TalentPLAYERS

TECHNICAL BOOKLET

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Collection of technical notes describing the technology behind TalentPlayers Tracking Devices and their performances under rigorous scientific tests.

Sport Performance Tracking: GPS vs Inertial Sensors

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Introduction

Sport performance tracking has gained a lot of interest and a great diffusion in recent years, especially in elite and sub-elite sport. The aim of performance tracking is to asses quantitatively the athlete's performance during training or matches and to choose and optimise the training strategy. This allows to increase the effectiveness of training, to calibrate and equalise workloads based on real energy expenditure, and to reduce the probability of injures due excessive physical stresses [1][2].

Today, top level professional clubs in different sports (e.g. Football, Rugby, etc.) routinely employs performance tracking technologies, acquiring parameter such as position, speed, distance, accelerations and change of directions of each athlete [3]. Starting from these data, other relevant information can be calculated a posteriori (i.e. after the session), such as metabolic load [4], speed/acceleration thresholds, change of directions, sprints, total distance, etc.

In past years a lot of experience has been done with GPS based performance trackers (note: the term "GPS" used in this paper also refers to other satellite positioning systems such as Galileo, GLONASS, Beidou, etc., that have similar characteristics in this context). This technology has proved to be a straightforward and effective way of acquiring and measuring relevant data from players [5][6].

In recent years however, the availability of miniaturised and accurate inertial sensors (namely accelerometers and gyroscopes) greatly extended the possibility of monitoring sport performances, making possible alternative and even more advanced approaches [7][8].

Next sections will explain the difference between the two technologies, highlighting possibilities, limitations, as well as pros and cons of each approach.

Understanding GPS technology

The GPS system is designed to provide the exact position of a receiving device on the surface of the planet. This position is calculated by solving very complex equations based on the timing of reception of signals sent from a satellite constellation. This calculation is done repeatedly, providing a new position at regular frequency. This allows also to track the movement of the receiver. Traditional GPS receiver provided just 1 position update per second (1 Hz), more recent devices allow much faster data rates (greater than 20 Hz) [9].

The receives also calculate its speed over ground and its heading direction. These data are particularly relevant in sports tracking applications. Both speed and heading are however obtained indirectly from the position data and satellites speeds. Other important information, such as acceleration and change of directions, are not calculated by the GPS at all, instead they are derived *a posteriori* starting from available data.

The accuracy of data provided by GPS is very difficult to predict and assess, since it is influenced by a large number factors. These include the number of visible satellites at a given time, their relative position, weather conditions, solid obstacles occluding the sky or reflecting the signals (creating the so-called multipath effect), and so on.

Even if the theoretical GPS error is well below 1 m, in real conditions errors in the order of 1.5 m to 3 m for each position point can be expected.

In some application, the error can be greatly reduced by averaging the data over time. Of course, this cannot be done in sports tracking applications where, on the contrary, data points are desired at the highest possible rate in order to closely track athlete's performance. Sports tracking is so a very challenging application for GPS technology, resulting in errors that are generally larger than in other applications. This problem is even worsened when considering derived data (total distance, accelerations, change of directions, metabolic load, etc.), where these errors can be even amplified. The above-mentioned adverse effects can be somewhat contained by using faster data rate GPS. However, errors in the order of 3-5% can be expected in any cases either in distance and in speed estimation [10][11].

Fast GPS receivers are also desirable to better track the fast motions of an athlete during its performance. It is worth to note in fact that, in just 1 second, an athlete (especially in elite or sub-elite sports), may change its position by more than 5 m, also making changes in speed and directions. Slow GPS tracker will miss most of these features, providing big errors either in speed and trajectory. Figure 1 illustrates this situation.

In recent years the awareness of these limitations pushed for the adoption of higher frequency GPS receivers for sport tracking.

