CENTRE OF MASS TRAJECTORY IN SNOWBOARD GIANT SLALOM USING INERTIAL SENSORS: LABORATORY AND IN-FIELD PRELIMINARY EVALUATION

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The purpose of the present study was to evaluate the reconstruction accuracy of the centre of mass during snowboard giant slalom using inertial sensors (Opal, APDM, 128 Hz). Two approaches were implemented and tested: i) a multi-segment model using 7 inertial sensors on the trunk, the pelvis, the thighs, the shanks, and the board; and ii) a double integration of the acceleration at L5 level measured with one inertial sensor. The accuracy of the algorithms was verified in two laboratory conditions: a) the multi-segment model approach was tested indoor during controlled movements using stereo-photogrammetry as gold standard, and b) the double integration of acceleration approach was tested outdoor in simulated movements on a longboard using GPS as gold standard. Successively, to verify the application in real conditions, an in-field acquisition of a forerunner athlete during a snowboard world cup competition was performed. The position of the centre of mass estimated indoor with multi-segmental model approach reported in the local reference frame of the board showed high correlation with respect to stereo-photogrammetry (r=0.87) and a RMS error of 3.8 [%] expressed as percentage of the range of motion during the trial (1.32m). For the simulated movements test in outdoor conditions on the longboard applying the double integration approach, high correlation was found with respect to the GPS data (r=0.95) on the trajectory but , for the 4 turns trial, a RMS difference on the distance equal to 15.3 [%] expressed as percentage of the whole distance covered (46m). Finally, the in-field acquisition showed how using inertial sensors is a viable option for collecting centre of mass data during training session useful for coaches and athletes. The approach using one sensors at L5 level showed low level of accuracy with respect to the one using a multi-segment model. Further developments should be performed in the direction of a better estimation of the orientation of the inertial sensors and of the boundary conditions for the integration algorithm.

KEYWORDS: kinematic analysis, IMU, winter sports, wearable technology.

INTRODUCTION: The recent developments in the design of miniaturized, low-cost, and low-power sensors allows for in-field biomechanical analysis of winter sports and thus open new scenarios for coaches and athletes having access to quantitative data during training sessions. Using objective biomechanical measurements is fundamental for injury prevention, technique improvement, and performance enhancement. One of the most important biomechanical parameters is the trajectory of the centre of mass (CoM) that can be used as representative of the athlete’s movement and for the analysis of mechanical energy changes.
In a recent systematic literature review regarding of the use of inertial measurements units (IMU) in sports performance evaluation, 23 papers specific of winter sports were found (Camomilla, Bergamini, Fantozzi & Vannozzi, 2018). Among them only four were applied on snowboarding and only two estimated CoM trajectory during free-style (Krüger & Edelmann-Nusser, 2009; Sadi & Klukas, 2013). However, similar to other studies on skiing in outdoor conditions (Fasel, Praz, Kayser & Aminian, 2016), both studies exploited the combined use of Global Positioning System (GPS) and IMU data. In order to be sufficiently accurate, GPS must

