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Influence of body segment parameter estimation on calculated ground reaction forces in highly dynamic movements

Julian Fritz ^{*}, Josef Kröll, Hermann Schwameder

Department of Sport and Exercise Science, University of Salzburg, Hallein-Rif, Austria

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ABSTRACT

The effect of body segment parameter estimation (BSP) on the inverse dynamics modelling results has not yet been demonstrated in specific groups during athletic movements with high segment accelerations. Therefore, the purpose of this study was to analyse this effect in ski-jumpers as representatives of a specific group (i.e. low body mass index) by comparing calculated and measured ground reaction forces during ski-jumping imitation jumps. Full body kinematics and vertical ground reaction forces were recorded of 9 ski-jumpers performing three imitation jumps each. BSP were estimated using three previously published, one individually optimized and one ski-jumper group specific model. Vertical ground reaction forces were calculated using the vertical acceleration of the segments as well as the BSP of the single models in a top-down approach. Statistical analysis revealed a main model effect concerning the root mean square error between the calculated and the measured ground reaction force with deviations between the models of 53%. Individual optimization and the application of the ski-jumper group specific model increased the accuracy of the calculated ground reaction forces by 11 and 7%, respectively, compared to the best performing published model. The results of inverse dynamics modelling are very sensitive to the BSP estimation for specific groups like ski-jumpers during movements incorporating high segment accelerations. This emphasizes the importance of selecting adequate BSP estimation models or methods when analysing specific groups in highly dynamic movements in order to increase the accuracy of the inverse dynamics analyses results.

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1. Introduction

Inverse dynamics modelling (IDM) allows for the calculation of ground reaction forces by solving the equations of motion from the topmost segment iteratively downwards without the need of force plate information (Yeadon and King, 2008). The only necessary input parameters are the kinematics and the body segment parameters (BSP). The IDM approach has been positively validated against force plate data in various activities of daily living (Fluit et al., 2014).

However, it is well known that the quality of the IDM is sensitive to inaccuracies of the input data (Pàmies-Vilà et al., 2012; Riemer et al., 2008). Kinematic inaccuracies can arise from instrumental errors of the measurement system, skin movement artefacts (Cappozzo et al., 1975), errors in joint center location (e.g. Holden and Stanhope, 1998) and processing of the kinematic data,

especially double differentiation (Cahouët et al., 2002; Challis and Kerwin, 1996; Kuo, 1998).

Another source of inaccuracies in the IDM is the selection or estimation of the BSP. The direct measurement of the BSP requires medical imaging systems, which are usually not available in biomechanics labs. Therefore, they are frequently estimated using related data from the literature (e.g. De Leva, 1996), by mathematical modelling (e.g. Hanavan, 1964) or by optimization techniques (Chen et al., 2011; Vaughan et al., 1982). It is well established that the BSP estimation is substantially affected by the models and calculation methods applied (Durkin and Dowling, 2003; Pearsall and Costigan, 1999; Rao et al., 2006). This is of particular relevance when investigating specific groups (e.g. children or obese). The application of published BSP estimation models can lead to inaccurate BSP estimates, because these specific groups are not represented by those models (Bauer et al., 2007; Chambers et al., 2010; Ganley and Powers, 2004). However, the effect of BSP estimation on the outcome of the IDM is discussed controversially and has mainly been assessed during gait (Bauer et al., 2007; Ganley and Powers, 2004; Pearsall and Costigan, 1999; Rao et al., 2006). There are no published studies regarding the effect of BSP

^{*} Corresponding author at: Department of Sport and Exercise Science, University of Salzburg, Schlossallee 49, 5400 Hallein-Rif, Austria.

E-mail address: julian.fritz@sbg.ac.at (J. Fritz).

estimation on the IDM results for specific groups while performing highly dynamic movements, where significantly higher segment accelerations occur compared to gait.

Ski-jumping take-off is an example of an athletic movement which incorporates high segment accelerations (Schwameder, 2008). Due to their very low BMI, these athletes are representatives of a specific group (Müller, 2009; Schmölzer and Müller, 2002). During standardized lab performance diagnostics, the take-off is mimicked by imitation-jumps because physical and motor abilities can be assessed more specifically in imitation jumps compared to squat jumps or counter movement jumps (Pauli et al., 2016; Schwameder, 2012; Virmavirta and Komi, 2001). High level performance diagnostics in this setting require synchronized body kinematics and kinetics for the assessment of technical and physical characteristics of the jump. The collection of kinematic data (e.g. video recordings) is easier in general compared to those of kinetic data. Measuring kinetics during imitation jumps requires the utilization of expensive force plates and is mostly restricted to stationary jumps from a static position (Pauli et al., 2016; Schwameder, 2008), although instrumented rolling surfaces have already been presented (Lorenzetti et al., 2017). IDM could serve as a low cost alternative to calculate the kinetics based on kinematic records, especially in case the position of the segments can be tracked automatically based on silhouette recognition (Colyer et al., 2018). IDM has already been applied in on-hill ski jumps and imitation jumps to calculate the ground reaction forces with satisfying results (Fritz et al., 2018; Kaps et al., 1997). However, it is not known if the BSP estimation for this specific group in a highly dynamic setting has an effect on the accuracy of the IDM results and if it offers the opportunity to increase the accuracy of the calculated forces during performance diagnostics.