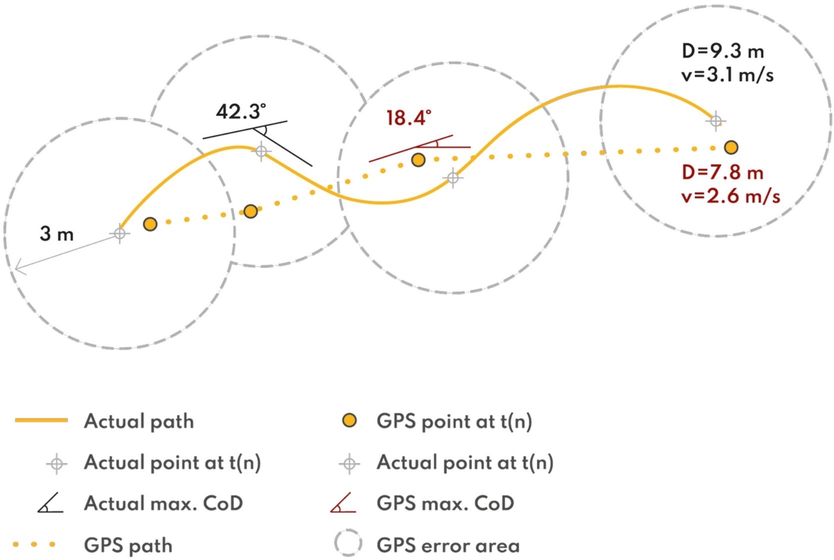

Figure 1 – GPS data obtained simulating an athlete running at 3.1 m/s (average) along a winding path (the drawing is at scale). As it can be seen, by using a GPS with a data rate of 1 Hz and a maximum position error of 3 m, significant errors can be expected in speed, distance and change of directions (CoD). These errors are stochastic in nature, so cannot be predicted nor compensated. GPS with faster data rate (>10Hz) are needed to limit these inaccuracies.

How fast a GPS receiver can be?

The GPS signals transmitted by the satellites have a bit rate of 50 Hz. The timing signals, used for calculating the position are obtained in the bit detection process (by performing a cross-correlation). This means that it will be extremely difficult, if not impossible, to achieve an output data rate greater than 50 Hz for a GPS receiver. Moreover, a correlation with few bits imply a very noisy signal, so the resulting position data will be affected by larger errors.

Usually the timing derived from a number of bits are averaged to reduce these errors, this process however takes some time and so reduce the final data rate. The same considerations apply for the speed estimation: a faster update will be characterised by larger noise (either if speed is derived from position or from satellite signal Doppler shift). These limitations are intrinsic to the physics of the systems, does not depend on the quality of the receiver.

According to some authors [11], the best trade-off between data rate and accuracy is achieved at about 20 Hz. It must be noted however that commercial GPS receivers usually employ some kind of filtering or averaging process to reduce errors and noise (low pass, Kalman filter, data fusion, etc.). This allows to achieve higher data rate, but resulting data is somewhat interpolated rather than measured [12].

In spite of these considerations, it can be foreseen that the availability of higher data rate GPS tracker will increase in the next few years, and their costs will decrease. The real accuracy however, with good probability, will not increase much.

GPS trackers limitations

GPS sports trackers are valuable tools in sport performance tracking. They are easy to use, widely available and quite effective in most situations. There is also a lot of shared experience in their use, either as practical knowledge as well as scientific background.

However, as previously seen, they have some characteristic drawbacks, that limit their usage or the quality of results. There are:

Outdoor use only: the GPS satellite signal cannot penetrate solid barriers, so GPS tracker cannot be used indoor, only outdoor sports can benefit from this technology;

Waiting for the fix: GPS receivers need a certain time at start-up in order to find and synchronise with the satellites. This time is unpredictable and can be as high as 20 minutes (in case of cold start). Without a proper fix, GPS data is unreliable;

Power consumptions: due to their complexity, GPS receivers (especially higher data rate models) require high electrical power. This means that tracker batteries are usually bulky (big and heavy) compared to other wearable technologies;

GPS trackers dimensions: due to the need of large batteries, quite large antennas, and robust enclosures, trackers dimensions are not negligible, so positioning and stabilising the devices on the athlete's body may be an issue;

Lack of direct physical measurements: data provided by GPS are somewhat unrelated to athlete's actual motion patterns, in particular to finer/faster movements. Moreover, some important parameters (such as acceleration or change of directions) are only indirectly evaluated, not measured. This limit has been addressed by integrating inertial sensors in some GPS tracker, but the affectivity of this approach is limited by the constraints in positioning the tracker on the athlete's body;

They cannot be used during competitive matches: many sport federations forbid the use of GPS trackers during official competitive matches. This limitation is intended to prevent injures due to the mass and volume of the worn devices. This does not allow to collect critical data during important events;

High costs: best in class GPS trackers (particularly >20 Hz models) are currently very expensive. This can be a limiting factor in team sports, where a kit of 10-20 units have to be purchased.

Discovering wearable inertial sensors

Inertial sensors are wearable units employing very small electronic devices (Micor-ElectroMechanical Systems, MEMS) able to sense linear and angular forces related to motion. In particular, accelerometers are able to sense accelerations and gravity force, while gyroscopes are used to measure speed of rotations.

