MEMS sensors for sport engineer applications

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Abstract. In this paper it is presented a brief introduction about the Micro Electro-Mechanical Systems (MEMS) sensors technology and their application and use in healthcare and sport activity in the literature. In these two fields, our research group’s applications will then be analyzed with the support of a numerical tool able to replicate human body behavior performing a sport activity, in particular Nordic Walking and Alpine Skiing. The main goal was to obtain a comparison between the numerical and experimental results, in order to validate of the numerical tool and to better understand the sport gesture. The integrated monitoring systems enable a new interpretation of the sport gesture providing the athletes the maximum freedom of movement and allowing them to better perform in their natural training environment.

1. Introduction
The exponential growth of smart sensor technologies opens to new frontiers in the studying and monitoring of healthcare, physical activities and safety systems. It’s emerging a need for innovative sensor technologies and monitoring devices able to sense, classify and provide feedbacks to user’s health status and physical activities. In particular there is a growing interest in the monitoring of the sport activity, because from that several benefits can be obtained as the increasing of the gesture effectiveness, preventing and avoiding injuries, increasing sport activity benefits and the performance. With a monitoring device it possible to reach a deep knowledge of the sport and to have the capability to know the causes of an injuries and adopt the strategies to avoid them [1]. This activity can help both the coach and the athlete to get the best out of their sport [2]. Thanks to the growing of the MEMS wearable sensors, the monitoring of the sport also for non-professional users is now available [3]. MEMS sensors have been studied in recent years. In particular, mini-pointed devices have been studied to measure different quantities using low consumption. The research team has been active with numerous researches oriented towards the development of sensors on the reliability of MEMS devices [4, 5, 6, 7, 8]. Taking into account both aspects of material reliability at the microscopic level and dynamic behavior of the devices.

So, there was a spread of this technologies in the sport system, also because the wearable sensors seem to solve some problems that affected the traditional optical motion capture method. In fact, one drawback of this technology is the limited work volume restricted to the laboratory environment, but also the limits of some movements of the athletes that are constrained on a treadmill [9]. About that, the MEMS and the wearable technology open an innovative method to investigate the sport activity , enable the athlete to practice their sport into the proper environment, indoor or outdoor. This kind of technology often completely integrated in the sport equipment is able to measure the sport activity in a proper environment and let a completely
freedom in movements to the athletes [10], [11]. This paper proposed two experimental set-up for different sport applications: the Nordic Walking (NW) and the Alpine Skiing. The purpose of these studies is the monitoring of the proper gesture in order to improve the benefits of the NW [12] and to enhance the performance in the Alpine Skiing. The peculiarity of this research approach is that both the two experimental apparatus are supported by a numerical simulation.

This simulation is built with a multibody model designed specifically for these sports activities and it is able to replicate the gesture of these two sports. Two are the main advantages of these models: a deeply knowledge of the sport gesture in order to correctly simulate it in a virtual environment and the possibility of a first comparison with the experimental results. Understand completely the sport gesture is important also during the design phase of the experimental set-up. Because this can help to understand the suitable position of the sensors, the quantity to measured and the type of sensors to use. Usually, a multibody analysis is considered when studying complex mechanisms and vehicle dynamics on different ground conditions [13, 14, 15] but are also used to replicate the human body motions in different context like the cross country ski [16], the alpine ski [17] or to study a human fall [18]. This biomechanical humanoid Multibody (MTB) model can be considered an innovative form of investigation of the sport’s dynamics. With this approach, it is possible to study several biomechanical aspects, like the kinematics of each body segment, estimating loads applied to the joints for given tasks. Several hypotheses are required to model the human body and make it able to perform realistic movements during the simulation. For now, no muscle behavior was simulated, instead focusing the attention on the system, rather than the subsystem performance. The main peculiarity of this model is the parametrization, in terms of weight and height, to perform a more accurate comparison with the experimental set-up, adapting the MTB model to the proportion of the athletes. An inverse kinematic approach was used, starting from a set of kinematic laws for the joints involved in the movement derived from experimental measurements available in the literature.