Therefore, the aims of this study were to investigate the effect of the BSP input on the accuracy of the IDM during an athletic movement performed by a specific group by comparing calculated (F_{IDM}) and measured (F_{FP}) vertical ground reaction forces during ski-jumping imitation jumps regarding (i) three different BSP estimation models presented in the literature, (ii) an individually optimized BSP estimation model and (iii) a ski-jumper group-specific BSP estimation model. It was hypothesized that the published BSP estimation models would show differing results, and that an individually optimized BSP estimation model would lead to improved accuracy. Consequently, the individually optimized BSP estimation model can be replaced by a group-specific BSP estimation model, which is based on the individual optimization.

2. Methods

2.1. Participants

Nine male junior ski-jumpers (age: 17 ± 1 yrs, mass: 64 ± 5 kg, height: 179 ± 4 cm, BMI: 20 ± 1 kg/m²) gave written informed consent to participate in this study, approved by the ethics committee of the University.

2.2. BSP estimation models

The body was modeled using 14 rigid segments (hands, forearms, arms, head + neck, torso + pelvis, thighs, shanks and feet) with hinge joint connections (Fig. 1). The BSP (center of mass location and segment mass) were estimated using three frequently used BSP estimation models presented in the literature (M_{L1} , M_{L2} , M_{L3}), one individually optimized BSP estimation model (M_{indopt}) and one ski-jumper group specific BSP estimation model (M_{sj}).

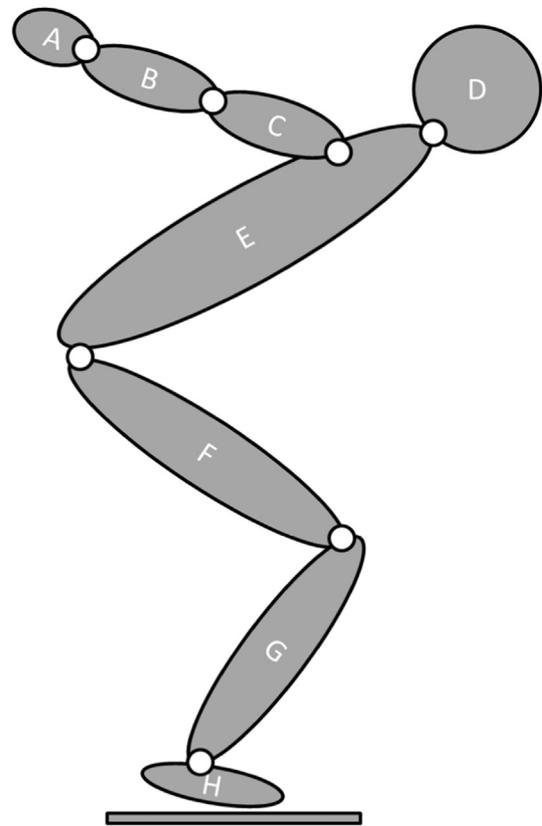


Fig. 1. Lateral view of the schematic representation of the body model with the single segments used for this study. A: Hand, B: Forearm, C: Arm, D: Head + neck, E: Torso + pelvis, F: Thigh, G: Shank, H: Foot. The white circles illustrate the hinge joint connections between the segments.

2.2.1. Published BSP estimation models (M_{L1} , M_{L2} , M_{L3})

The three published BSP models consisted of two in vivo scanning models based on living subjects (De Leva, 1996 (M_{L1}); Zatsiorsky and Seluyanov, 1985 (M_{L2})), and a mathematical model (Hanavan, 1964 (M_{L3})) applied in combination with the density values published by Dempster (1955). The additional anthropometric measurements required for M_{L2} and M_{L3} were collected as described in the respective publications.

2.2.2. Individually optimized BSP estimation model (M_{indopt})

For the individually optimized BSP estimation model (M_{indopt}) M_{L2} was used as base model. M_{L2} was selected due to the highest observed IDM accuracy of the published models, which will be described in detail below.