MEMS inertial sensors (sometime referred to as Inertial Measurement Units, IMU) can acquire the movement of a single physical point with 6 Degree of Freedom (3 are related to translation, 3 to rotation), with a very high sampling frequency (from few tens of Hz up to some KHz). This allow to precisely track and measure every possible movement of a physical point in time.

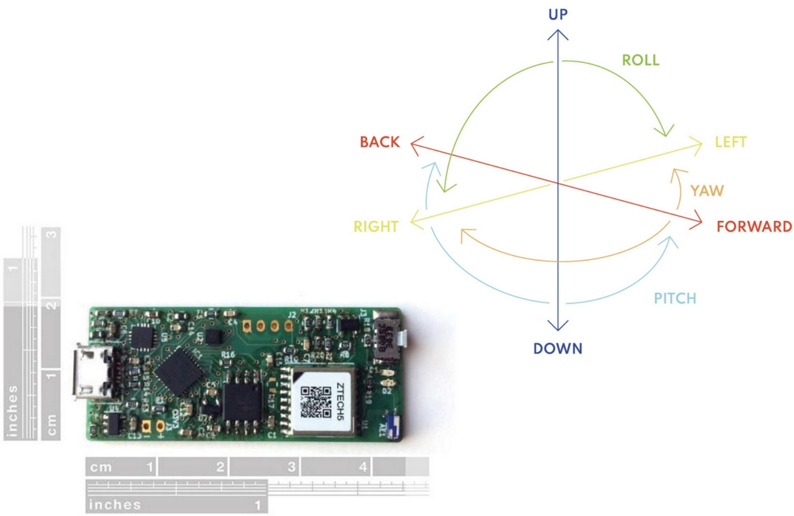

Figure 2 – A 6 Degree of Freedom (6DoF) inertial sensor is able to acquire linear accelerations along 3 axes (Up-Down, Front-Back, Right-Left) and angular velocity around the same 3 axes (Yaw, Roll, Pitch). These data allows to precisely track the movement and the rotation of a point in three-dimensional space. Image on the left shows the TalentPlayer dev 1.0 circuit, an inertial sensor with integrated GPS unit.

The application of inertial sensors in sport performance tracking is relatively new compared to GPS. This is due not only to their more recent availability, but also to the huge and diversified possibilities they offer. A comprehensive and interesting review of their use can be found in [13][14].
Due to their characteristics, namely small dimensions and very high data rate, inertial sensors can be used in many sport applications to provide important insight about temporal (minimum/maximum values, time of movements, durations, etc.), kinematic (movements, orientation, displacements, etc.) and dynamic (speed, accelerations, etc.) parameters of actions. This opened to entire new fields of scientific research, recording a fast-growing number of publications every year.
One key point to note is that inertial sensors can be used not only for tracking global performances, but they also allow to analyse in detail athlete motion patterns to correct or improve their technique and to diagnose or prevent injuries. So their applications and usefulness go far beyond the ones of GPS trackers.

Inertial sensor placement

Since inertial sensors are very small and lightweight, they can be easily placed in any part of athlete's body (from shoelaces to ear/hair), without hindering its movement. The device will track and analyse the motion of that specific part of the body during physical performance. The choice of the location is essential to obtain the desired information.
In golf, for example, a good location to place the sensor is the back of the leading hand: this will provide valuable information about the swing (timing, speed, plane, rotations, etc.). Placing the sensor on the leading foot would not provide any useful insight.
Sports involving running will benefit from placing the sensor on the lower body, so it will be possible to track more accurately the motion dynamics and energy expenditure. Placing the sensor in the upper body will provide only partial or global information.
In sports like football, where feet and lower leg dynamics are of chief importance, it is desirable that sensors would be placed in the lower limbs (foot, ankle, shin).

A number of scientific papers have been published on best sensor placement, especially with reference to gait analysis during walking and running or to specific sports [14][15].

