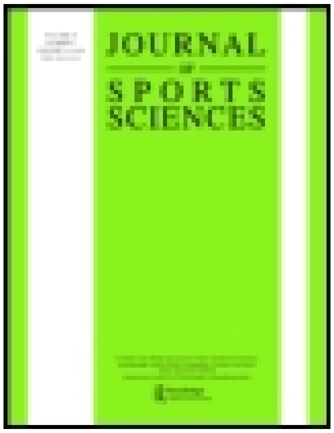




Journal of Sports Sciences
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rjsp20

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Published online: 07 Jan 2015.

*Journal of Sports Sciences*, 2015
http://dx.doi.org/10.1080/02640414.2014.977934

# Determination of the centre of mass kinematics in alpine skiing using differential global navigation satellite systems

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(*Accepted 14 October 2014*)

**Abstract**

In the sport of alpine skiing, knowledge about the centre of mass (CoM) kinematics (i.e. position, velocity and acceleration) is essential to better understand both performance and injury. This study proposes a global navigation satellite system (GNSS)-based method to measure CoM kinematics without restriction of capture volume and with reasonable set-up and processing requirements. It combines the GNSS antenna position, terrain data and the accelerations acting on the skier in order to approximate the CoM location, velocity and acceleration. The validity of the method was assessed against a reference system (video-based 3D kinematics) over 12 turn cycles on a giant slalom skiing course. The mean (± *s*) position, velocity and acceleration differences between the CoM obtained from the GNSS and the reference system were 9 ± 12 cm, $0.08 \pm 0.19\ \text{m} \cdot \text{s}^{-1}$ and $0.22 \pm 1.28\ \text{m} \cdot \text{s}^{-2}$, respectively. The velocity and acceleration differences obtained were smaller than typical differences between the measures of several skiers on the same course observed in the literature, while the position differences were slightly larger than its discriminative meaningful change. The proposed method can therefore be interpreted to be technically valid and adequate for a variety of biomechanical research questions in the field of alpine skiing with certain limitations regarding position.

**Keywords:** *position–velocity–acceleration, GPS and GNSS, technical validation, video-based 3D kinematics, alpine skiing*



## Introduction

Competitive alpine skiing is a popular and highly dynamic sport with relatively high-injury rates (Florenes, Bere, Nordsletten, Heir, & Bahr, 2009). For both performance enhancement and injury prevention, a deeper understanding of the biomechanical background is essential (Kröll, Spörri, Gilgien, Chardonnens, & Müller, 2013; Reid, 2010; Reid et al., 2008; Spörri, Kröll, Schwameder, & Müller, 2012; Spörri, Kröll, Schwameder, Schiefermüller, & Müller, 2012; Supej, Kipp, & Holmberg, 2010). In this context, centre of mass (CoM) kinematics (i.e. position, velocity and acceleration) have been proposed as reference measures representing the athlete's overall movement in space (Schiefermüller, Lindinger, Raschner, & Müller, 2004). While earlier studies mainly used three-dimensional (3D) video-based systems for the reconstruction of the CoM (Federolf, Reid, Gilgien, Haugen, & Smith, 2012; Klous, Müller, & Schwameder, 2010; Raschner et al., 2001; Reid, 2010; Reid et al., 2007; Spörri, Kröll, Schwameder, & Müller, 2012; Supej, Kugovnik, & Nemec, 2004), recent approaches have suggested the use of differential global navigation satellite systems (GNSS) (Gilgien, Singer, & Rhyner, 2010; Gilgien, Spörri, Chardonnens, Kröll, & Müller, 2013; Gilgien, Spörri, Kröll, Crivelli, & Müller, 2014; Gilgien, Spörri, Limpach, Geiger, & Müller, 2014; Lachapelle, Morrison, Ong, & Cole, 2009; Limpach & Skaloud, 2003; Skaloud & Limpach, 2003; Supej, 2010; Supej & Holmberg, 2011; Supej et al., 2013). GNSS systems allow larger capture volumes with reasonable set-up and processing requirements. The GNSS antenna cannot be placed at the CoM since CoM position is changing with time and satellite signals would be shaded by the skiers own body. To overcome this problem, previous researchers have placed the antenna on either the head (Brodie, Walmsley, & Page, 2008;

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Gilgien et al., 2013; Gilgien, Spörri, Kröll, et al., 2014; Gilgien, Spörri, Limpach, et al., 2014; Lachapelle et al., 2009; Skaloud & Limpach, 2003) or back (Gilgien, Singer, et al., 2010; Supej, 2010; Supej & Holmberg, 2011; Supej et al., 2013). In order to overcome the problem that in neither approach was the GNSS antenna placed at the COM location, modelling methods were implemented to estimate the COM position from the antenna so that COM kinematics could be calculated (Brodie et al., 2008; Supej et al., 2013). Placing the antenna on the back is advantageous in that the antenna is closer to the CoM, which as a result is likely to make the modelling of the CoM position from the antenna position simpler (Meyer, 2012). The disadvantage of this approach is that signal shading by the body could seriously compromise measurement accuracy of the antenna position. Placing the antenna on the head minimises signal shading allowing full use of the available satellites to obtain an accurate as possible antenna position.