An *a priori* analysis to clarify the contribution of each single segment to the total vertical impulse during the push-off phase revealed that the trunk and both thighs contributed on average more than 65% to the total vertical impulse, while all other segments contributed less than 10% each (Fig. 2). Hence, only the trunk and thigh segments were considered for the optimization process. The implementation of each of the remaining segments was assumed to have little influence on the IDM accuracy due to their small contribution to the total vertical impulse during the push-off phase, but would have increased the calculation efforts substantially and disproportionately.

Furthermore, bilateral symmetry was assumed for the left and the right thigh due to the small inter-limb difference (Fig. 2). Therefore, both thighs were treated equally during optimization (i.e. equal alteration to the left and the right thigh during an iteration of the optimization process). Treating both thighs equally

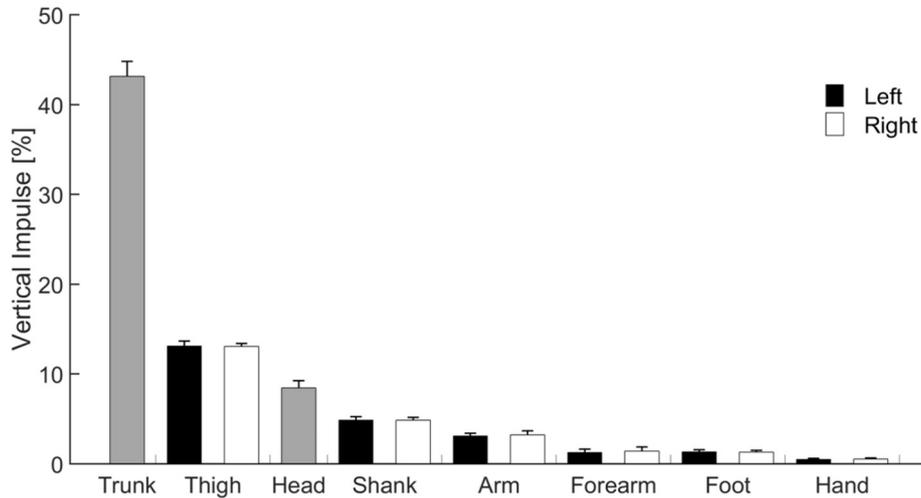


Fig. 2. Percentage contribution ($M \pm SD$) of the single segments to the total vertical impulse during push-off based on M_{L2} as input BSP estimation model.

further decreased the calculation efforts of the optimization. The BSP of the trunk and the thighs were chosen as the design variable vector bsp as follows

$$bsp = (com_{tr}, m_{tr}, com_{th}, m_{th})^T \quad tr = trunk, th = thigh \quad (1)$$

where com represents the relative center of mass location of the segment (ratio of distal segment length to total segment length) and m represents the relative mass of the segment (percentage of total body mass).

The values of com and m were varied in ten equal steps within a defined range for each segment (Pearsall and Costigan, 1999). This range was defined by placing lower (lb) and upper (ub) bounds based on the mean value and the range of com and m , respectively, of M_{L2} ($lb = \text{mean} - \text{range}$ and $ub = \text{mean} + \text{range}$) for the trunk and the thigh segments. The masses of the remaining segments were adapted according to their percentage of total mass minus the masses of the trunk and the thighs from the base model such that the sum of all segment masses \times gravity equaled the measured body weight. The optimized set of BSPs (bsp_{opt}) was obtained for each trial of each participant (see section Data collection below) by minimizing the RMSE (root mean square error) between F_{IDM} and F_{FP} within the push-off phase as shown in Eq. (2).

$$bsp_{opt} = \min(RMSE(bsp)) \\ = \min \left(\sqrt{\frac{1}{T} * \sum_{t=1}^T (F_{IDM,t}(bsp) - F_{FP,t})^2} \right) \quad (2)$$

where t are the time steps of the collected data and T is the duration of the push-off phase.

2.2.3. Ski-jumper group specific BSP estimation model (M_{sj})

The ski-jumper group specific BSP estimation model (M_{sj}) was defined as the mean values of the individual bsp_{opt} from the M_{indopt} for thigh and trunk. For the remaining segments, the mean values of the adapted segment masses from M_{indopt} (percentage of total body mass) as well as the M_{indopt} CoM positions (i.e. kept constant according to the base model M_{L2}) were used.

2.3. Data collection

Each participant performed three imitation jumps. Whole body kinematics were recorded using a full body marker set (Cleveland Clinic Marker Set) and a 10 camera infrared motion capture system (Vicon, Oxford, Oxford Metrics Ltd, UK), sampling at 250 Hz. Posi-

tion and orientation of the single segments were determined using the Six Degrees of Freedom pose estimation algorithm (V3D; C-motion, Rockville, MD, USA). F_{FP} was measured simultaneously at 250 Hz with an AMTI force plate (AMTI, Advanced Mechanical Technology Inc., Watertown, Massachusetts, USA).