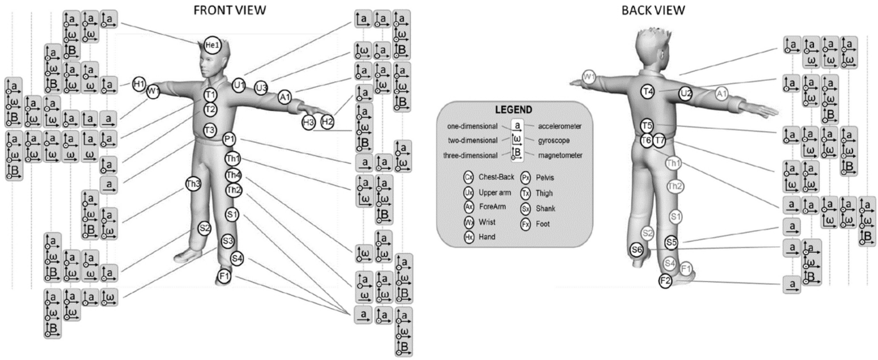

Figure 3 – Possible placement of inertial sensors on the athlete's body, as reviewed in [14]. The optimal position is determined by the specific motion that has to be analysed, by its features and by employed algorithms.

Algorithms make the difference

The algorithms employed for processing inertial sensor data must be considered an important part of the system. The final quality of data in fact relies more on the algorithms than in the sensor itself. This is due to the fact the relevant information has to be extracted from a large amount of raw data. Every single parameter that has to be measured requires a dedicated algorithm. Also, these are strictly dependent from the body position of the sensor.

In general, algorithms employ a physical model of the part of the body where the sensor is attached. This model uses acceleration and angular velocity acquired by the sensor and behaves just like its physical equivalent, but providing all internal variables.

An alternative approach involves the use of pattern recognition and Artificial Intelligence (AI) algorithms. These are often used for motion identification, classification and segmentation (e.g. video auto-tagging) features.

Due to this huge variety of scenarios, it is not possible to find on the market a "general purpose" inertial sensor tracker. Instead, specific solutions exist dedicated to specific applications and sports. The features and performances of these products may vary a lot, because they usually employ different design choices (placement, algorithms, parameters, etc.). For this reason, attention must be paid on the evaluation and benchmarking of a product before adoption. This will be particularly important in the near future, when the commercial offer will increase due to the growing interest in this kind of solutions.

Assessing the performance of inertial sensors

As previously explained, it is almost impossible to draw generic performance metrics for inertial sensors because of the huge range of applications and setups.

For sure, one important figure to consider is the sampling rate. Most inertial sensors sample data (accelerations and angular speeds) at about 100 Hz, i.e. each second 3x100 accelerations and 3x100 angular velocities are acquired. Higher sampling rate are possible (up to some KHz), but since human motions have a bandwidth lower than about 20 Hz, it is not convenient to employ higher sampling frequencies. Data resolution generally is in the range of 12 to 16 bit, allowing very good dynamic performance and a resolution of less than 1 mg of acceleration and some tens of mdeg/s (millidegree per second) for angular velocity.

For the most common applications, a lot of scientific literature exists describing typical achievable performance, accuracy and evaluation procedures. These applications include mainly the measurement of walking and running speed and acceleration, total distance covered and change of directions. These are the same basic quantities usually provided by GPS trackers. So, apart from the substantial underlying differences, a rough comparison between the two technologies can be done. By considering references [15][16][17][18], it can be concluded that, across a variety of different designs, inertial sensors can achieve an average error in the range of 1% to 5% either in measured distance and speed. Older references report larger errors due to the use of old analog inertial sensors and less advanced algorithms. More recent references tend to settle around 1-3% for distances in the range of few km and speed ranging from 1 to 17 km/h.

As it can be noted, this accuracy is quite good, comparable or even better than the one achievable with GPS trackers [10][11].

Figure 4 shows a direct comparison between a GPS and an inertial sensor tracker during a short training session. An athlete ran at variable speed a rectangular track long 320 m (considering linear trajectory only). Two laps were run: the first lap at constant speed, the second performing two short sprints.
The data was obtained by using simultaneously the Runtastic app with a GPS fitness tracker and TalentPlayer v1.0 inertial tracker fixed to the athlete's right shin. The GPS tracker was activated 5 minute before the run (warm start), in order to get a good fix. TalentPlayer tracker measured speed and distance by using an integration algorithm with the zero velocity update technique [15].

As it can be seen, the inertial sensor was noticeably more precise on measuring the covered distance than the GPS. The inertial sensor also provided a much more detailed speed profile compared to the GPS. The acquired speed was quite similar.

The athlete's path was provided only by the GPS tracker, since inertial sensors are generally not suitable to acquire the absolute position, as commonly done with GPS. Even if this is theoretically possible, the results would be affected by significant errors.
It has to be noted however that the GPS track is not very precise, having significant deviation from the actual athlete's path (that was more linear and repeatable over the two laps). This explains the erroneously longer distance measured by the GPS tracker.