The previous GNSS-based methods have not been validated against independent reference systems.

Therefore, this study had two aspects. The first aim was to estimate the CoM kinematics using a GNSS antenna mounted on the helmet of the athlete. To this end, a biomechanical model considering terrain data and 3D GNSS kinematics was designed, and CoM position, velocity and acceleration were computed based on the data from the GNSS antenna mounted on the helmet. The second aim was to evaluate the performance of the proposed method by comparison with the gold standard reference system for field measurements: video-based 3D kinematics.

## Methods

### *Measurement protocol*

Six male athletes (former World Cup or current Europa Cup skiers) were enrolled for this study. For each athlete, two runs were collected, simultaneously using the reference video-based system and the GNSS system. The Giant Slalom course consisted of 12 gates set at an average distance of 27.2 m apart with an offset of 8 m (Spörri, Kröll, Schwameder, Schiefermüller, et al., 2012). For the analysis, one turn cycle was recorded. The start and end of the turn was defined according to Supej, Kugovnik, and Nemec (2003). In total, 12 runs were recorded. The experimental conditions were typical for World Cup races: the snow surface was injected with water and the mean terrain slope in the area of investigation (i.e. between gates seven and eight) was 26°. This study was approved by the Ethics Committee of the Department of Sport Science and Kinesiology at the University of Salzburg, and the athletes were informed of the investigation's purpose and procedures.

### *3D terrain model*

The geomorphology of the slope (i.e. snow surface) was determined by terrestrial surveying with a tachymeter (Leica TPS 1200, Leica Geosystems AG, Heerbrugg, Switzerland). The surveyed points were triangulated following Delaunay's method (de Berg, Otfried, van Kreveld, & Overmars, 2008), gridded (grid spacing of 0.3 m) and low-pass filtered using bi-cubic splines (Gilgien, Reid, Haugen, & Smith, 2008; Hugentobler, 2004). The terrain model was transformed from the local coordinate system (LCS) to the global WGS84 coordinate system as described in the Appendix.

### *GNSS measurement system*

The GNSS measurement system was composed of an antenna mounted on the helmet of the athlete (G5Ant-2AT1, Antcom, USA) and a GPS/GLONASS dual frequency (L1/L2) receiver (Alpha-G3T, Javad, USA) recording position signals at 50 Hz and carried in a small cushioned backpack (Figure 1). The total weight of the measurement equipment carried by the skier was 940 g (receiver 430 g, backpack 350 g, antenna 160 g). To enable differential positioning, two base stations were located at the start of the course and equipped with antennas (GrAnt-G3T, Javad, USA) and Alpha-G3T receivers (Javad, USA). The second base station was used for redundancy. As a first step, accurate absolute global positions of the GNSS base stations were computed with the geodetic GNSS software Justin (Javad, San Jose, USA) using reference data from the Austrian Positioning Service (APOS, Wien, Austria). The differential GNSS measurements were determined in the global coordinate

Figure 1. Skier with GNSS antenna mounted on the helmet.

system WGS84 (Universal Transverse Mercator zone 32, Northern Hemisphere).

The kinematic positions of the skier's GNSS antenna were computed in post-processing with the geodetic GNSS software GrafNav (NovAtel Inc., Canada), using the L1 and L2 carrier phase signals of the GPS and GLONASS satellite systems. On average, 13 satellites were used for the GNSS solution computation. Fixed ambiguity solutions were achieved throughout the entire course for all skiers. Each component of the antenna positions was then low-pass filtered based on cubic spline filtering according to Skaloud and Limpach (2003), applying a tolerance factor of 0.5 for the horizontal components and 0.7 for the vertical component. The filtered positions yielded the 3D position vector $\boldsymbol{P_{GNSS,ANT}}$. Based on the obtained trajectory vectors ($\boldsymbol{P_{GNSS,ANT}}$), the velocity and acceleration vectors ($\boldsymbol{V_{GNSS,ANT}}$ and $\boldsymbol{A_{GNSS,ANT}}$) were derived according to Gilat and Subramaniam (2008).

### *GNSS measurement system: CoM computation*

A biomechanical model was developed to compute the CoM position, velocity and acceleration using the GNSS antenna mounted on the helmet of the athlete and the snow surface. The skier's movements were represented by an inverted pendulum (Gilgien et al., 2013; Morawski, 1973; Supej et al., 2013). During straight skiing, the pendulum is in neutral position while during turning the pendulum is deflected from its neutral position to model the lateral inclination of the skier since skiers incline to balance the radial forces and gravity acting on them. The pendulum deflection was therefore approximated using the radial acceleration derived from the GNSS antenna trajectory, gravity and the snow surface model.

