ESTIMATION OF THE CENTRE OF MASS KINEMATICS IN ALPINE SKI RACING USING INERTIAL AND MAGNETIC SENSORS

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For performance analysis in alpine ski racing, an accurate and precise estimation of the centre of mass (CoM) kinematics is indispensable. Currently available systems satisfying this need are video-based stereo-photogrammetry or differential global navigation satellite systems (GNSS). However, they are impractical to use in regular training settings. Inertial sensors could be used instead but suffer from significant drifts in speed and position estimation due to the integration of acceleration and angular velocity data. The aim of the present study was to propose and validate an inertial and magnetometer sensor-based algorithm to estimate CoM kinematics in alpine ski racing. Relative CoM position and speed between-run comparisons were found to be highly accurate and precise with mean absolute deviations <0.15 m and <0.28 m/s.

INTRODUCTION: Obtaining precise centre of mass (CoM) kinematics is of key interest in alpine skiing research. CoM kinematics is relevant for performance analysis (Hébert-Losier, Supej, & Holmberg, 2014; Spörri, Kröll, Schwameder, & Müller, 2012; Supej, Kipp, & Holmberg, 2011) or injury risk evaluation (Gilgien, Spörri, Kröll, Crivelli, & Müller, 2014; Spörri, Kröll, Schwameder, Schiefermüller, & Müller, 2012). In previous studies, CoM kinematics was most commonly obtained by video-based stereo-photogrammetry or with differential global navigation satellite systems (GNSS). Both systems require a complex and time-consuming setup and technical experts for data processing. While the capture volumes of video-based systems are usually only a few turns long, differential GNSS can record longer sections up to the entire race course. However, satellite signal quality can degrade due to shading effects typically from terrain and forest along the course and therefore position and speed accuracy can be degraded severely. When being applied in training settings, these systems are limited in usability, and coaches would prefer a transportable, light-weight system without complex setup and post-processing. Nevertheless, for the purpose of performance analysis, accuracy and precision must be high. For example, CoM trajectory differences between skiers in the order of magnitude of 0.2 m can be considered relevant to explain performance (Spörri, Kröll, Schwameder, & Müller, 2012). However, as the skiers have to follow a pre-defined course marked by gates, CoM positions are not required to be known in an absolute reference frame. For most performance applications, it would be sufficient to express CoM kinematics relative to gate positions. In a recent study, we have shown that magnets could be used for detecting gate crossings (Fasel, Spörri, Kröll, & Aminian, 2016) and that reference gate positions can be used in a fusion scheme to remove inertial sensor drift from integration and GNSS drift from changing satellite constellations and atmospheric conditions (Fasel, Spörri, & Aminian, 2016). However, in this approach, gate positions had still to be obtained with land surveying techniques. While reference positions could be obtained quickly (<30 minutes) in the field using land surveying technologies, such surveying could be a constraint in regular training sessions. Under the assumption that inertial sensor drift is independent between different runs and with zero mean, it should be possible to cancel it out when averaging multiple runs. Thus, in a first step gate positions could be estimated by averaging the drift-affected gate positions of individual runs. Having enough runs collected, such estimate of gate positions should converge to the

true gate position. In a second step, CoM kinematics could then be computed relative to the gate positions estimated in step 1.
Therefore, the aim of this project was to propose and validate an easy-to-use system which allows to accurately and precisely measure CoM kinematics in alpine ski racing without the need to survey terrain or using a differential GNSS.

