoM.

RESULTS: The force-time courses (four trails each) of the calculated (F_{ID}) and the measured (F_{PL}) vertical ground reaction forces of one representative athlete are presented in Fig. 1. Both courses show similar shapes. The increase and decrease of F_{PL} was steeper compared to F_{ID}. Furthermore, the starting point of the F_{ID} was detected to be earlier compared to F_{PL}. The peak forces of F_{ID} occurred earlier and exceeded the F_{PL} values (Fig. 1).

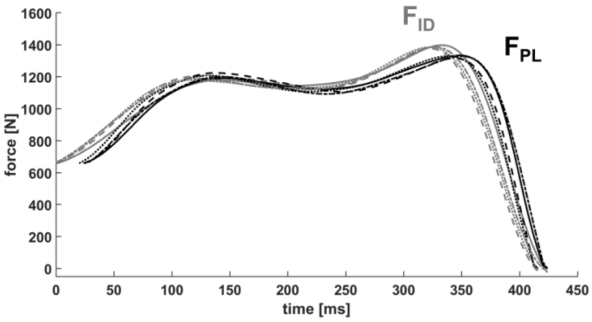

Fig. 1: F_{ID} and F_{PL} of four ski-jumping specific imitation jumps of one representative athlete.

The overestimation of $F_{peak\text{-}ID}$ was observed for all trials with a mean accuracy of 60 N and a mean precision of ± 20 N (Fig. 2a). The single athlete analysis obtained accuracy values within a range of 34 N and 77 N and precision values between ± 2 N and ± 27 N (Fig. 2b).

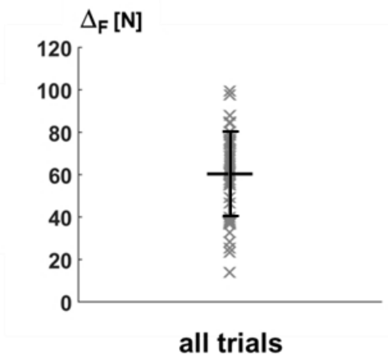

Fig. 2a: ΔF_{peak} for all trials depicted by the grey crosses. Black lines show mean and standard deviation.

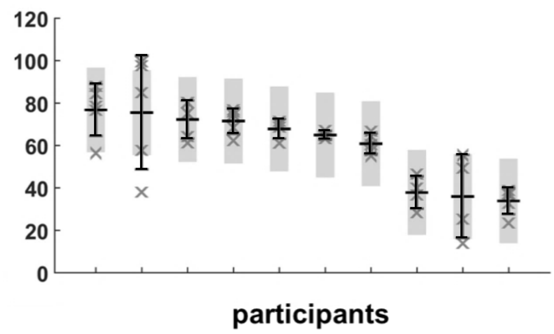

Fig. 2b: ΔF_{peak} grouped by athletes. Grey boxes show the standard deviation over all trials (from Fig. 2a). Black lines show mean and standard deviation of each athlete.

Concerning jump height, the H_{ID} partly overestimated and partly underestimated the H_{PL} with a mean accuracy of -0.3 cm and a mean precision of ±1.6 cm (Fig. 3a). The individual evaluation showed accuracies between -2.7 cm and +3.0 cm and a precision between ±0.1 cm and ±1.0 cm (Fig. 3b).