The pendulum deflection direction vector ($\boldsymbol{L}$) was modelled by a linear combination of the accelerations acting on the skier, according to Equation (1) and Figure 2:

$$\boldsymbol{L} = \frac{-\boldsymbol{A}_{GNSS,radial} + \boldsymbol{g}_N}{\|-\boldsymbol{A}_{GNSS,radial} + \boldsymbol{g}_N\|} \cdot D + \frac{\boldsymbol{P}_{GNSS\rightarrow N}}{\|\boldsymbol{P}_{GNSS\rightarrow N}\|} \cdot (1 - D) \qquad (1)$$

where $\boldsymbol{A_{GNSS,radial}}$ is the radial acceleration vector derived from the antenna position ($\boldsymbol{P_{GNSS,ANT}}$) according to Gilat and Subramaniam (2008); $N$ is the plane oriented normal to the velocity vector $\boldsymbol{v_{gnss,ant}}$ and containing the antenna position; $\boldsymbol{g}_N$ corresponds to the gravity vector projected onto $N$; $\boldsymbol{P_{GNSS\text{->}N}}$ is the vector between the antenna position and its projection ($\boldsymbol{P_N}$), first on the snow surface then to $\boldsymbol{N}$ (Figure 2(B)); and $D$ corresponds to the minimum turn radius divided by the instantaneous turn radius calculated following the method of Reid (2010). The pendulum modelling along with its projection into plane $\boldsymbol{N}$ normal to the velocity vector was tailored to compensate for both lateral and fore–aft inclinations of the skier. The factor $D$ was introduced in Equation (1) to take into account the derivative artefacts in the radial acceleration computation.

The CoM position vector of the GNSS ($\boldsymbol{P_{GNSS,CoM}}$) corresponded to 53% of the vector $\boldsymbol{L}$ from the antenna position to its snow surface intersection (Figure 2(C)). The 53% value was obtained as an average value for the entire turn cycle from the data set of Reid (2010). Then the CoM position vector was low-pass filtered (second-order Butterworth filter; cut-off frequency of 4 Hz). Similarly to the GNSS antenna kinematics, the GNSS CoM velocity ($\boldsymbol{V_{GNSS,CoM}}$) and acceleration ($\boldsymbol{A_{GNSS,CoM}}$) vectors were obtained from the time differentiation of the GNSS CoM position vector ($\boldsymbol{P_{GNSS,CoM}}$) (Gilat & Subramaniam, 2008).

### *Reference measurement system*

Six panned, tilted and zoomed HDV cameras (Sony, PMW-EX3) at 50 Hz and a DLT-based panning

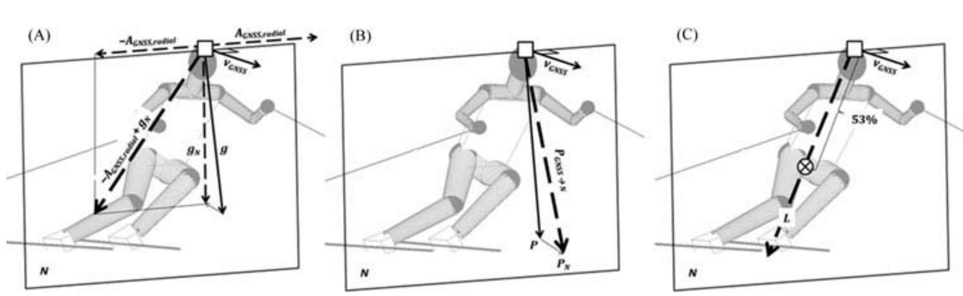


Figure 2. Illustration of the pendulum modelling: (A) antenna (▯), radial acceleration (AGNSS, radial), gravity vector ($\boldsymbol{g}$) projected in the $N$ plane ($\boldsymbol{g}_N$); (B) successive projection of the antenna position on the snow surface ($P$) then on the plane $N$ ($PN$); (C) the combination of illustrations A and B leads to the illustration (C): CoM position (⊗) and direction vector of the pendulum modelling ($\boldsymbol{L}$). The CoM position corresponds to 53% of $\boldsymbol{L}$ from the antenna to its snow surface intersection.

algorithm by Drenk (1994) were used to capture the skier's kinematics over one turn within a 12 turn giant slalom turn section. The coordinates of the control points, video cameras and gates were determined by geodetic tachymeter surveys in an LCS. Camera images were calibrated and synchronised using a gen-lock signal. Twenty-two joint centres and landmarks on the skier's body (head, neck, right and left (r/l) shoulder, (r/l) elbow, (r/l) hand, (r/l) stick tail, (r/l) hip, (r/l) knee, (r/l) ankle, (r/l) ski tip and tail), as well as the GNSS antenna ($\boldsymbol{P_{REF,ANT}}$), were manually digitised and their position was reconstructed in the 3D space. Position data were low-pass filtered using a second-order Butterworth filter with a cut-off frequency between 2 and 4 Hz determined according to the Jackson Knee method (Jackson, 1979). Thereafter, a segment length normalisation technique (Smith, 1994) was applied to adjust the computed segment lengths to the measured lengths of the skier's segments. In terms of accuracy, the method used was found to have a mean resultant photogrammetric error of 23 mm with a standard deviation of 10 mm as in an earlier study (Klous et al., 2010; Reid, 2010). The coordinates of the reconstructed body landmarks, control points, video cameras and gates were transformed from the LCS to the global WGS84 coordinate system as detailed in the Appendix.