be differential (Fasel, 2017) and for this reason the device becomes particularly cumbersome for the athlete and difficult to be used during a routine training session.
The purpose of the present study was to perform a preliminary evaluation of the accuracy in the estimation of CoM trajectory in snowboarding using IMU without the use of GPS data. Two type of tests were carried out: the first in simulated conditions as a comparison with other devices can be performed for controlled movements and the second one in in-field setting to investigate the feasability in real conditions.
METHODS: Two approaches were implemented: i) a multi-segment model using seven inertial sensors reported in the local reference frame of the board (Multi-link), and ii) the double integration of the acceleration of a single sensor attached at L5 level reported in the global reference frame (L5-acc). Different reference frames were used for the two approaches, as the two methods intends to extract different types of information for coacheds and athletes: in the first case (Multi-link) how the athletes is moving the CoM with respect to the base of support, while in the second case (L5-acc) the entire trajectory of the CoM. We considered 5% as an accetable level of accuracy.
The Multi-link approach required the use of seven sensors attached to the body segments (trunk, pelvis, thighs, and shanks) and to the board. For the estimation of the body segments orientation, the Outwalk protocol was applied (Cutti, Ferrari, Garofalo, Raggi, Cappello & Ferrari, 2010) with the exception of the IMU position for the shanks and the feet. The shank sensors were positioned closer to the knee as the boots did not allow to attach the IMU just above the lateral malleolus, however the alignment with the anatomical axis was maintained. Regarding the sensors feet positions, for the same reason and considering the hard attack of the boots to the board in the giant slalom discipline, only one IMU was used for the two feet and it was fixed to the board. Relative positions between sensor and boots were measured and taken into account. The upper part of the body constituted by the head, the arms and the upper part of the trunk was considered as one segment. The length and the CoM of each body segment were estimated using anthropometric data (Dumas, Cheze & Verriest, 2007). The CoMs of the body segment were estimated iteratively by means of roto-traslation matrixes starting from the board. Subsequently, the body CoM was estimated as the mass-weighted average. The CoM position was, in this second approach, reported in the local reference frame of the board (y axis from the right to the left boots, z axis perpendicular to the board, and x-axis applying the right-hand rule is positive towards the front side).
The L5-acc approach required a very simple set-up as only one sensor was attached to L5. This position was chosen as it is the place where approximately the CoM of the body is located in the standing up-right posture. First, gravity is removed from the acceleration data using the IMU orientation estimated by a Kalman filter implemented in the software device. Successively, double integration of the acceleration was applied using the trapezoidal approximation. In order to reduce drift problems, 15-s of static data were acquired at the beginning and at the end of the motor task and relevant velocity and position used as boundary conditions for the integration. The CoM position was reported in the global reference frame (x axis pointing the magnetic north, y axis the vertical axis defined from g in static acquisition, and z axis applying the right-hand rule).
Laboratory accuracy test in simulated condition. To verify the accuracy of the estimated CoM position, two tests were performed for simulated motor tasks: a) controlled movement trials were performed in laboratory and stereo-photogrammetry was used as gold standard; b) simulated turns on a longboard were performed on defined trajectories in outdoor conditions and GPS was considered as gold standard. In both cases the mean, standard deviation and root mean square error (RMS) were estimated together with the Pearson product-moment correlation coefficient (r) between the two data.
For the indoor laboratory test specifically designed for Multi-link algorithm, one participant performed three repetitions of two types of movement considered as basic for the snowboard discipline: antero-posterior and medio-lateral oscillations on a board. Seven IMUs (Opal, APDM, 128 Hz) were attached to the body segments using bi-adhesive tape. Following the Outwalk protocol, two acquisitions of knee flexion-extension, for right and left limbs, were performed to estimate the functional flexion-extension axis of the knee. PiG marker set and

protocol was used (Davis, Ounpuu, Tyburski & Gage ,1991) and 3D positions were reconstructed using a stereo-photogrammetric system (SMART-D, BTSBioengineering, 6TVC cameras, 200Hz).
For the outdoor controlled test specifically designed for L5-acc algorithm, one participant performed on a sloping road 3 repetitions of three types of 100-m long trajectories: rectilinear without turns, with one wide radius turn, and with four turns defined using 4 cones distant from each other about 10 m. One IMU was attached to L5 (Opal, APDM, 128 Hz). For comparison, CoM trajectory was reconstructed using wearable GPS devices (GPEXE LT, 18.18Hz). The typical error of estimate of this specific GPS device was reported to be lower than 8% of the total distance covered (Hoppe, Baumgart, Polglaze, & Freiwald, 2018). For this reason, the GPS in this case was considered more for comparison than a gold standard.
In-field test in competition setting. To verify the application in real conditions, an in-field acquisition of a male forerunner athlete during a snowboard world cup competition of giant slalom (Cortina d'Ampezzo, Italy, 15/12/2018) was performed. In this case, the slope was divided in 11 cycles, considering one cycle as constituted by 2 phases: backside and frontside turns using the change of ski edge for the identification of the beginning/end of a turn. The same set-up of IMUs and protocol adopted in the indoor and outdoor laboratory tests were implemented. The IMU placed on the board was inserted in a waterproof round box and attached to the surface between the boots.

RESULTS: The indoor laboratory test showed a mean error equal to 3.2 ± 2.8 cm in the reconstruction of CoM in local reference frame applying the Multi-link approach. More details are reported on Table 1. No differences were found between the antero-posterior and medio-lateral oscillations.
The outdoor laboratory test showed a mean percentage error equal to 12.1 ± 3.4 with respect to the total distance and high correlation (r=0.95) in the reconstruction of CoM trajectory in the global reference frame with the L5-acc approach. More details are reported on Table 2.

