# USING INERTIAL SENSORS FOR RECONSTRUCTING 3D FULL-BODY MOVEMENT IN SPORTS – POSSIBILITIES AND LIMITATIONS ON THE EXAMPLE OF ALPINE SKI RACING

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The present study investigates if inertial sensors could be used for reconstructing 3D full body movements in sports. On the example of alpine ski racing, it was demonstrated that inertial sensors allow computing meaningful parameters related to a skier's overall posture. While some parameters were obtained with sufficient accuracy and precision, others were not obtained reliably using inertial sensor-based systems. Main error sources were discussed and it was found that an accurate and precise functional calibration is most important for short duration measurements. In cases where it is not possible fixing inertial sensors to all relevant body segments (e.g. skis and arms) their orientations could be estimated. In this case parameter validity needs to be carefully verified, as even strongly related parameters may show different validities, as demonstrated in this study.

**KEY WORDS:** inertial sensors, validation, centre of mass, alpine skiing, fore-aft position, vertical distance, posture.

**INTRODUCTION:** In sports, motion capture is a key tool for a dynamic posture analysis and may provide essential information for efficient coaching. In alpine ski racing, for example, the skier's dynamic posture during a turn is commonly analysed using specific aspects of vertical and anterior/posterior movement (Kipp et al., 2008; Reid, 2010): (1) $d_{CoM\text{-}ankle}$, the distance between the skier's centre of mass (CoM) and the ankle joint of the outside leg; (2) $p_{fore\text{-}aft}$, the projection of the outside leg's ankle-CoM vector onto the outside ski's longitudinal axis (Fig. 1). Furthermore, these variables have been suggested to be related to performance (Kipp et al., 2008; Läuppi et al., 2014; Reid, 2010) and are specifically trained on different athlete levels (Läuppi et al., 2014).
Traditionally, motion capture is performed using video-based 3D kinematics, as this method is known to provide the highest possible accuracy under field conditions (Reid, 2010). Alternatively, in recent days inertial measurement units (IMU) composed of accelerometers, gyroscopes and magnetometers have been used (Chardonnens et al., 2012; Fasel et al., 2013). IMUs allow measuring an unlimited capture volume and data processing can by fully automatized. However, unlike the method of video-based 3D kinematics, IMUs do not allow a direct measurement of the skier's posture. Finding a posture based on IMUs involves the following three processing steps: 1) obtain sensor orientation through integration of inertial signals, 2) relate sensor orientations to segment orientations using functional calibration movements, and 3) estimate posture from the individual segment orientations using biomechanical models. Each of these three steps may induce errors in the final posture estimation. The five most important error sources are the following: i) drift in the sensor orientations from the integration of the inertial signals, ii) bias in the alignment sensor frame – segment anatomical frame because of inaccuracies from the functional calibration movements, iii) soft tissue artefact from muscle contractions and wobbling changing temporarily the sensor frame – segment anatomical frame alignment, iv) errors in the interpolation of segment orientations that were not directly measured, and v) inaccuracies in the underlying biomechanical model for posture estimation. Since all of these errors might be amplified when applying higher sophisticated or model-based algorithms, it is important to know the impact of each error source on specific parameter outcomes.

In order to illustrate this methodological challenge and to emphasise the importance of a careful, sport-/ and parameter-specific in-field validation prior using IMUs, the aims of the current study were the following: first, it was to compute $d_{CoM\text{-}ankle}$ and $p_{fore\text{-}aft}$ based on inertial measurements and to validate these ski racing specific parameters using a video-based reference system. Second, it was to discuss the impact of the above cited error sources on the parameter validity.

**METHODS:** Six European Cup level alpine ski racers were selected for the study. Two runs per athlete on a 12 gate giant slalom course were recorded. Gates were set with a constant gate distance of 27.2m and offset of 8m where the left turn of gate 7 was analysed. The study was approved by the University Ethics Committee of the Department of Sport Science and Kinesiology at the University of Salzburg.