METHODS: The proposed system comprised seven inertial sensors (Physilog IV, Gait Up, Switzerland) attached to the left and right shanks, left and right thighs, sacrum, sternum, and head. Acceleration and angular velocity was sampled at 500 Hz and the sensors were wirelessly synchronized. In addition, the sacrum sensor contained a magnetometer sampling at 125 Hz. Strong bar magnets (18 cm long, 2 cm diameter) were placed at each gate of a skiing course. Segment orientation was obtained with strap-down integration followed by joint drift correction as described in (Fasel et al., 2017). Based on the segment orientations and body segment inertia parameters the athlete's posture and relative CoM was computed (Fasel, Spörri, Gilgien, et al., 2016). Gate passages were detected based on peak detection of the magnetic field intensity recorded by the magnetometer (Fasel, Spörri, Kröll, et al., 2016).
Finally, CoM trajectory was obtained in five steps. First, the drift-affected position of the sacrum trajectory was computed from the inertial sensor fixed on the sacrum. An Extended Kalman Smoother (EKS) with twelve states (position, speed, acceleration, acceleration offset) was designed. Gravity corrected acceleration in the global frame was integrated to find speed and position, and speed drift was corrected based on a zero-speed constraint at race start and finish. Second, relative gate position with respect to the sacrum was estimated for each gate passage. In an additional lab assessment, magnetic field intensity was related to the sensor-magnet distance and was subsequently used to estimate the distance between the sacrum and the gate in-field. To find the components of the distance vector, a trigonometric model using a triangle with corners sacrum, the sacrum projected onto the snow surface, and the gate position was constructed. The triangle surface was constrained to be normal to the sacrum velocity vector at gate crossing. Third, absolute gate position was computed by adding the sacrum's position at gate crossing to the relative gate position. Fourth, an estimate of gate positions was defined as the mean gate positions recorded for all runs on the same course. Prior to averaging, each run's trajectory was aligned and scaled such that the positions of the first and last gates would match between all runs. Fifth, sacrum trajectory was improved with a second EKS where the estimated gate positions were used in addition to the zero-velocity constraint. Final CoM trajectory was then the sum of the improved sacrum trajectory and relative CoM obtained from the body model.
To validate the system, nine European-cup level athletes were enrolled to the study (written informed consent was obtained from each athlete and the study was approved by EPFL's Ethical committee (HREC 006-2016)). Each athlete skied two runs on a giant slalom course consisting of 28 gates spaced with varying gate distances and a total of ten runs were measured simultaneously with the reference system. Measurements took place during two days on a glacier with good GNSS conditions. All gate locations were surveyed with a differential GNSS. The reference system to assess skier kinematics consisted of a differential GNSS which was integrated with the inertial sensor-based body model as described in (Fasel, Spörri, Gilgien, et al., 2016). Accuracy (precision) for CoM position of this system was 0.04 m/s (0.14 m/s), and 0.08 m (0.06 m).
For validation purposes, the IMU global frame was matched to the GNSS frame. Azimuth difference was corrected and the IMU frame was shifted in order to match the position of the first gate in both global frames. Position errors were computed for each gate. Accuracy (mean error) and precision (error standard deviation) were computed for CoM speed and position differences between the second and second last gates of each run. For selected turn performance parameters (i.e. the distance to gate, as well as speed at turn start, gate crossing, and turn end) were computed and compared relative to each day's fastest turn (defined as shortest time between the turn start and end). Mean absolute difference (MAD) between the two systems was computed for the relative performance parameters. In order to

test system differences regarding the aforementioned performance parameters, a paired sample t-test was used. Level of statistical significance was set at $p<0.05$.

RESULTS: CoM kinematics were successfully obtained for nine runs from day one and eight from day two. Gate position errors increased during the run reaching up to 9.3 m and 18.1 m at the last gate for the first and second day, respectively. Mean absolute CoM speed accuracy (precision) was 0.25 m/s (0.46 m/s). Mean CoM position accuracy (precision) was 7.42 m (4.06 m). Mean relative differences were <0.15 m for the distance parameters and <0.28 m/s for the speed parameters. No statistical differences were found between the two systems.

DISCUSSION: An inertial and magnetometer sensor-based system was proposed and validated to obtain alpine ski racing CoM kinematics which can be expressed in a global frame but without the requirement to capture terrain geomorphology using advanced surveying techniques nor the necessity to use of GNSS on the athlete. Magnets placed at gates allowed to detect gate crossings. An estimate of gate positions was found by averaging the gate positions recorded from multiple runs. With the help of an Extended Kalman Smoother (EKS) each run's trajectory was then matched to the estimated gate positions.