*Reference measurement system: CoM computation*

CoM position of the reference system ($\boldsymbol{P_{REF,CoM}}$) was computed using the body segment model of Zatsiorsky (2002) with adjustments of de Leva (1996) and taking the athlete's equipment into consideration. For the CoM and ANT, the velocity ($\boldsymbol{V_{REF,CoM}}$ and $\boldsymbol{V_{REF,ANT}}$) and acceleration vectors ($\boldsymbol{A_{REF,CoM}}$ and $\boldsymbol{A_{REF,ANT}}$) were computed according to Gilat and Subramaniam (2008).

*Error analysis*

The GNSS system and the reference system were time-synchronised using an electronic gen-lock between the video-based and the GNSS system. The position, velocity and acceleration of the CoM and antenna obtained from the GNSS system were compared for the 12 turn cycles to the corresponding values of the CoM obtained from the reference system (i.e. $\boldsymbol{P_{GNSS,CoM}}$ vs. $\boldsymbol{P_{REF,CoM}}$, $\boldsymbol{P_{GNSS,ANT}}$ vs. $\boldsymbol{P_{REF,CoM}}$, and so on for the velocity and acceleration). This characterisation allowed an assessment of the performance of the proposed method with and without the effect of the pendulum modelling. In addition, to characterise the raw performance of the GNSS measurement system, the position, velocity and acceleration of the antenna obtained from the GNSS system and the reference system were compared ($\boldsymbol{P_{GNSS,ANT}}$ vs. $\boldsymbol{P_{REF,ANT}}$, and so on for the velocity and acceleration). For each turn cycle, the mean and standard deviation of these vector differences were calculated. Thereafter the mean and standard deviations were averaged over the 12 turn cycles. These difference measures are termed the vector difference average mean and the vector difference average standard deviation. The vector difference average mean describes the systematic difference (offset) between the measurement systems, while the vector difference average standard deviation describes the random difference (precision). In addition, the position difference was also decomposed into components tangent to the trajectory (fore–aft component), radial (lateral component) and normal to the snow surface (inferior–superior component). The mean and maximum values of the velocity and acceleration amplitude were extracted for each turn cycle and both the GNSS and the reference system. Then the mean and standard deviation of the difference between GNSS and reference system were computed across all turn cycles. These difference measures are termed turn mean and turn maximum. The normality of the data was verified prior to applying parametric statistics using the Lilliefors test ($P < 0.05$).

## Results

Using the previously described GNSS-based method, the CoM position, velocity and acceleration were calculated for 12 runs of 12 gates. Simultaneously, CoM kinematics were analysed for one turn on each run using standard, video-based methodology. For the 12 turns which were captured by both methods, the position differences of the antenna were 0 ± 4 cm (Table I). Comparing the GNSS antenna position and the pendulum model as an approximation of the CoM, the pendulum model had substantially smaller positioning differences to the reference CoM position (Figure 3 and Table I): 9 ± 12 cm using the pendulum model, 69 ± 34 cm without using the pendulum model. The differences were mainly reduced in the lateral and inferior–superior directions (Table I).

The efficiency of the pendulum model in computing the CoM position within the turn cycle is illustrated in Figure 4.

For velocity, pendulum modelling also showed a smaller average mean vector difference ($0.08\ \mathrm{m \cdot s^{-1}}$) compared to the absence of modelling ($0.20\ \mathrm{m \cdot s^{-1}}$), while the precision (vector difference average standard deviation) did not decrease (i.e. $0.19\ \mathrm{m \cdot s^{-1}}$ with modelling vs. $0.16\ \mathrm{m \cdot s^{-1}}$ without modelling) (Table II and Figure 5). When analysing the pattern of the differences, it can be seen that the maximum

Table I. Average mean and average standard deviation ($s$) of position differences for the turn cycles ($N$ = 12) in cm.

| Vector difference | | $P_{GNSS,CoM}$–$P_{REF,CoM}$ | $P_{GNSS,ANT}$–$P_{REF,CoM}$ | $P_{GNSS,ANT}$–$P_{REF,ANT}$ |
|---|---|---|---|---|
| Norm | Mean | 9 | 69 | 0 |
| | $s$ | 13 | 34 | 4 |
| Fore–aft | Mean | 7 | 7 | 0 |
| | $s$ | 5 | 5 | 1 |
| Lateral | Mean | 2 | 5 | 0 |
| | $s$ | 10 | 32 | 2 |
| Inferior–superior | Mean | 5 | 69 | 0 |
| | $s$ | 6 | 9 | 4 |

*Notes*: The position differences are in m. $P_{GNSS,CoM}$–$P_{REF,CoM}$ is the difference between the CoM approximation of the pendulum model ($P_{GNSS,CoM}$) and the CoM of the reference system ($P_{REF,CoM}$). $P_{GNSS,ANT}$–$P_{REF,CoM}$ is the difference between the antenna position computed by the GNSS method ($P_{GNSS,CoM}$) and the CoM of the reference system ($P_{REF,CoM}$). $P_{GNSS,ANT}$–$P_{REF,ANT}$ is the difference between the antenna position computed by the GNSS method ($P_{GNSS,ANT}$) and the antenna position computed by video-based 3D kinematics ($P_{REF,ANT}$).