2.4. Data processing

To evaluate the accuracy of F_{IDM} for each BSP model data were processed repeatedly with the BSP estimates from the five models as input for the IDM. F_{FP} and marker trajectories were low pass filtered with 30 and 7 Hz cut-off frequencies respectively, using a 2nd order, zero-lag Butterworth filter. Numerical double differentiation was conducted using a centered difference scheme to obtain the acceleration of the single segments center of mass (Cahouët et al., 2002). F_{IDM} was calculated by solving the equations of motion iteratively in a top down approach (Yeadon and King, 2008). Mean RMSE between F_{IDM} and F_{FP} within the push-off phase was calculated for the three trials ($n = 3$) of each participant. The mean RMSE of each participant ($n = 9$) was further used to evaluate the accuracy of the IDM results based on the BSP estimates of the five BSP models. The push-off phase was defined as the time between the start of the movement (F_{FP} exceeded 101% body weight) and the take-off ($F_{FP} = 0$ N).

Additionally, a comparison between the models regarding the BSP estimates of the optimized segments (trunk and thighs) was included (Appendix A). The BSP estimates of the remaining segments (according to the published models) are shown in the Appendix B.

2.5. Statistics

To test for BSP estimation model effects on the RMSE between F_{IDM} and F_{FP} as well as on the BSP estimates of the optimized segments, one-way ANOVAs with repeated measures and t-tests with Bonferroni correction were conducted. The significance level was set to $p = 0.05$ (main effects) and $p = 0.01$ (t-tests). Additionally, mean percentage of variation (MPV) was calculated and was defined as the range of the RMSE divided by the corresponding mean value $\times 100$ (Rao et al., 2006). Qualitative analysis of the effect of the five BSP models on the IDM results was conducted using one representative jump of one participant as well as the mean error \pm standard deviation between F_{IDM} and F_{FP} of all jumps

of each participant ($n = 27$). The error (ΔF) was defined as the difference between F_{IDM} and F_{FP} .

3. Results

The RMSEs ($M \pm SD$) between F_{IDM} and F_{FP} calculated using the three published models ($M_{L1} - M_{L3}$), the individually optimized model (M_{indopt}) as well as the ski jumper group specific model (M_{sj}) are shown in Fig. 3. Statistical analysis showed a significant main model effect ($p < 0.001$, $\eta^2 = 0.874$). The highest accuracy of the three published estimation models was achieved by M_{L2} with a mean RMSE of $44 N \pm 9 N$. This model was significantly different from M_{L1} ($66 N \pm 13 N$) and M_{L3} ($66 N \pm 14 N$). Regarding all analyzed models, M_{indopt} showed the highest accuracy ($39 N \pm 7 N$) and differed significantly from the three published models, but not from M_{sj} ($41 N \pm 8 N$), which also differed from all the published models. Mean percentage of variation was 53%.

The force-time histories of one representative jump of F_{IDM} and F_{FP} as well as the corresponding differences (error) are shown in Fig. 4. The error band ($M \pm SD$) between F_{IDM} and F_{FP} of all jumps of all participants is shown in Fig. 5. In general, similar characteristics can be observed for M_{L1} and M_{L3} as well as for M_{L2} , M_{indopt} and M_{sj} . At the beginning of the movement (-400 ms) F_{FP} was overestimated by F_{IDM} for all five models (Fig. 4). All models overestimated the peak force, with M_{L1} revealing the biggest deviation compared to the other models. The biggest differences during the entire sequence were observed in the unloading phase, after reaching the force peak (Figs. 4 & 5). M_{L1} and M_{L3} mainly underestimated F_{FP} during this phase while M_{L2} , M_{indopt} and M_{sj} first underestimated and then overestimated F_{FP} shortly before release. It is worth to be noted that the change of F_{IDM} over time at the beginning and at the end of the push-off phase was smaller compared to that of F_{FP} (Fig. 4).

4. Discussion

The main aim of this study was to investigate the effect of different BSP models on the accuracy of the IDM during an athletic movement performed by a specific group by comparing calculated (F_{IDM}) and measured (F_{FP}) ground reaction forces. It was shown that the IDM accuracy was very sensitive to the BSP input, revealing a main model effect concerning the RMSE between F_{IDM} and F_{FP}

with a MPV of 53% (Fig. 3). Although the number of participants was generally low in this study, it can be assumed that an increased number of participants would not have changed the results considerably due to the large statistical effect ($\eta^2 = 0.874$, $power = 1.0$).