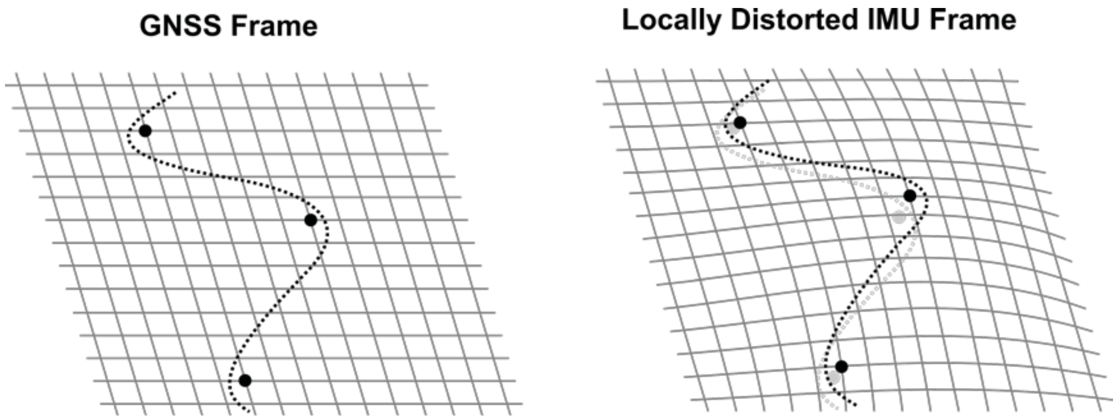

Figure 1: Left: Differential GNSS reference frame. Right: local distortion created by the non-complete drift cancelling after computing the average gate positions from multiple runs. The very light grey shading illustrates the undistorted trajectory in the GNSS frame.

The proposed approach allowed to partially cancel out speed and position drift from integrating the acceleration signal. However, the number of recorded runs per day was not sufficient to cancel out the drift completely. The remaining drift led to inaccuracy in the estimated gate positions where relative position error changed in extreme cases by up to 1.5 m between two subsequent gates. The system's main advantage was that once the estimated gate positions were known all runs could be expressed in the exact same coordinate system. Thus, even though drift was not completely removed, it became identical for all runs of the same day. The remaining drift was interpreted as slowly changing spatial distortions, as illustrated in Figure 1. Thus, absolute CoM kinematics were distorted with respect to the GNSS speed, resulting in the observed absolute position and speed errors; however, for a direct relative comparison between several runs measured on the same course this seems not to be a problematic issue. For example, mean absolute difference of the relative performance parameters (position and speed differences at gate crossing and turn switches) was smaller than the reported performance differences between the fastest and slowest run of a world-class athlete (Spörri, Kröll, Schwameder, & Müller, 2012). Thus, the proposed system could be used for between-run performance analysis.
In order to be able to better cancel out the drift, more runs than analysed in the current study should be recorded per training session. In a regular training, each athlete skis the same course 5-10 times. Therefore, by measuring multiple athletes in parallel, twenty or more runs could be available for computing the estimated gate positions. On a final note, it is worth

mentioning that the averaging scheme used was quite simple and assumed linear drift changes over the entire run. However, as drift is movement-dependent and, therefore, is non-linear over the run, more sophisticated averaging procedures might help to better cancel out drift and to obtain more accurate and precise CoM kinematics.

CONCLUSION: This study proposed a novel system to compute CoM kinematics for alpine ski racing without the need of terrain surveying and GNSS on the athlete. Mapping individual runs onto a common reference frame allowed to obtain accurate and precise relative performance parameters for between-run comparison. Thus, the system could be used for performance and relative line analysis in regular training settings. However, due to incomplete drift cancellation caused by slowly changing local coordinate system distortions, absolute CoM kinematics might not be accurate and precise enough for absolute line and speed comparisons. Moreover, since the system did not use GNSS, it would be ideally suited for applications in indoor skiing halls.

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