Title: Using inertial sensors to compute an alpine ski racing specific full body kinematic model – an application to track the distance between ankle joint and athlete's center of mass

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Abstract:

Introduction:

Vertical movements are an inherent characteristic of modern skiing technique and may affect performance in alpine ski racing [1], [2]. Consequently, they are extensively discussed within coaches' manuals and technical guidelines all over the globe [3]–[5]. Despite their functional role during the turn switch, they have also been suggested to increase the skier´s velocity within some very specific skiing situations [6], [7]. However, to date, the quantification of vertical movements while skiing remains very complex.

Traditionally, vertical movement has been analyzed using camcorder-based 2D or 3D kinematics. However, in order to obtain a 3D model of the skier multiple cameras are needed and the capture volume is restricted to a small number of turns. Moreover, data processing is highly time-consuming as the videos need to be labeled manually. Thus, different analysis systems have to be found that allow recording the skier's movement over an entire race. Solutions were proposed to use inertial sensors to obtain body posture information [8], [9]. Even though inertial sensors do not allow obtaining the absolute position of the skier, the relative position of body segments with respect to each other can be determined and used to construct a kinematic model. One application of this approach could be to track the distance between ankle joint and athlete's center of mass, which can be considered as an overall measure of vertical movement while skiing.

Therefore, the goal of the current study was, 1) to design a full body 3D skiing model based on inertial sensor data, 2) to apply this model to compute the vertical distance between the ankle joint and the athlete's center of mass and 3) to demonstrate the validity of this parameter to explain the overall vertical movement differences between the disciplines slalom and giant slalom.

Methods:

Six European Cup level athletes were recruited for the study. Three athletes performed two runs on a slalom (SL) course, while the other three athletes performed two runs on a giant slalom (GS) course. Both courses were set with regular gate distances (SL: 10m, GS: 25m) on a slope with a constant inclination of 25°. For each run, a central section of 8 SL turns and 4 GS turns was selected for the analysis, respectively. This study has been approved by the Ethics Committee of the Department of Sport Science and Kinesiology at the University of Salzburg.

The athletes were equipped with 7 miniature inertial sensor units (Physilog® IV, GaitUp, Switzerland) placed on the head, sternum, sacrum, thighs, and shanks as shown on Figure 1A. Before each run functional calibration movements were performed to align the sensor axes with the anatomical frame of the body segments [10]. An alpine skiing specific algorithm [9] was used to compute the segment orientations.

All joints were modelled as ball joints and normalized segment dimensions and weights were taken accordingly to [11]. The relative joint positions of hip, knee, ankle, trunk center, and neck were computed recursively using Eq. 1 (see Figure 1B) where the trunk center joint was defined as the origin of the model. Arm movement was hypothesized to play only a minor role and was therefore excluded.

$$p_{i+1}(t) = p_i(t) + \boldsymbol{R}_s(t)\, d_s \tag*{\textit{Equation 1}}$$

where $p_{i+1}(t)$ is the position of the $i+1$th joint at time t, $p_i(t)$ the position of the ith joint, $\boldsymbol{R}_s(t)$ the orientation of the segment between joint i and $i+1$ expressed in the global frame, and d_s the segment's dimension in its anatomical frame.

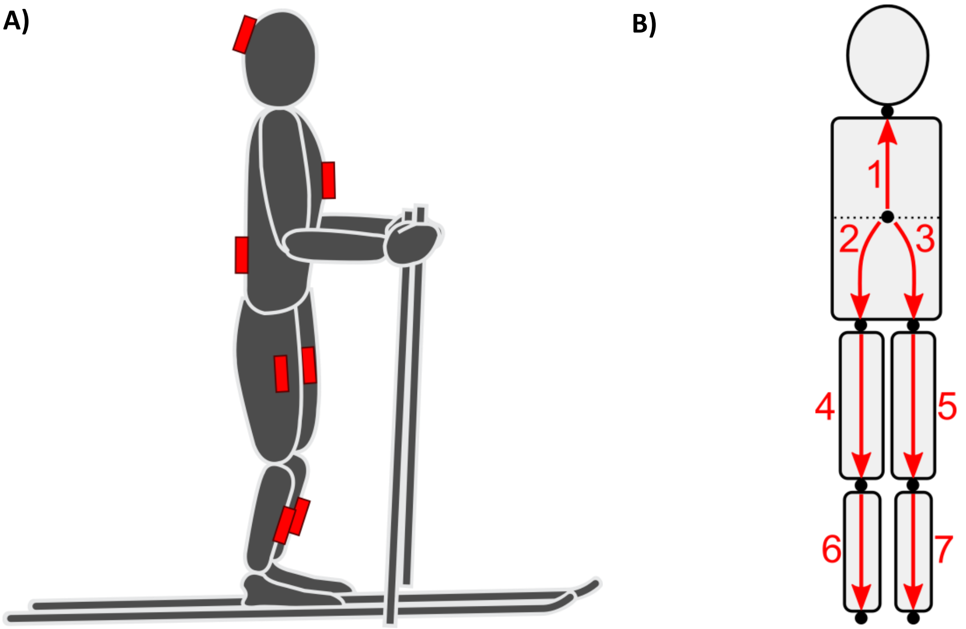

Figure 1: A) Sensor placement, B) full body kinematics model used to compute the joint positions relative to the trunk center.