Results showed that even a very simple optimization of only the trunk and the thigh segments increased the accuracy of F_{IDM} compared to the literature models (accuracy increase by 27 N (=41%) compared to M_{L1} and M_{L3} , respectively and 5 N (=11%) compared to M_{L2}). The optimization process delivered very plausible data with the optimized BSP estimates of M_{sj} falling within the bounds of the three published models except for the trunk mass, which was slightly lower compared to the others. Similar attempts have been made by Vaughan et al. (1982) and Chen et al. (2011) to determine subject specific BSP estimates using optimization techniques. Vaughan et al. (1982) used running, jumping and kicking movements to optimize the BSP estimates for one participant and also obtained values, which were within the range of three commonly used published models. Chen et al. (2011) used the measured center of pressure as well as the kinematic records during static postures to optimize the segment densities for their group under investigation. The BSP estimates from their optimization showed only small differences compared to the BSP estimates derived from a magnetic resonance imaging based model (Cheng et al., 2000). The fact that the optimized BSP estimates did not markedly differ from the published models can be seen as justification for the plausibility of the BSP estimates determined using optimization techniques (Vaughan et al., 1982). Despite the increase in accuracy in the present study, a mean RMSE between F_{IDM} and F_{FP} of 39 N was observed. The majority of this remaining error was most likely caused by other error sources like kinematic inaccuracies (Cahouët et al., 2002; Kuo, 1998; Pàmies-Vilà et al., 2012; Riemer et al., 2008), but could also be derived from neglecting segments in the optimization process. Neglecting segments with small contribution to the total vertical impulse during the jumping push-off, however, was assumed not to severely affect the accuracy of the IDM. Considering the improvements in accuracy by optimizing the BSP of all segments for running (62 N (37%)), long jumping (58 N (33%)) and kicking (50 N (26%)) presented by Vaughan et al. (1982), the present study showed comparable results (27 N (41%) compared to M_{L1} and M_{L3} and 5 N (11%) compared to M_{L2}), though optimizing the segments, mainly involved during push-off only.

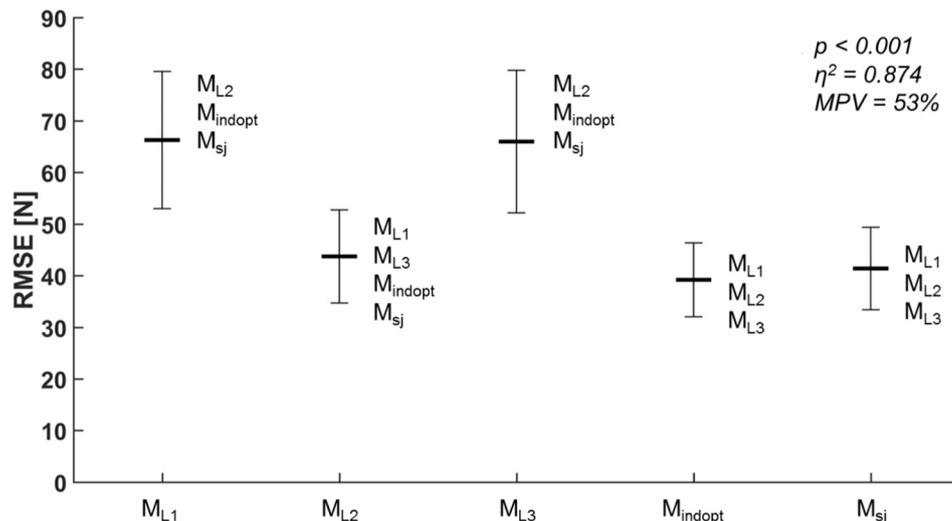


Fig. 3. RMSE ($M \pm SD$) between F_{IDM} and F_{FP} during the push-off phase of all trials of each participant. Annotated the corresponding models which showed significant differences in pairwise comparison.