Table 1: Results of the accuracy for the Multi-link approach with respect to stereo-photogrammetry for resultant positions for both antero-posterior and medio-lateral oscillations. Mean, standard deviation and RMS error in the reconstruction of anatomical landmark and CoM position expressed in cm and as percentage of the range of motion (1.32m)

Position	Mean±Std [cm]	RMS [cm]	Mean±Std [%]	RMS [%]
Knee Joint Center (Left)	3.7±6.1	7.2	2.8±4.6	5.4
Knee Joint Center (Right)	3.8±5.6	6.8	3.1±4.7	5.6
Hip Joint Center (Left)	4.5±4.3	6.2	3.7±3.5	5.1
Hip Joint Center (Right)	3.9±3.6	5.3	3.3±2.9	4.5
L5	4.7±3.8	6.0	3.6±2.9	4.7
Trunk	5.2±4.7	7.0	2.6±2.3	3.5
CoM	3.6±3.6	5.1	2.7±2.7	3.8

Table 2: Mean, standard deviation, and RMS difference of resultant CoM position obtained with L5-acc approach with respect to GPS expressed as percentage of the whole distance covered and correlation for x and y axis

Position	Mean±Std [%]	RMS [%]	r_x	r_y	Distance [m]
Straight line	14.9±13.1	19.9	0.93	0.94	66
Wide radius turn	12.9±10.4	16.6	0.94	0.99	344
4 turns	9.9±11.6	15.3	0.94	0.94	46

During the in-field test of a forerunner in competition setting, L5-acc approach estimated the CoM entire distance of the slope with an error of 15.5% (considering the CAD file as reference, Figure 1 left as no GPS data was available for this acquisition). The position of the CoM estimated with the Multi-link approach expressed in the local reference showed repeatable patterns (Figure 1 right). In this case, unfortunately no gold standard was available and thus no accuracy evaluation was performed. Both approaches allowed to reconstruct completely the CoM trajectory of slope.

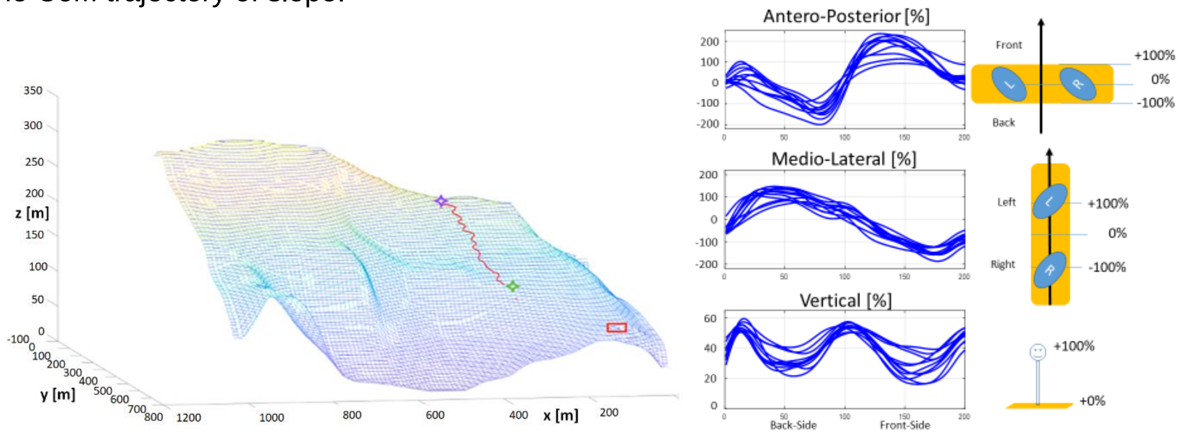

Figure 1: On the left, 3D trajectory of the CoM of the forerunner (red curve) obtained with L5-acc approach and reported in the global reference system superimposed on the mountain surface (CAD file from repository CadMapper). The purple and the green stars represent the beginning and the end of the slope, respectively. The red rectangle represents the place where all the IMUs were calibrated and attached to the athlete. On the right, CoM trajectory of the forerunner estimated with Multi-link approach and reported in the local reference frame of the snowboard for the antero-posterior direction expressed as percentage of the dimension of the board (top), for the medio-lateral direction (middle) expressed as percentage of the distance between the two attacks, and for the vertical direction expressed as percentage of the height of the participant (down), in the three directions the origin was the same and considered on the board in the middle between the two boots..