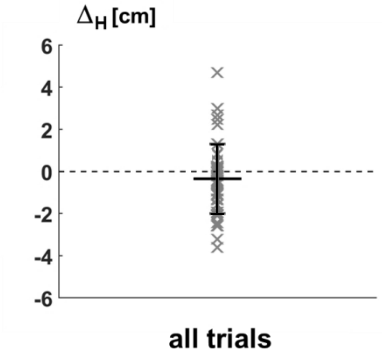

***Fig. 3a:** ΔH of all trials depicted by the grey crosses. Black lines show mean and standard deviation.*

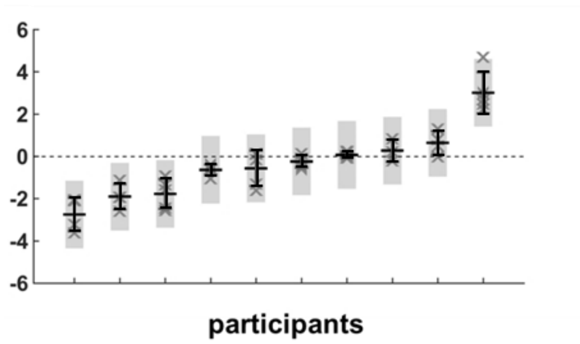

***Fig. 3b:** ΔH grouped by athletes. Grey boxes show the standard deviation over all trials (Fig.3a). Black lines show mean and standard deviation of each athlete.*

DISCUSSION: The present study aimed to evaluate an alternative method for performance diagnostics in ski-jumping imitation jumps by calculating kinetics using an inverse dynamics approach. Due to the high accuracy concerning the observed values it can be assumed that the presented method is basically applicable for the performance assessment of imitation jumps from a static position. Some issues have to be considered and optimized, however, before this method can be implemented into a video based setting and be applied to different imitation jump types. In order to optimize the force calculations, the sources of errors have to be discussed and their possible influence on the accuracy and the precision of the results has to be evaluated.

Some errors are random such as marker artefacts, marker placement or wobbling mass, which are difficult to be controlled and have specific implication on the precision of the results. One source of systematic errors (which are rather related to accuracy) is based on the filter techniques. The gradient of F_{ID} increase and decrease was smaller compared to the gradient of F_{PL}, which could explain the detection of earlier start in the F_{ID} approach. This could be a result of the low cut-off frequency of the filter, which had to be applied to the marker trajectories before numerical double differentiation. Further considerations have to be given in investigating the effect of other filter routines and smoothing.

Another source of systematic errors is the estimation of the SIV (segment mass, inertia of segments and CoM position). Estimating SIV for ski-jumpers based on published measurements is challenging due to the specific anthropometric conditions for this specific group of athletes. In this study values from De Leva (1996) have been used based on the general good agreement of the athletes' anthropometrics. Between the two groups, however, differences concerning anthropometric measures are evident. Mean mass and height of the subjects from De Leva´s study were 73 kg and 1.74 m and for the ski-jumpers 63 kg and 1.80 m. These differences can influence the estimation of SIV and therefore negatively influence the force calculation. For the ski-jumpers the SIV should be adopted individually; for example by using additional anthropometrical measurements (Zatsiorsky & Seluyanov, 1985) or by means of geometric modelling (Hanavan, 1964). Recently it has been shown that optimization approaches using individual anthropometrics improve the estimation of vertical ground reaction forces exclusively from kinematic data substantially and significantly (Fritz et al., 2018).

Optimizing filter techniques and estimation of SIV should help to increase the accuracy of the calculated forces during imitation jumps and is necessary before implementing this approach into a video based setting. This is even more important as the replacement of the gold standard measurement system by a video camera will reduce kinematic data quality and possibly impair the accuracy and precision of F_{ID}.

CONCLUSION: Theoretically, the vertical forces measured must equal the according forces calculated with an inverse dynamics approach. Latter requires, however, some general assumptions regarding anthropometrics and mechanical considerations (e.g. rigid segments, no wobbling mass, ideal and frictionless hinge joints). This leads to inaccuracies of the calculated values and consequently to differences of the measured and calculated forces. From this background the results of both approaches match quite well and the differences can be even reduced using athlete specific anthropometric optimizations. Based on the outcome of this study it can be concluded that an inverse dynamics approach can serve as a methodology to estimate vertical ground reaction forces exclusively from kinematic data with sufficient accuracy and precision so it can be used for the development of a universal diagnostics tool for ski-jumping imitation jumps.

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