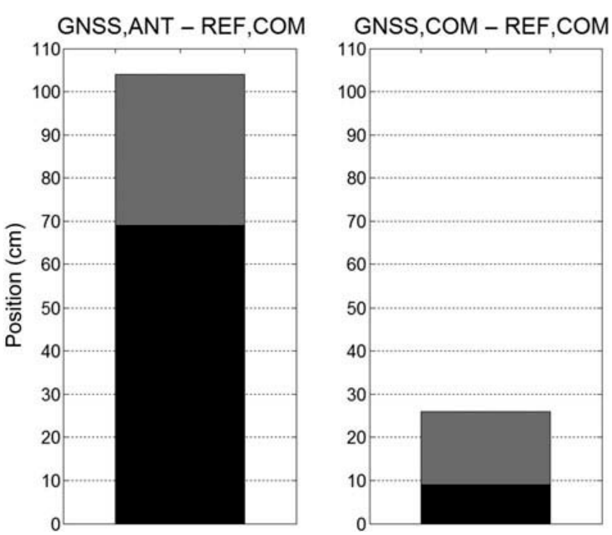


Figure 3. Illustration of the maximal (grey) and mean (black) difference between CoM obtained from the GNSS antenna and the CoM obtained from the reference (GNSS,ANT – REF,COM) and the GNSS minus CoM from the reference (GNSS,COM – REF,COM) for position.

error in the pendulum modelling occurred during the first third of the turn cycle (Figure 7). Comparing the turn maximum values of velocity, the offset and precision were improved with the pendulum model (Table II). It is worth noting that the standard deviation of the antenna velocity between the GNSS and the reference system was 0.12 m · s$^{-1}$ (Table II).

The vector difference mean and standard deviation of the acceleration were slightly lower using the pendulum model (Table II and Figure 6). While the offset was minimally improved (0.22 m · s$^{-2}$ with pendulum model vs. −0.34 without pendulum model), the precision increased to a larger extent (1.28 m · s$^{-2}$ vs. 1.92 m · s$^{-2}$). On examining the pattern differences, the maximum vector difference was observed during the last quarter of the turn cycle, both with and without the pendulum model (Figure 7). For the turn mean and maximum values of acceleration, a smaller offset and a better precision were found using the pendulum model, except for the precision of the turn mean (Table II).

## Discussion

The findings of the current study indicate that the proposed GNSS method is valid for the assessment of CoM velocity and acceleration and with a lower validity for the estimation of the CoM position. As long as the investigated differences are smaller than the precision boundaries required by the research question, the proposed method can be considered as technically valid.

The proposed method facilitates motion capture over large capture volumes with reasonable measurement and analysis effort. The relatively simple measurement set-up on the skier and recent miniaturisations of the GNSS receivers reduce interference with the athlete to an extent which allows motion capture in ski racing competition situations. The development of a valid motion capture device allowing the assessment of entire alpine ski races might open up new possibilities for ski biomechanics research.

There are however limitations to the model presented, which are discussed below. With respect to CoM velocity and acceleration, in an earlier study using a video-based system, Spörri, Kröll, Schwameder, Schiefermüller, et al. (2012) found differences of 0.3–0.5 m · s$^{-1}$ and of 2.6 m · s$^{-2}$ when comparing the CoM kinematics of different course settings. The reported offset and precision of the proposed pendulum model was within the range of these discriminative meaningful changes (0.08 ± 0.19 m · s$^{-1}$ and 0.22 ± 1.28 m · s$^{-2}$). Even the velocity and acceleration offset and the precision of the GNSS antenna (without pendulum model) might be sufficient for various applications since it was found to be 0.20 ± 0.16 m · s$^{-1}$ and −0.34 ± 1.92 m · s$^{-2}$. The velocity and acceleration errors of the model might be mainly caused by the position modelling of the CoM approximation methods and derivative artefacts. The derivative artefacts might result from the fact that in order to calculate velocity and acceleration, for both GNSS and reference systems, derivation operations are required. This may increase the signal-to-noise ratio. Another reason might be that body segment movements (e.g.