Seven IMUs (Physilog® III, GaitUp, Switzerland; 3D accelerometers, 3D gyroscopes, sampling rate 500Hz) were fixed to the skier's helmet, sacrum, sternum, left and right thigh, and left and right shank using a custom underwear suit. Squat movements and upright standing posture were used for the functional calibration (Chardonnens et al., 2012; Fasel et al., 2013). Strapdown integration with gravity drift and joint drift correction adapted from (Dejnabadi et al., 2006; Favre et al., 2006) was used to estimate each segment's orientation. A seven segment (head, upper trunk, lower trunk, left and right thigh, and left and right shank) and eight ball joint (neck, trunk centre, left and right hip, left and right knee, and left and right ankle) body model was used for pose estimation. The segment lengths were obtained from the video-based reference system described below. Segment inertia parameters and body CoM were obtained according to Dumas et al. (2007). Left and right arm centre of mass was hypothesized to lay 5cm anterior and 10cm inferior of the trunk centre. The ski's longitudinal axis was fixed perpendicular to the shank's medio-lateral anatomical axis and 17 degrees rotated with respect to the shank's anterior-posterior anatomical axis. Feet and skis were ignored for the computation of the body centre of mass. ${}^{imu}d_{ankle\text{-}CoM}$ was defined as the norm of ${}^{imu}v_{ankle\_CoM}$, the vector relying the outside leg's ankle joint centre with the body CoM. ${}^{imu}p_{fore\text{-}aft}$ was defined as the length of ${}^{imu}v_{ankle\_CoM}$ projected onto the ski's longitudinal axis (Fig. 1).

Six panned, tilted and zoomed HDV cameras recording at 50Hz were used as a reference system to record joint centres' positions over one turn cycle (left turn) as described in (Gilgien et al., 2015). An electronic trigger was used to synchronize the cameras with the inertial sensors. The ski's longitudinal axis was defined as the vector relying the ski's tail and tip. ${}^{ref}d_{ankle\text{-}CoM,}$ and ${}^{ref}p_{fore\text{-}aft}$ were defined the same way as for the wearable system. The curves for ${}^{imu}d_{ankle\text{-}CoM}$ and ${}^{imu}p_{fore\text{-}aft}$ were low-pass filtered and resampled to 50Hz to match the sampling rate of the reference system. All data were time normalized prior to computing mean curves and errors. Accuracy (precision) was defined as the mean (standard deviation) of the difference between the curves of the wearable and reference systems.

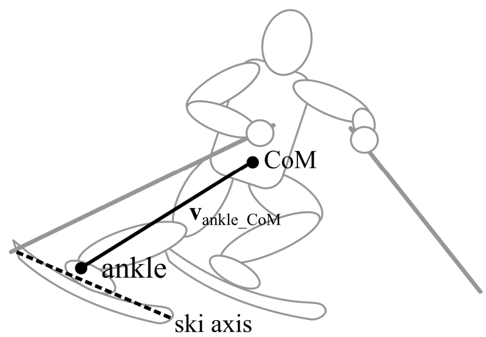

**Figure 1: Illustration of the athlete's center of mass (CoM), ankle joint, ski axis and $v_{ankle\_CoM}$, the vector connecting the ankle with CoM.**

**RESULTS:** Accuracy and precision of ${}^{imu}d_{ankle\text{-}CoM}$ were -0.65cm and 2.67cm, respectively. For ${}^{imu}p_{fore\text{-}aft}$ accuracy and precision were -5.02cm and 4.03cm, respectively. Fig. 2 and 3 show the mean curves and standard deviations for all the twelve turns. From a purely descriptive perspective, it can be seen that ${}^{imu}d_{ankle\text{-}CoM}$ and ${}^{ref}d_{ankle\text{-}CoM}$ had a similar shape. ${}^{imu}p_{fore\text{-}aft}$ and ${}^{ref}p_{fore\text{-}aft}$ did not only have a curve offset but a different shape: the range for ${}^{imu}p_{fore\text{-}aft}$ was smaller than for ${}^{ref}p_{fore\text{-}aft}$. The peak at around 25% of turn cycle was less pronounced in the wearable system than the reference. The peak at around 85% of turn cycle was not present in the wearable system.

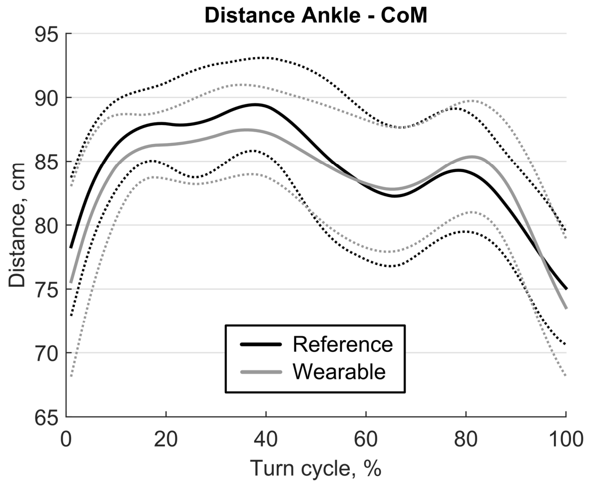


**Figure 2: Mean curves (solid lines) ± standard deviation (dotted lines) for the distance ankle-CoM. The reference system is shown in black; the wearable system is shown in grey.**