For the first activity, the Nordic Walking, the system developed integrates an accelerometer, a GPS and load cell. The aim of this first application is both the healthcare monitoring of the users and the enhance of performance of the athletes. For the Alpine Ski application, the athletes are monitored by five Inertial Measurements Units (IMU) and a barometric sensor. This set of sensors permit to compute the slope, the number of curves and the angle of ski boots during the ski run. In this case the principal aim is to enhance the performance of the athletes. Both of these two sensors set-up is explained in detailed in the Method and Material section of this paper. Thanks to an in-house software it is possible to study the activity recorded and obtain many fundamental information to understand the characteristics of the movement. The data coming from the monitoring system offer the opportunity to track errors and the growing of performance. The detection of errors could help to prevent and avoid injuries as well as helping users in a rehabilitation program or for the athletes to improve their sport technique.

2. Method and Material
In this section are described the experimental set-up used to study the Nordic Walking and the Alpine Skiing.

2.1. Nordic Walking
For the Nordic Walking activity, the sensors used are show in the picture below and summarize in the Table 1 and Figure 1.

This kind of hardware components is a customize set-up already described in previous works by the authors [19, 20, 21]. The tri-axial accelerometer is used to evaluate the number of walking cycles and angle of the poles during the contact phase. The integrated load cell measured the force applied on the pole and a GPS system tracked the user during the workout sessions. The signal from the accelerometer is sample at 50 Hz. This frequency has proved to be the best in
Figure 1: Hardware components

Table 1: Hardware components description

| N  | Components      | Code      | Description                        |
|----|-----------------|-----------|------------------------------------|
| 1  | Accelerometer   | ADXL345   | Accelerations along x, y, z axes   |
| 2  | GPS             | MTK3339   | Position, data and hour            |
| 3  | Load cell       | KM26z-500N| Force along x axis                 |
| 4  | Memory          | µSD Card  | Saving data                        |
| 5  | Microcontroller | ATMEGA 328P| System management                  |

terms of good accuracy in recognizing the Nordic Walking pattern and also leaves the acceleration sufficiently free of noise. From this first prototype the development of this project came to a completely integrated monitoring system in the hands of the Nordic Walking pole. The design is miniaturizing, and the data are transmitted with a wireless communication and it is expected a mobile app and cloud technology integration. Thanks to a software developed in Matlab it is possible to analyze the data coming from the sensors and give some important information to the user, like the angle of the pole during the contact phase that give the information of the technique, but also other information regarding the cycle time, the number of cycle, the duty cycle.

2.2. Alpine Skiing

For the Alpine Skiing instead the Inertial Measurements Units (IMU) are used. The IMU adopted are five MetaMotionnR by Mbientlab [22] and these sensors are mounted on the athletes. This kind of sensor integrated three MEMS sensors: an accelerometer, a gyroscope and a magnetometer. The accelerometer specification in this case are reported in Table 2 and it is able to measure the acceleration of a body. Aliike, the gyroscope can measure the angular velocity of the body and the magnetometer the magnetic field, their specifications are reported in Table 3 and 4. Five IMU are placed on the skier body, two of them are placed on the back of each ski-boot, others two on the thighs and one on the trunk. The IMU are fixed to the body and to the ski-boot with elastic straps purchased together with the IMU, in order to avoid misalignment of the sensors. The X axis of the IMU is oriented as the vertical axis of the boot pointing superiorly, the Y axis with the lateral axis pointing left and the Z axis with the anterior-posterior axis pointing opposite to the slope (Figure 2).

The sampling frequency for this study is fixed to 50 Hz because it can guarantee a good precision of the data and a removal of some noise. The data obtained from the IMU are used to compute the angle of each body segment on which are mounted. During this first phase of the


Figure 2: Alpine Skiing setup

| Table 2: Accelerometer |
|------------------------|
| Description | Min | Max | Units |
| Measurement range | ±2 | ±16 | g |
| Resolution | 2048 | 16384 | counts/g |

| Table 3: Gyroscope |
|-------------------|
| Description | Min | Max | Units |
| Measurement range | ±125 | ±2000 | ◦/counts |
| Resolution | 16 | 262 | counts/◦ |

| Table 4: Barometer |
|-------------------|
| Description | Min | Max | Units |
| Measurement range | 300 | 1100 | hPa |
| Resolution | 0.01 hPa (<10 cm) | |

Experimental set up two testers run these tests on the same slope.