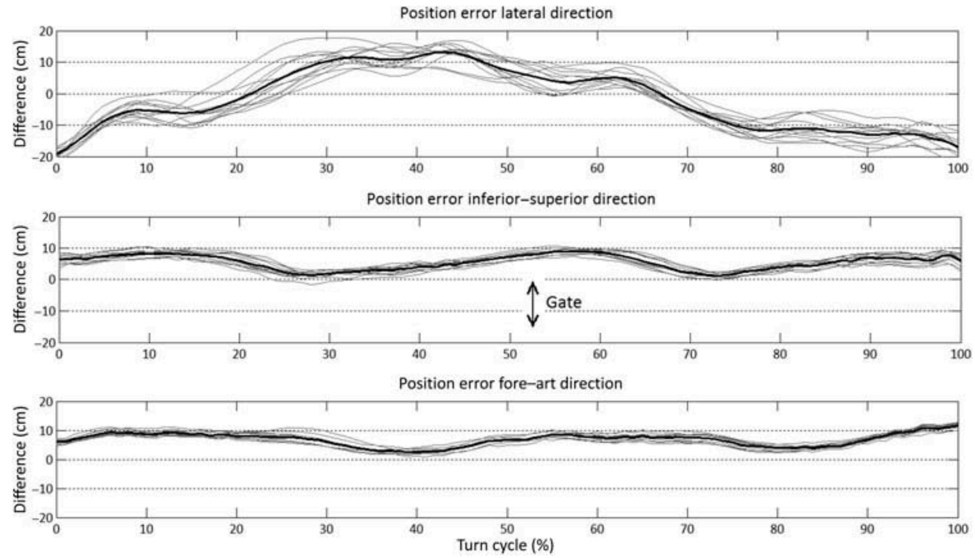


Figure 4. Illustration of the position differences in lateral, inferior–superior and fore–aft direction during the turn cycle for CoM obtained from the GNSS minus CoM from the reference. Averages were calculated based on the 12 turns and were time normalised (0–100%) over the turn cycle (solid line). Individual differences are shown by thin grey lines. The approximate gate position is at 53% of the turn cycle.

Table II. Average mean and average standard deviation (*s*) of velocity and acceleration differences for the turn cycles and for the typical extracted features (mean and maximum value of a turn) ($N$ = 12).

| Turn cycle differences | | $V_{GNSS,CoM}$–$V_{REF,CoM}$ | $V_{GNSS,ANT}$–$V_{REF,CoM}$ | $V_{GNSS,ANT}$–$V_{REF,ANT}$ | $A_{GNSS,CoM}$–$A_{REF,CoM}$ | $A_{GNSS,ANT}$–$A_{REF,CoM}$ | $A_{GNSS,ANT}$–$A_{REF,ANT}$ |
|---|---|---|---|---|---|---|---|
| Vector difference norm | Average mean | 0.08 | 0.20 | 0.01 | 0.22 | −0.34 | −0.57 |
| | Average *s* | 0.19 | 0.16 | 0.12 | 1.28 | 1.92 | 0.48 |
| Turn mean and maximum | Turn mean | 0.06 | 0.19 | 0.00 | 0.01 | 0.42 | 0.47 |
| | *s* of turn mean | 0.05 | 0.05 | 0.02 | 0.43 | 0.23 | 0.22 |
| | Turn maximum | 0.06 | 0.08 | −0.03 | 0.06 | 0.08 | −0.03 |
| | *s* of turn maximum | 0.13 | 0.16 | 0.07 | 0.13 | 0.16 | 0.07 |

*Note*: The velocity and acceleration differences are in $m \cdot s^{-1}$ and $m \cdot s^{-2}$, respectively. $V_{GNSS,CoM}$–$V_{REF,CoM}$ and $A_{GNSS,CoM}$–$A_{REF,CoM}$ are the differences between the CoM approximation of the pendulum model and the CoM of the reference system. $V_{GNSS,ANT}$–$V_{REF,CoM}$ and $A_{GNSS,ANT}$–$A_{REF,CoM}$ are the differences between the antenna computed by the GNSS method and the CoM of the reference system. $V_{GNSS,ANT}$–$V_{REF,ANT}$ and $V_{GNSS,ANT}$–$V_{REF,ANT}$ are the differences between the antenna computed by the GNSS method and the antenna computed by video-based 3D kinematics.

body extension of turn initiation and completion) were not directly considered in the proposed modelling. This concern is reflected in Figure 4, where the maximum error can be observed during the turn transitions (0–20% and 80–100% of the turn cycle). These turn phases are known to involve extensive body segment movements (Müller & Schwameder, 2003). Another source of error in the initiation and completion phases might be the fact that Equation (1) assumes the athlete to be in balance with the external forces. However, this assumption might not always hold. For instance, the skier may not be in balance with the external forces during turn initiation as they dive or fall into the new turn in anticipation of balancing the large forces which develop during the turn phase Another interesting finding was that the offset and standard deviation of the turn mean and maximum velocity and acceleration were rather small. This indicates that the comparison of turn mean and turn maximum values between turns based on both the pendulum model and directly from the GNSS antenna can be considered to be valid.