The center of mass (CoM) for each segment was computed using Eq. 2

$$p_s^{CoM}(t) = p_i(t) + \boldsymbol{R}_s(t)\, d_s^{CoM} \tag*{\textit{Equation 2}}$$

where p_s^{CoM}(t) is the position of the CoM of segment s at time t, $p_i(t)$ the position of the segment's proximal joint, $\boldsymbol{R}_s(t)$ the segment's orientation expressed in the global frame, and d_s^{CoM} the distance vector between the proximal joint i and segment's CoM.

The athlete's CoM was computed using Eq. 3

$$p^{CoM}(t) = \frac{\sum(m_s\, p_s^{CoM}(t))}{\sum m_s} \tag*{\textit{Equation 3}}$$

where m_s is the mass of segment s.

The vertical distance between the left / right ankle and CoM, v_{left} and v_{right}, was defined following Eq. 4 and normalized for body height.

$$\begin{aligned} v_{left}(t) &= |p^{CoM}(t) - p_{left\ ankle}(t)| \\ v_{left}(t) &= |p^{CoM}(t) - p_{right\ ankle}(t)| \end{aligned} \tag*{\textit{Equation 4}}$$

The turn switches have been automatically segmented into right-left double turns by detecting the intersections of the left and right vertical distance curves. Each turn cycle was time normalized to 100%. Mean curves have been computed and maximum and minimum distances were extracted for each leg and discipline. Paired t-test was used to compare maxima and minima of left and right leg of the same subject and same run. Unpaired t-test was used to compare maxima and minima between the disciplines SL and GS. Significance level was set to 5%.

Results:

In total 24 and 12 right-left double turns were analyzed for SL and GS, respectively. Figure 1 shows the mean curves for the vertical distance between left / right ankle and CoM. Table 1 shows the maximum and minimum distances for each leg and each discipline.

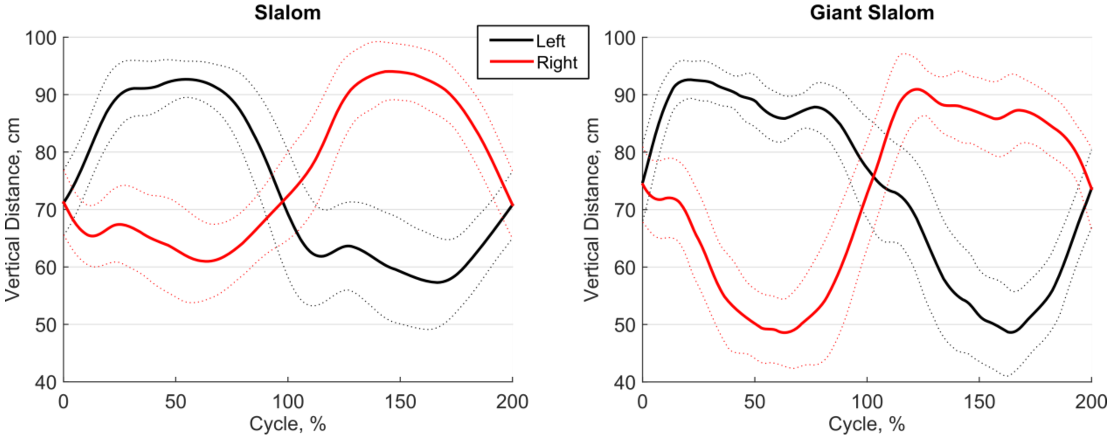

Figure 1: Vertical distance between left / right ankle and CoM over two turn cycles for the disciplines SL and GS. The thick curves are the mean vertical distance and the dotted curves delimit one standard deviation. The black color denotes the left side and the red the right side. 0%-100% right turn, 100%-200% left turn.

	Slalom		Giant Slalom	
	Mean	SD	Mean	SD
Left minimum vertical distance, cm	55.3^{*}	7.9	47.2^{++}	7.2
Right minimum vertical distance, cm	58.3	6.5	46.4^{++}	6.7
Left maximum vertical distance, cm	94.0	3.7	94.5	2.9
Right maximum vertical distance, cm	95.2	4.6	93.1	4.2

Table 1: minima and maxima of the vertical distance between left / right ankle and CoM for the disciplines slalom and giant slalom. SD = standard deviation, * = left/right difference $p<0.05$, ** = left/right difference $p<0.01$, $^{+}$ = discipline difference $p<0.05$, $^{++}$ = discipline difference $p<0.01$

Discussion/Conclusion:

Inertial sensors were successfully used to build a full body kinematic model for alpine ski racing. The model allowed computing the vertical distance between left / right ankle and CoM with a high accuracy and precision. In a related validation study the vertical distance's accuracy (error mean) and precision (error standard deviation) were found to be 0.9cm and 3.0cm, respectively (Fasel et al., unpublished data). This study further supported the relevance and validity of the parameter by highlighting differences in the overall vertical body movements between the competition disciplines SL and GS. However, in order to verify the preliminary findings of a higher range of motion of the vertical distance in GS compared to SL, further more sophisticated studies should investigate this aspect within different course settings and/or slope inclinations.

One of the key advantages of the proposed system is the unlimited capture volume. It allows for the first time to measure overall vertical body movement for an entire race course. For the future, the model could be used to extract other posture related information such as the overall fore-aft position or the overall body inclination as well. The model could also be used for analyzing body coordination. Moreover, the model could be fused with a global navigation satellite system to provide information about instantaneous speed and skiing trajectory.

However, despite the great potential of the proposed method, its setup is still quite complex and may not be the most practicable approach for daily training as seven inertial sensor units per athlete are needed. Consequently, further studies should also aim at simplifying the model for these daily training purposes.

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