2.3. Multibody Model
The Multibody model is developed within the MSC ADAMS environment. The humanoid model built is the same for both the simulations of the two sports. In fact, the first model is a parametric humanoid that change proportion with the height and weight, in order to be adapt to the users that perform the sport. The human body part are simulated troughs different rigid bodies and the human joints are simulated with a proper DOF mechanical joints. Each rigid body has a simplify geometry, each element was parametrized in terms of the total mass
Table 5: Mass distribution on the human body

| Body parts | Men(%) | Women(%) |
|------------|--------|----------|
| Hands      | 1.3    | 1.0      |
| Forearms   | 3.8    | 3.1      |
| Arms       | 6.6    | 6.0      |
| Feet       | 2.9    | 2.4      |
| Thigh      | 9.0    | 10.5     |
| Legs       | 21.0   | 23.0     |
| Torso      | 55.4   | 54.0     |

and total height of the humanoid as indicated in the literature [23, 24] and reported in Table 5 (mass distribution) and Figure 3 (geometric proportions). In this way, the inertia properties of each subsystem of the humanoid could be easily adapted to the characteristics of the athlete from which data are gathered. This point is crucial to relate some important parameters and indicators for performance analysis to the real physical activity. Also, the specific equipment for the two sports activity, in this case the poles for the Nordic Walking and the poles and the skies for the Alpine Skiing are also parametrized.

Following the inverse dynamic approach, kinematic laws were imposed as relative motion between the pair of bodies connected. The angular variation of each joint was introduced as kinematic constraint, using the ‘Motion’ object in MSC ADAMS. The kinematic laws considered in this work were derived from experimental measurements available in the literature [25] where the angular variation of the lower limb joints (hip, knee and ankle) related to NW sessions was shown. Considering the equations of motion of the lower limbs and how they were obtained in the literature, the equations of the upper body (shoulder, elbow) were derived accordingly. Thus, from the time-angular displacement vectors of points for each measured joint motion, a Fourier series expansion was evaluated to obtain periodic and continuous laws. For the Alpine

Figure 3: Height proportion
Skiing the number of data available is different than the Nordic Walking and the Walking data presented in literature. So, the equation of motion used in this model are derived both from the multiple test developed with the numerical model and from the experience of the research group.

3. Results

3.1. Nordic Walking activity

In this section are presented the results obtained with the experimental apparatus and the comparison with the multibody model. In particular for this activity the comparisons are done for:

- Force applied during the pushing phase

A comparison between the measured pole force applied to the ground for a given Nordic session and the simulated one was performed. The test was developed by four nordic walkers and it was about a 30-step indoor path maintain a constant speed. In order to compare the experimental results with the numerical one, the humanoid model was adapted to the users who performed the monitored NW sessions. For the different testers a similar behavior of the measured and the numerical force is obtained, as it is shown in Figure 4 where the force of the numerical simulations is represented. Assuming a time cycle of 1 s, the contact phase occupies almost half of the total cycle. This time is when the pole is in contact with the ground and in this phase is included the impact and the pushing phase. The first phase is when the pole touches the ground and the force starts to increase. The pushing phase is when the force reaches the peak and then starts decreasing. What it was observed from the comparison of the experimental data and the numerical one is that both the measured and simulated pole’s peak occurred during the mid-pushing phase, as is shown in the literature [19, 20, 13]. Still remains a slightly different time evolution between the numerical and experimental curves, but the similar trend and peak values translated to comparable values of the impulse, which is an interesting quantity, especially in an energy analysis. In Figure 5 is shown an example of the numerical-experimental comparison and the impulse obtained in one of these cases were collected as shown in Table 6. The values reported in the table are the average values of the impulse during all the NW sessions developed for the test.