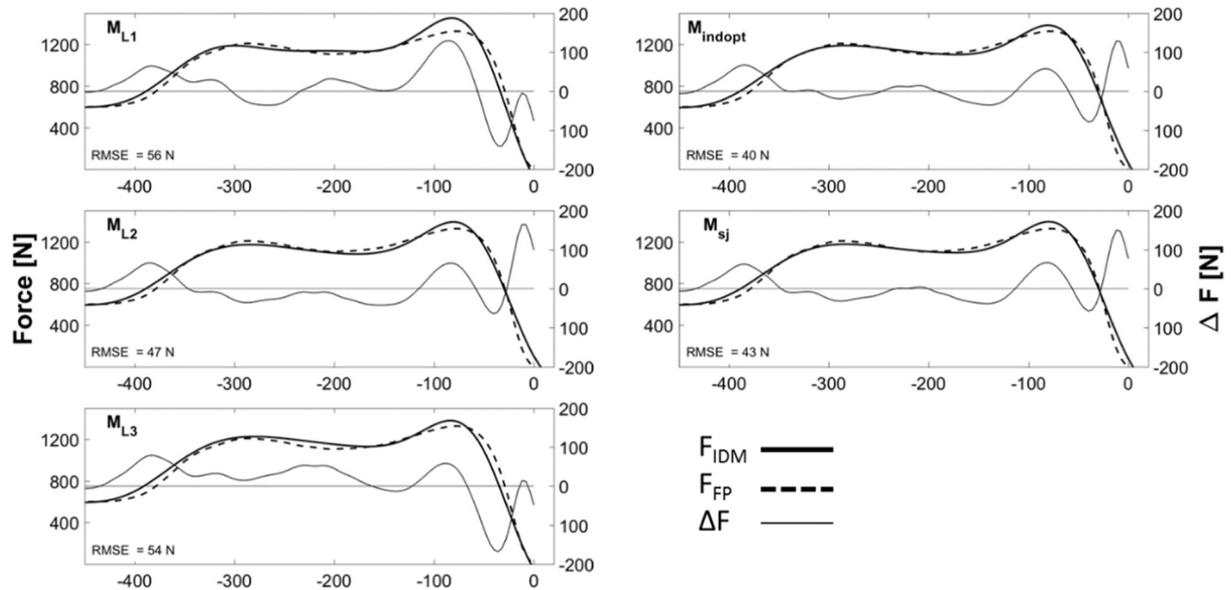


Fig. 4. F_{IDM} (calculated using the BSP estimation models M_{L1} – M_{L3} , M_{indopt} & M_{sj}) and F_{FP} of one representative jump during push-off phase as well as the corresponding error ΔF ($t = 0$: take-off).

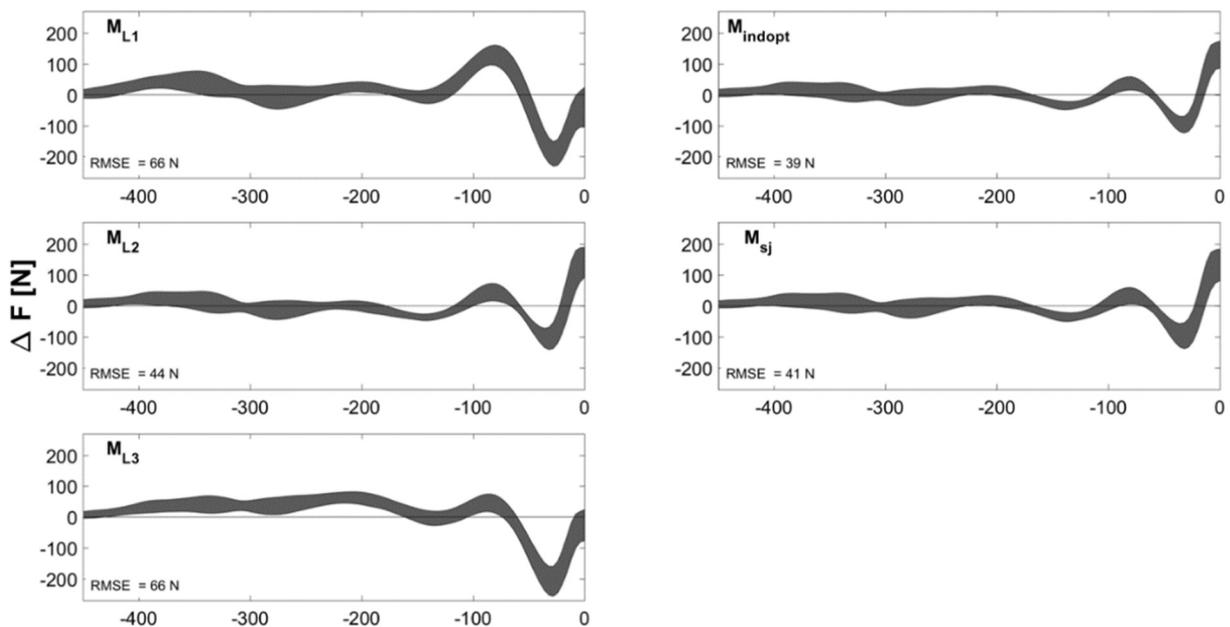


Fig. 5. Error band ΔF ($M \pm SD$) between F_{IDM} (calculated using the BSP estimation models M_{L1} – M_{L3} , M_{indopt} & M_{sj}) and F_{FP} during push-off phase of all trials of all participants ($t = 0$: take-off; $n = 27$ jumps).

The individual optimization of the BSP allowed for the definition of a ski-jumper group specific model (M_{sj}) by building the mean of the bsp_{opt} . The application of M_{sj} to each participant also increased the accuracy of the IDM result compared to the published models (increase of 38% compared to M_{L1} and M_{L3} and 7% compared to M_{L2} , respectively) and yielded only slightly larger differences compared to M_{indopt} (accuracy decrease of 5%).