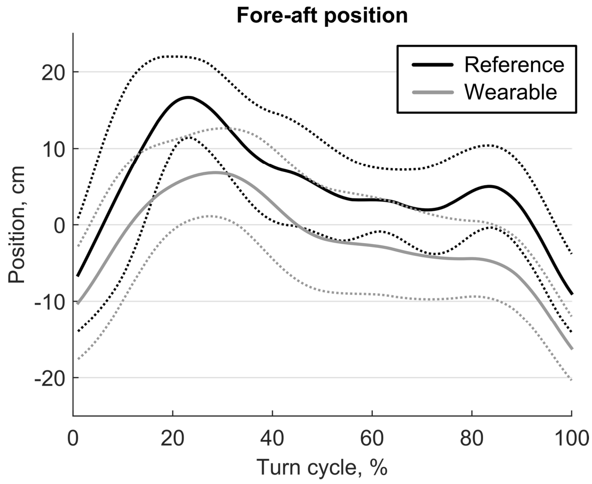


**Figure 3: Mean curves (solid lines) ± standard deviation (dotted lines) for the fore-aft position. The reference system is shown in black; the wearable system is shown in grey.**

**DISCUSSION:** For twelve turns in giant slalom skiing, ankle-CoM distance, $d_{ankle\text{-}CoM}$, and fore-aft position, $p_{fore\text{-}aft}$, were computed using a wearable IMU system and compared to a video-based reference. Mean differences of $d_{ankle\text{-}CoM}$ of 2cm and range of motion differences of 8cm have been reported for two different course settings in slalom skiing (Reid, 2010). Additionally, the same study reported different mean curve shapes between the two course settings. ${}^{imu}d_{ankle\text{-}CoM}$ would allow measuring the same differences: mean curve differences could be measured as long as they are larger than the system's precision (2.67cm). Curve shape differences (e.g. range of motion) could also be found, as ${}^{imu}d_{ankle\text{-}CoM}$ was well correlated to ${}^{ref}d_{ankle\text{-}CoM}$ (Pearson's correlation coefficient of 0.89). Therefore, it can be concluded that $d_{ankle\text{-}CoM}$ can be computed with sufficient accuracy and precision using IMU-based systems.

In contrast to ${}^{imu}d_{ankle\text{-}CoM}$, ${}^{imu}p_{fore\text{-}aft}$ may not be accurate and precise enough. A case study by Spörri et al. (2015) reported differences in the order of 5-10cm for the fore-aft position for the second half of the turn. Larger horizontal gate offsets led to a less pronounced forward position. As ${}^{imu}p_{fore\text{-}aft}$ was underestimated and missed the peak at 85% turn cycle in the current study, the validity for analysing the absolute fore-aft position values might not be considered sufficient when using the IMU-based approach. However, ${}^{imu}p_{fore\text{-}aft}$ may still give valuable partial information about the fore-aft position of the athlete when comparing different dependent interventions: as all twelve turns were the same, the curves of individual turns must be similar. Indeed, the coefficient of multiple correlation (adapted from Kadaba et al., 1989) was higher for the wearable IMU system (0.66) than for the video-based reference system (0.35), indicating that the wearable IMU system was able to measure the parameter with a good repeatability.

Relating the results of ${}^{imu}d_{ankle\text{-}CoM}$ and ${}^{imu}p_{fore\text{-}aft}$ to the error sources cited in the introduction, the following can be concluded: i) the drift in orientation from integration of inertial signals did not impact the results substantially because of the short measurement period (<30sec). For longer measurements results should be critically inspected for drift. In the presence of drift, the curves' shapes would show a higher variability between trials; ii) the functional calibration plays an important role for the correct computation of the segment's orientation. For both ${}^{imu}d_{ankle\text{-}CoM}$ and ${}^{imu}p_{fore\text{-}aft}$ some outlier curves were observed and could be related to inaccurate functional calibration; iii) the present setup did not allow quantifying the effect of soft tissue artefacts on the computed parameters: its impact remains unclear; iv) the interpolation of unknown segment orientations (e.g. arms and skis) did most likely affect ${}^{imu}p_{fore\text{-}aft}$. Already small arm movements might have a considerable influence on the CoM with regards to its fore-aft position, while their influence on the vertical position of CoM remains small. The relative orientation of the skis with respect to the shanks may not be fixed as ski boots may allow minor ankle flexion. Hence, these two effects could serve as an explanation for the attenuated peak in ${}^{imu}p_{fore\text{-}aft}$ at 25% and 85% of the turn cycle; v) inaccuracies in the underlying biomechanical model could be assumed to play only a minor role as other error sources were much larger. Joint rotation was not restricted to natural range of motion (e.g. for removing soft tissue artefact) which could be an error source. However, restrictions of joint rotations may be problematic, especially if the joint model does not fit the reality well.