With respect to CoM position, in an earlier study using video-based systems, Schiefermüller et al. (2004) observed CoM position differences of 0.1 m between different skiing techniques. Considering this value as the range of meaningful changes, the reported precision of the proposed pendulum model (0.09 ± 0.12 m) was larger than the range found by Schiefermüller et al. (2004). Consequently, there might be some limitation of the proposed method when analysing trajectories with small but still substantial spatial differences as they are in giant slalom or slalom. In this case, the use of camcorder-based 3D kinematics might be indispensable. However, the

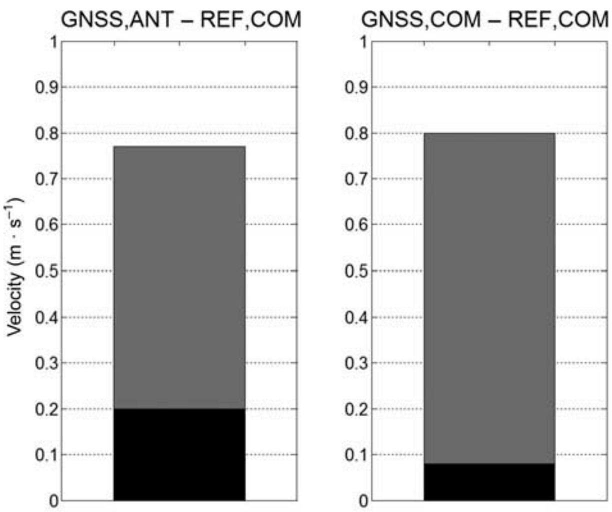


Figure 5. Illustration of the maximal (grey) and mean (black) difference between CoM obtained from the GNSS antenna and the CoM obtained from the reference (GNSS,ANT – REF,COM) and the GNSS minus CoM from the reference (GNSS,COM – REF,COM) for velocity.

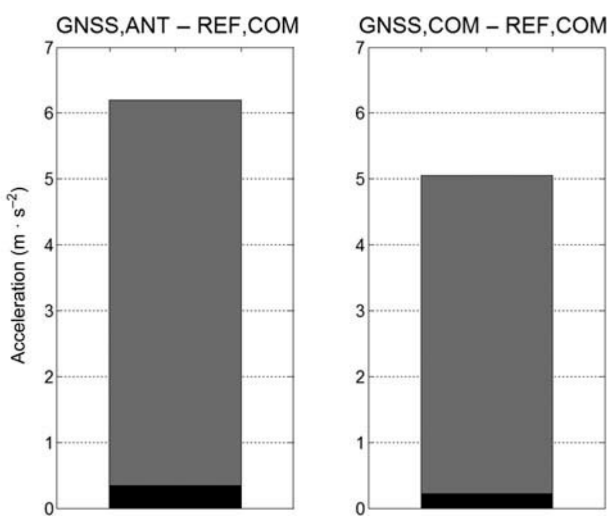


Figure 6. Illustration of the maximal (grey) and mean (black) difference between CoM obtained from the GNSS antenna and the CoM obtained from the reference (GNSS,ANT – REF,COM) and the GNSS minus CoM from the reference (GNSS,COM – REF,COM) for acceleration.

precision requirements with respect to position for the relative comparison between skiers/runs might be reduced for the speed disciplines (i.e. super-g and downhill), where spatial differences in trajectories are expected to be larger. The position error of the pendulum model in inferior–superior direction might be mainly influenced by the 53% value to affix the CoM approximation along the pendulum. This value was obtained from a data set in slalom and might be somewhat different for the use in giant slalom. However, based on the current data, it was found that if a value of 56% instead of 53% would be used the position error in inferior–superior direction would be reduced by 5 cm. Moreover, this adjustment would increase the standard deviation in lateral direction by 1.5 cm.

Generally, it has to be stressed that the validity found in this study is reliable for the specific GNSS method and modelling and the specific set-up (giant slalom on an even slope) of the current study. If different GNSS methods are used, the validity of the antenna kinematics is likely to be different. The number of satellites in view might have effect on the goodness and stability of the positioning solution. Thus, the combination of several satellite systems such as GPS and GLONASS might be advantageous when measuring in obstructed locations. Further, the number of GNSS signal frequencies, the differential processing algorithm, the measurement frequency, the filtering technique and the used hardware might be significant for the goodness of the GNSS antenna data. Furthermore, the pendulum model might perform differently when it is applied in disciplines other than giant slalom or on non-even terrain. When skiing over convex terrain transitions, the pendulum model might underestimate the skier lateral inclination if skiers are actively unweighting. In the case that the skiers are air born, the pendulum model is unable to predict the CoM position in vertical direction since the body extension cannot be limited by the intersection of the pendulum with the terrain. Hence, the body extension has to be estimated for the phases when the skiers are air born. If the terrain model is not reconstructed in detail, the pendulum length can be under- or overestimated. In slalom, the difference between head and CoM acceleration is larger than in giant slalom and the CoM and head trajectories are less in parallel compared to giant slalom (Gilgien, Reid, Haugen, Kipp, & Smith, 2010). Therefore, it can be expected that the pendulum model faces bigger challenges when being applied in slalom and that its validity is poorer than in giant slalom. At the same time, the limits of meaningful changes might be smaller in slalom. Consequently, the use of alternative methods for the reconstruction of CoM kinematics might be indispensible for slalom. In contrast, for the speed disciplines the limits of meaningful changes might be larger and the head and CoM kinematics might be more identical than in giant slalom. Hence, the method might be applied for detailed spatial trajectory analysis in super-G and downhill. In giant slalom spatial comparisons have to be limited to the differences bigger than the position accuracy found in this study. The method could be improved by adding other measurement systems, such as inertial measurement units or devices to measure distance between body landmarks, to enhance the reconstruct of the skier kinematics and the pendulum model.