The low accuracy of M_{L1} can be explained by anthropometrical differences between the group used for the definition of M_{L1} and the investigated ski-jumpers group (M_{L1} group: mean body mass = 73 kg, mean height = 1.74 m (De Leva, 1996) vs ski-jumper group: mean body mass = 63 kg, mean height = 1.80 m). As the BSP in M_{L1} are determined as fractions of total segment length and total body mass only, the BSP estimation is especially

affected if there are discrepancies between the groups (i.e. body weight and body height).

Although the population M_{L1} and M_{L2} were based on was the same, the BSP estimates of these models showed significant differences in pairwise comparison for the segments, which were included in the optimization, except for the thigh mass (Appendix A). The use of additional anthropometric measurements in M_{L2} seemed to reduce the effect of the discrepancy between the groups by customizing the model for each person (Durkin and Dowling, 2003; Yeaton and Morlock, 1989). It can be assumed that the BSP of M_{L2} were close to the optimum values, because the optimization process could not find a better BSP solution for the trunk segment (no statistical difference, Appendix A), which was the main contributor to vertical impulse during push-off phase

(Fig. 2). Therefore, M_{L2} yielded IDM results with the highest accuracy of the three published models, but still was 11% less accurate compared to the individually optimized model.

The low accuracy of M_{L3} was mainly due to the simplified assumptions of the model concerning geometry and density of the segments. Errors in the calculation of the center of mass and the segment mass arise, because the segments are modeled as simple geometric solids and therefore cannot illustrate the complex contours of the segments (Rao et al., 2006). Assuming uniform density within one segment can also lead to inaccurate BSP estimates and therefore yielding inaccurate IDM results, especially if the group under investigation and the group upon which the density values are based differ from each other (Kyle et al., 2001; Wei and Jensen, 1995).

The results of the accuracy evaluation were in line with Rao et al. (2006), who also showed that the application of different frequently used BSP estimation models does not only influence the BSP estimates but also the IDM outcome. They reported variations in joint kinetics up to 17.9% based on the MPV of the normalized root mean square (see Cahouët et al., 2002) during gait and therefore emphasized the importance of the selection of an adequate BSP estimation model. Although Pearsall and Costigan (1999) observed only small influence of BSP estimates on the IDM outcome, they discussed that this effect could operate differently depending on the analyzed movement, especially if significantly higher segment accelerations occur, as is the case in ski-jumping imitation jumps.

Generally, high agreement was observed between F_{IDM} and F_{FP} (Fig. 4). Considering this high agreement with respect to coaching aspects, F_{IDM} allows for qualitative and quantitative analysis of the imitation jumps and therefore offers the opportunity to use an inverse dynamics approach for performance diagnostics purposes in ski-jumping imitation jumps on a low cost basis. However, further work is required to show if this approach also yields sufficiently accurate results if the kinematic data are sourced from video recordings taken in a daily training setting (Colyer et al., 2018). The error between F_{IDM} and F_{FP} was shown to be sensitive to the BSP input, especially towards the end of the movement (Figs. 4 & 5). Analysis of the trunk segment acceleration revealed that the peak acceleration occurred during this phase. Therefore, differences in the trunk BSP estimation (most dominant segment

with respect to vertical impulse contribution) resulted in the biggest differences between F_{IDM} and F_{FP} during this phase. This is confirmed by the similar errors of F_{IDM} calculated using M_{L2} , M_{indopt} and M_{sj} , where no statistical differences concerning the trunk BSP were found (Appendix A). The smaller changes over time of F_{IDM} at the beginning and the end of the push-off phase could be a result of the low cut-off frequency, which is required for digital filtering of the CoM trajectories due to the consecutive double differentiation (Cahouët et al., 2002; Giakas and Baltzopoulos, 1997).

This study provided further evidence that the application of different BSP estimation models results in differences concerning the IDM outcome and therefore offers the opportunity to increase the accuracy of the IDM. This emphasizes the importance of selecting BSP estimation models, which closely match the group under investigation when applying inverse dynamics analyses on specific groups during movements with high segment accelerations. The selection of an adequate model often has to be violated if there is no published model for a specific group under investigation. Subject specific BSP estimation using optimization techniques can be used to overcome this problem and yield IDM results with the highest degree of accuracy. In this study ski-jumpers were used as representatives of a specific group. However, such an optimization based approach might also be transferred to other specific groups, which are not represented in the literature (e.g. children or obese). The high accuracy achieved by the application of M_{sj} could allow practitioners to replace time consuming individual optimization processes with group specific models derived from individual optimization, while still yielding more accurate results compared to published models.