**CONCLUSION:** The current study has illustrated the possibilities and limitations of using IMUs for reconstructing 3D full-body movement on the example of alpine ski racing. Two variables, which are commonly used to analyse vertical movement ($d_{ankle\text{-}CoM}$) and anterior/posterior movement ($p_{fore\text{-}aft}$) in research and coaching practice, have been computed. The validity of ${}^{imu}d_{ankle\text{-}CoM}$ has been demonstrated. However, ${}^{imu}p_{fore\text{-}aft}$ seemed not to provide enough precision for a full quantification of the fore-aft positon. As this example demonstrates, knowing the impact of each error source is essential before applying more sophisticated or model-based algorithms as they might amplify certain errors. In this context, the use of simple algorithms has been demonstrated to be helpful for understanding and separating different error sources. Moreover, the current study has emphasised the importance of sport and parameter specific in-field validated algorithms: while one parameter might be valid (e.g. $d_{ankle\text{-}CoM}$), a closely related parameter (e.g. $p_{fore\text{-}aft}$) may not be valid. Nevertheless, once these methodological aspects have been carefully assessed, IMUs might open a broad spectrum of new possibilities for reconstructing 3D full-body movement in sports, particularly for in-field conditions.

**REFERENCES:**


Chardonnens, J., Favre, J., Le Callennec, B., Cuendet, F., Gremion, G., & Aminian, K. (2012). Automatic measurement of key ski jumping phases and temporal events with a wearable system. *Journal of Sports Sciences*, 30(1), 53–61.

Dejnabadi, H., Jolles, B. M., Casanova, E., Fua, P., & Aminian, K. (2006). Estimation and visualization of sagittal kinematics of lower limbs orientation using body-fixed sensors. *IEEE Transactions on Bio-Medical Engineering*, 53(7), 1385–93.

Dumas, R., Chèze, L., & Verriest, J.P. (2007). Adjustments to McConville et al. and Young et al. body segment inertial parameters. *Journal of Biomechanics*, 40(3), 543–53.

Fasel, B., Spörri, J., Chardonnens, J., Gilgien, M., Kröll, J., Müller, E., & Aminian, K. (2013). 3D measurement of lower limb kinematics in alpine ski racing using inertial sensors. *Abstract book international congress on science and skiing 2013*.

Favre, J., Jolles, B.M., Siegrist, O., & Aminian, K. (2006). Quaternion-based fusion of gyroscopes and accelerometers to improve 3D angle measurement. *Electronics Letters*, 42(11), 612.

Gilgien, M., Spörri, J., Chardonnens, J., Kröll, J., Limpach, P., & Müller, E. (2015). Determination of the centre of mass kinematics in alpine skiing using differential global navigation satellite systems. *Journal of Sports Sciences*.

Kadaba, M.P., Ramakrishnan, H.K., Wootten, M.E., Gainey, J., Gorton, G., & Cochran, G. V. (1989). Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *Journal of Orthopaedic Research*, 7(6), 849–60.

Kipp, R.W., Reid, R.C., Gilgien, M., Moger, T., Tjorhom, H., Haugen, P., & Smith, G. (2008). Slalom Performance in Elite Alpine Ski Racing can be Predicted by Fore / Aft Movement Dynamics. *Medicine and Science in Sports and Exercise*, 40(5), S165.

Läuppi, P. & Spörri, J. (2014). Ski Alpin Racing Concept. Muri bei Bern: Swiss-Ski.

Reid, R.C. (2010). A kinematic and kinetic study of alpine skiing technique in slalom. *Dissertation from the Norwegian School of Sport Sciences.*

Spörri, J., Kröll, J., Schwameder, H., Schiefermüller, C., & Müller, E. (2012). Course setting and selected biomechanical variables related to injury risk in alpine ski racing: an explorative case study. *British Journal of Sports Medicine*, 46(15), 1072–7.