![Figure 4: Numerical pole force varying weight-height of testers](image1)

![Figure 5: Experimental and numerical force comparison for the four testers](image2)
Table 6: Experimental and numerical impulse computation for the four testers

| Height (m) | Mass (kg) | $I_{numerical}$ (Ns) | $I_{experimental}$ (Ns) |
|-----------|-----------|-----------------------|-------------------------|
| 1.65      | 65        | 35                    | 23                      |
| 1.70      | 70        | 40                    | 29                      |
| 1.75      | 75        | 47                    | 35                      |
| 1.80      | 80        | 60                    | 40                      |

- The pole angles

Another important information during a Nordic Walking session is the inclination of the pole during a whole cycle. This data can give a lot of useful information both to the trainer and both to the user to understand the correct procedure of this sport. So, an additional comparison of the experimental data and numerical simulation is developed within the measured pole angle and pole angle obtained from the MTB simulation (Figure 6). The experimental pole angle can be evaluated by this experimental set-up only during the contact-phase, when the tip pole is in contact with the ground.

![Figure 6: Numerical pole angle variation in a NW cycle](image)

In the contact phase is included the impact phase and the pushing phase as it was explained in the previous paragraph. During the second phase it is assumed that only the gravitational force acts. Instead during the initial impact, the computation of the pole angle cannot be performed, only with a gyroscope it is possible to have the complete angle variation, as it is shown in a different context by Bruzzo et al. [26]. This is due to the sum of the vibrations caused by the impact and the dynamic component of the accelerations that make the signal noisy. These considerations were confirmed in the authors’ previous work [19, 20, 21]. So, it is possible only an approximation of the angle during the impact phase, an example of this computation is
developed with an interpolation of the angle curve in the second phase. What was observed is the same trend of curves of the MTB simulations during the phase when the contact angle was evaluated with the measurement device. This work has to be completed and the approximation validated with a motion capture approach to be able to compare with more accuracy the data obtained with the interpolation algorithm.

3.2. Alpine Skiing activity
In this sport discipline there are three fundamental angle that can be evaluated with an IMU and that can give a lot of useful information. These are:

- The lateral inclination of the skier, that is evaluated with the roll. This represent the typical movement of the skier and it is also can be considered as an index of the ability of the athlete.
- The rotation of the ski during the slope, that is evaluated with the yaw. This represent the direction of the ski boot during the ski run and it is directly connected with the trajectory performed.
- The angular variation on the slope plane, that it is measured with the pitch. With this angle it evaluated both the inclinations of the ski boot but also the slope, so to be able to compute only the inclination of the ski-boots it is necessary to have a relative measure, for example between the ski and the ski boot.

From the angular velocity obtained by the gyroscope these angles are computed. Due to the drifting of the data a high pass filter is mandatory. Here in this workflow are summarized all the passages in order to obtain the three angles.

\[
\begin{align*}
\text{Angular velocity} & \quad \omega_x, \omega_y, \omega_z \\
\text{LP filter} & \quad \text{(removing the high frequency noise)} \\
\text{Integration of the angular velocity} \\
\text{HP filter} & \quad \text{(removing drift)} \\
\text{Angles} & \quad \theta_x, \theta_y, \theta_z
\end{align*}
\]

Where:
- LP filter is a Low Pass with a cutoff frequency of di 5 Hz.
- HP filter is a High Pass with a cutoff frequency of di 0.1 Hz.

For this first step of the project this algorithm is used, in further studies can be evaluated the advantages of different sensors fusion algorithm already presented in the literature [27, 28, 29, 30]. According with this procedure it is possible to obtain the variation of the lateral inclination of the ski boots (but also of the other body segment) and the curves can be evaluated. In the images below are reported some of the results obtain in the same ski run from two different tester.