Conflict of interest

We declare that we have no financial or personal relationships with other people or organizations that could inappropriately influence (bias) our work.

Acknowledgements

The authors thank the ski-jumpers who participated in this study as well as their coaches who enabled the participation.

Appendix A

BSP estimates M (\pm SD) of the optimized segments based on the published models (M_{L1} – M_{L3}) as well as on the ski jumper group specific model (M_{sj}), which is the mean of the individually optimized BSP (bsp_{opt}) from M_{indopt} .

	Thigh		Trunk	
	CoM [cm]	m [kg]	CoM [cm]	m [kg]
M_{L1}	27.7 (1.1) ^{2,3,4}	9.0 (0.8) ^{3,4}	29.8 (0.9) ^{2,3,4}	27.7 (2.4) ^{2,3,4}
M_{L2}	29.4 (1.4) ^{1,3,4}	9.1 (1.0) ^{3,4}	26.8 (0.7) ^{1,3}	26.0 (2.3) ^{1,3}
M_{L3}	26.9 (1.1) ^{1,2,4}	6.5 (0.6) ^{1,2,4}	28.8 (0.8) ^{1,3}	30.4 (2.5) ^{1,2,3}
M_{sj} (M_{indopt})	27.4 (1.1) ^{1,2,3}	8.5 (1.0) ^{1,2,3}	27.6 (1.5) ¹	24.8 (2.5) ^{1,3}
MPV [%]	9	31	11	21
P	<0.001	<0.001	< 0.001	<0.001
η^2	0.894	0.953	0.801	0.871

¹Different from M_{L1} ; ²different from M_{L2} ; ³different from M_{L3} ; ⁴different from M_{sj} .

Appendix B

BSP estimates M (\pm SD) of the remaining segments based on the published models ($M_{L1} - M_{L3}$).

		M_{L1}	M_{L2}	M_{L3}	MPV[%]	p	η^2
Foot	CoM	10.1 (0.8)	8.7 (1.8) ³	10.9 (0.6) ²	22	0.021	0.491
	m	0.9 (0.1) ^{2,3}	1.0 (0.1) ¹	1.0 (0.1) ¹	10	0.004	0.659
Shank	CoM	22.7 (1.1) ^{2,3}	24.6 (1.3) ^{1,3}	20.9 (1.2) ^{1,2}	16	<0.001	0.985
	m	2.8 (0.2) ^{2,3}	3.2 (0.3) ¹	3.1 (0.3) ¹	13	<0.001	0.906
Thigh	CoM	27.7 (1.1) ^{2,3}	29.4 (1.4) ^{1,3}	26.9 (1.1) ^{1,2}	9	<0.001	0.895
	m	9.0 (0.8) ³	9.1 (1.0) ³	6.5 (0.6) ^{1,2}	32	<0.001	0.974
Trunk	CoM	29.8 (0.9) ^{2,3}	26.8 (0.7) ^{1,3}	28.8 (0.8) ^{1,2}	11	<0.001	0.931
	m	27.7 (2.4) ^{2,3}	26.0 (2.3) ^{1,3}	30.4 (2.5) ^{1,2}	16	<0.001	0.953
Arm	CoM	13.0 (1.0) ^{2,3}	15.7 (1.1) ^{1,3}	16.4 (0.9) ^{1,2}	23	<0.001	0.98
	m	1.7 (0.2) ^{2,3}	1.9 (0.2) ¹	1.9 (0.2) ³	11	<0.001	0.712
Forearm	CoM	14.0 (1.0) ^{2,3}	12.4 (1.6) ^{1,3}	14.5 (1.2) ^{1,2}	16	0.004	0.641
	m	1.0 (0.1) ^{2,3}	0.9 (0.1) ^{1,3}	1.2 (0.1) ^{1,2}	29	<0.001	0.947
Hand	CoM	7.0 (0.3) ²	10.3 (1.8) ^{1,3}	7.7 (1.4) ²	40	0.003	0.644
	m	0.4 (0.0)	0.4 (0.1) ³	0.5 (0.0) ²	23	<0.001	0.835
Head	CoM	14.6 (0.9) ^{2,3}	13.9 (0.9) ¹	13.8 (0.7) ¹	5	<0.001	0.881
	m	4.4 (0.4) ³	4.7 (0.5)	5.1 (0.4) ¹	15	<0.001	0.671

¹Different from M_{L1} ; ²different from M_{L2} ; ³different from M_{L3} .

The published models M_{L2} and M_{L3} provide the BSP estimates in absolute values, while M_{L1} presents these data in percentage numbers relative to the total segment length and the total body mass, respectively. Therefore, all numbers were transformed in absolute values.

Appendix C. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiomech.2018.12.008>.

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