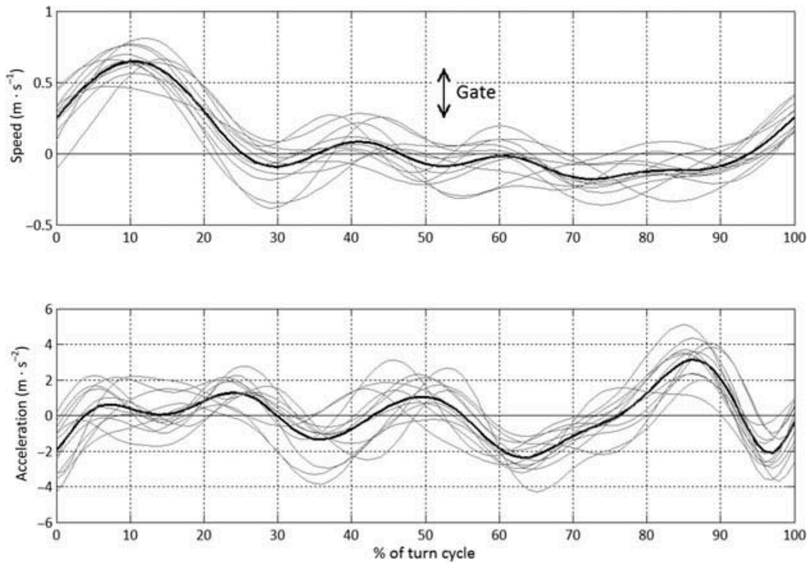


Figure 7. Illustration of the vectorial difference norm for the velocity and acceleration during the turn cycle for CoM obtained from the GNSS minus CoM from the reference. Averages were calculated based on the 12 turns and were time-normalised (0–100%) over the turn cycle (solid line). Individual differences are shown in thin grey lines. The double arrow indicates the approximate gate position.

In a previous study using GNSS methodology along with a pendulum model for the reconstruction of the CoM kinematics in alpine skiing (Supej et al., 2013), the antenna was mounted on the skier's back. Using this mounting point, the reconstruction of the CoM kinematics might be simpler since the kinematics of the back is closer to the kinematics of the CoM (Meyer, 2012). But on the other hand, a GNSS antenna mounted on the skier's helmet, as it was used for the current study, eliminates satellite signal shading by the skier's body. This may, therefore, avoid large positioning errors due to loss of the differential GNSS solution in obstructed terrain. Hence, the measurement location with its satellite signal shading characteristics might guide the user in the choice of method.

The proposed method allows motion capture across large volumes and thus different skiing situations in the same run. The capture of the snow surface geomorphology is a prerequisite for the pendulum modelling, but at the same time it might be an important characteristic to describe the different skiing conditions along a run. The time-consuming tachymeter-/GNSS-based recording of the snow surface can be overcome by the use of terrestrial or airborne laser scanning instead. Alternative approaches which do not require the snow surface as a model input parameter but use additional segment/joint kinematic information provided by inertial measurement units were previously suggested (Brodie et al., 2008; Chardonnens, Favre, Gremion, & Aminian, 2012; Krüger & Edelmann-Nusser, 2009; Supej, 2010).

## Conclusion

The current study proposed and validated a GNSS-based method for the estimation of CoM kinematics in alpine skiing (i.e. position, velocity and acceleration) against a video-based measurement system. The suggested method has been shown to provide sufficient precision with respect to CoM kinematics, in particular for velocity and acceleration, and to be technically valid under field conditions for a broad field of applications. Hence, in future studies, the proposed method could be used for efficiently analysing performance and injury-related aspects of alpine skiing over large capture volumes and/or under race conditions.


## Acknowledgement

The authors would thank Jan Cabri, Geo Boffi, Philip Crivelli and the company Javad, San Jose, CA, USA, for their contribution to this study.

## Funding

This study was partly supported by the International Skiing Federation (FIS).


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## Appendix: Spatial transformation from local to global coordinate system

To enable comparison between the global (WGS84) and LCS, the LCS was transformed into WGS84 after data collection. The matching of the coordinate systems was based on five reference points surrounding the area of investigation and the Helmert least-square resection method using Leica Geo Office (Leica Geosystems, Heerbrugg, Switzerland). The coordinate system matching was accomplished both before and after the motion capture period. To account for drift, the difference between the solution before and the solution after the motion capture period was distributed by time interpolation. The mean difference of the resection at a reference point was below 0.9 cm in the horizontal and below 1.3 cm in the vertical component, with standard deviations of 0.3 and 0.4 cm, respectively.