1) Roll Angle
The peaks are maximum lateral inclination of the skier, this parameter can give the information about the ability of the skier, most the angle is high most the athlete is capable but can also give us the information about the direction of the curve. In fact, the positive part of the graph represents the right curves instead the negative one represents the left one. From this graph can be easily identify the number of the curves done during a ski run.

2) Yaw Angle
In these two graphs are shown the variation of the yaw angle during the same ski run by two different testers. This angle is zero when the skis are parallel to the slope that is coincide with the peak of the roll angle during the maximum inclination of the curve. Instead is reach the maximum value when the athlete is starting a new curve.
Figure 7: Roll angle for the ski-boots for Tester 1

Figure 8: Roll angle for the ski-boots for Tester 2

Figure 9: Roll angle

Figure 10: Yaw angle for the ski-boots for Tester 1

Figure 11: Yaw angle for the ski-boots for Tester 2

In the Table 7 below are collected all the data coming from the analysis of the roll and yaw angle for each tester.

Another important parameter to include during the study of the Alpine Skiing is the difference in level of the ski slope. The altitude variation can be computed with a barometer, that it is
Figure 12: Yaw angles

Table 7: Results of the two tester data analysis

| Quantities            | Tester 1 | Tester 2 | Units |
|-----------------------|----------|----------|-------|
| N of curves           | 14       | 22       |       |
| Right curves          | 7        | 11       |       |
| Left curves           | 7        | 11       |       |
| Downhill time         | 40       | 40       | s     |
| Average curve time    | 2.4      | 1.6      | s     |
| Roll inclination (ave.) | +46 -51 | +50 -51 | ◦     |
| Yaw inclination (ave.) | +41 -43 | +32 -31 | ◦     |
| Total altimetry       | 100      | 100      | m     |
| Curves/altimetry      | 0.14     | 0.22     |       |

included in the sensors used for this session. The sampling frequency for this sensor is 1 Hz and with the number of curves can give a first the approximation about the velocity of the athlete without using a GPS. Also with an higher sampling frequency could be possible to have a better estimation of the effective slope of the ski run, not only the information about the vertical displacement done.

Figure 13: Roll angle on altimetry

For this activity the multibody model is still in a first phase of the realization and so the experimental measures are used especially for the calibration of the motion imposed to the model. In particular for this activity the comparison is done in terms of lateral inclination and for the yaw for each body segment.
4. Discussion
In conclusion from this paper a use of the MEMS sensors to monitor different sport activity is presented. The first activity regarding the Nordic Walking is on a further stage and the comparison developed with the MTB model are more advanced. The MTB model for Alpine Skiing is also more difficult to design, because numerous factors come into play that are not involved in the NW activity. For example the contact between the snow and the ski that is a controversial topic and still today in literature is an open problem. Also, the lack of information regarding the equations of motions used to simulate the movements can be a problem to an optimal realization of this model. Although these first results obtained offer an optimistic prospective in this innovative fields of the monitoring of sport motion. A MTB model helps to estimate mechanical quantities, like forces and torques, acting on the main joints of the human body as a consequence of performing specific movements. The developed models were designed parametrizing both the humanoid model and the sport equipment to be adapted for different types of users. Moreover, this work proposes some mathematical parametric representations of the kinematic laws of the main joints of the human body during NW and Alpine Skiing. The parametric laws used in this work were obtained from measurements available in the literature. However, they can fit new experimental data to easily implement these motions inside a numerical simulation. The obtained numerical model was compared with measured experimental data to validate trends and representative values of the quantities. The models showed good agreement in terms of pole forces, pole angle and different angle during ski run. Thus, the MTB model showed overall good results in representing the NW and a first approximation for the Alpine Skiing technique in a simulation environment. Future works will consider for the Nordic Walking project the analysis of the same quantities on different ground conditions to understand their effects on the amount of force required to accomplish certain types of movements. Instead for the Alpine Skiing project the main work will be focus on the optimization of the model already presented in order to have a better representation of the reality. Moreover, also the experimental test will be revised, in order to have a better set of experimental results. Especially it is necessary to constrain the slope with some poles to have a better comparison in terms of curves between the testers.

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