DISCUSSION: In the present study, a preliminary evaluation of the accuracy of the CoM trajectory estimation during snowboard giant slalom was conducted. The aim was to investigate the feasibility of using only IMUs without a differential GPS system to reduce the encumbrance of the equipment for the athletes and, thus, to develop a methodology reliable and viable for daily training session. Two approaches were investigated, one requiring seven IMUs attached to the body and the board, and the other exploiting a very simple set-up as only one IMU was attached at L5 level. The algorithms were first tested in laboratory during controlled and simulated movements, and then employed during a competition setting.
The results found for the Multi-link approach were comparable with a previous study on an indoor carpet for alpine skiing (Fasel, Spörri, Schütz, Lorenzetti, & Aminian ,2017). In that study, a more detailed model was also investigated and by instrumenting the upper limbs a slightly higher accuracy was obtained (mean error of 2.57cm) (Fasel, 2017). The choice of the number of links in the model is a compromise between accuracy and encumbrance for the athlete, and depends from the examined motor task and from the level of accuracy needed for the specific analysis. At the moment, the accuracy found in the present and previous study (Fasel, 2017), is lower than that obtained with stereo-photogrammetry for in-field acquisition: <1.5 cm (Klous, Müller & Schwameder, 2010). However, stereo-photogrammetry requires time consuming set-up, tracking and elaboration of the data that prevents a routine use of this technology during training sessions.
As opposed to the Multi-link algorithm, the results obtained with L5-acc algorithm were consistent between laboratory and in-field settings, but showed not accetable accuracy. Future developments will investigate more accurate orientation algorithms for removing gravity contribution and more robust boundary conditions for the double integration procedure.

CONCLUSION: Although the present study is preliminary, considering the number of the participants and of the trials acquired, the results showed IMU may be a viable wearable technology to estimate CoM trajectory during in-field movements of snowboard giant slalom.

The present preliminary results showed that only the Multi-link algorithm reached an accetable accuracy.

REFERENCES

Camomilla,V., Bergamini,E., Fantozzi,S. & Vannozzi,G. (2018). Trends Supporting the In-Field Use of Wearable Inertial Sensors for Sport Performance Evaluation: A Systematic Review. *Sensors*,50,105-11.

Cutti, A.G., Ferrari, A., Garofalo, P., Raggi, M., Cappello, A. & Ferrari A. (2010). 'Outwalk': a protocol for clinical gait analysis based on inertial and magnetic sensors. *Med Biol Eng Comput*, 48, 17–25

Davis, R.B III, Ounpuu, S., Tyburski, D. & Gage, J.R. (1991) A gait data collection and reduction technique *Hum Mov Sci*, 10, 575-587

Dumas, R., Cheze L. & Verriest, J-P. (2007). Adjustments to McConville et al. and Young et al. body segment inertial parameters. *J Biomech*, 40, 543–53.

Fasel, B., Praz, C., Kayser, B. & Aminian, K. (2016) Measuring spatio-temporal parameters of uphill ski-mountaineering with ski-fixed inertial sensors. *J Biomech*, 49, 3052–3055

Fasel, B., Spörri, J., Schütz, P., Lorenzetti, S., & Aminian, K. (2017). An inertial sensor-based method for estimating the athlete's relative joint center positions and center of mass kinematics in alpine ski racing. *Frontiers in physiology*, 8, 850.

Hoppe, M. W., Baumgart, C., Polglaze, T., & Freiwald, J. (2018). Validity and reliability of GPS and LPS for measuring distances covered and sprint mechanical properties in team sports. *PloS one*, *13*(2).

Klous, M., Müller, E. & Schwameder, H. (2010). Collecting kinematic data on a ski/snowboard track with panning, tilting, and zooming cameras: is there sufficient accuracy for a biomechanical analysis? *J Sports Sciences,* 28, 1345–1353

Krüger, A. & Edelmann-Nusser, J. (2009) Biomechanical analysis in freestyle snowboarding: Application of a full-body inertial measurement system and a bilateral insole measurement system. *Sports Technol*, 2, 17–23.

Sadi, F. & Klukas, R. (2013) New jump trajectory determination method using low-cost MEMS sensor fusion and augmented observations for GPS/INS integration. *GPS Solut*, 17, 139–152.

ACKNOWLEGEMENTS: The authors would like thank the technical coach and the athletes of the Italian Federation of Snowboard (FSI).