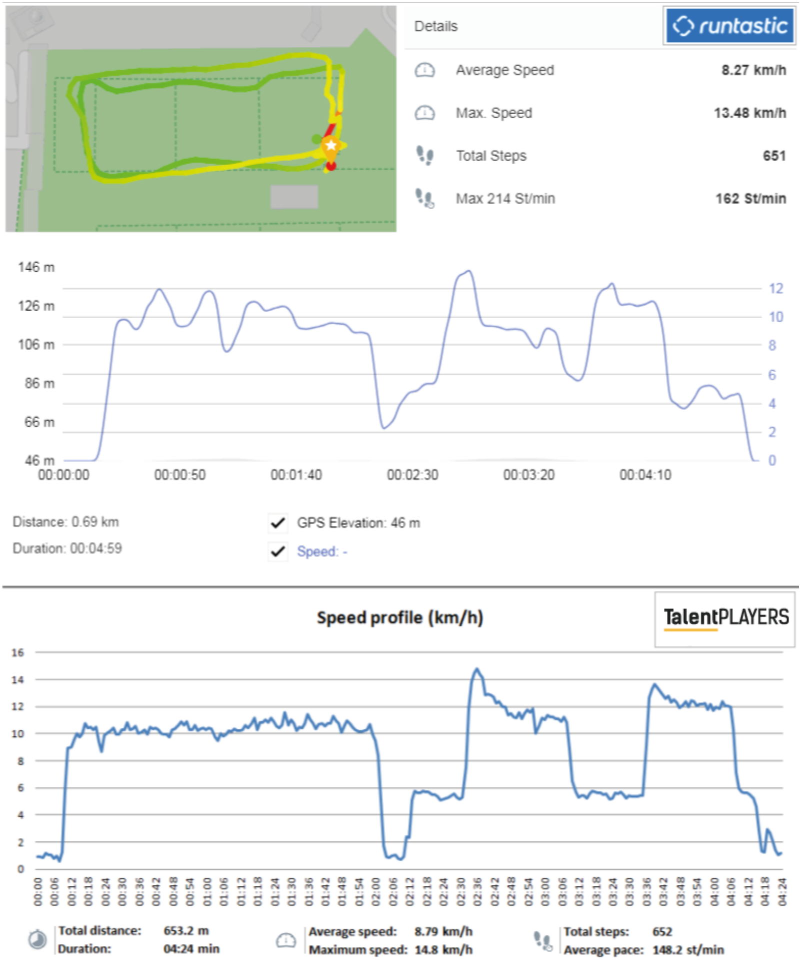

Figure 4 – Field comparison between a GPS tracker (based on Runtastic app) and an inertial sensor tracker (TalentPlayer dev 1.0). Results are comparable, but the distance measured by the inertial tracker was more accurate: 653.2m against a reference distance of 2x320 m + some extra due to slightly rounded trajectories. The GPS tracker measured 690 m (0.69 km). The speed profile provided by inertial sensor is much more defined compared to the GPS one, especially during fast changes in speed: this allow a more accurate evaluation of the sprint dynamics.

Inertial sensors pros and cons
As a general rule, inertial sensors allow to obtain almost the same information of GPS trackers, except for the position. The accuracy of data is in many cases comparable. On the other side, inertial sensors can provide a number of advanced parameters and specific insights that are impossible to obtain with GPS trackers. Some distinctive features of inertial sensors are summarised in the following points:

They can be used everywhere: compared to GPS trackers, inertial sensor trackers can be used in every location, namely indoor, on cluttered environments (i.e. with high building density) and even underwater;

They can suit every sport: by choosing the specific sensor placement and algorithms, whatever performance figure can be tracked and analysed;

They can provide very deep insights: inertial sensor can provide not only macroscopic and general figures (such as speed or energy consumption), but also very detailed technical information on specific movements, e.g. balance between feet or ground contact time in running, kick power, jump height and explosiveness in football, etc.;

Easy to wear: due to their light weight, wearing inertial sensor trackers is usually simple and does not hinder the athlete movements;

Easy to couple with AI and machine learning: since data provided by inertial sensor is very rich in features, AI techniques can be used to extract relevant information about athlete achievable performance and condition, and even to forecast its maximum capabilities;

Useful in injure prevention and detection: inertial sensor can be used to monitor mechanical stress on specific points of athlete's body, falls or shocks. This can provide precise information on the probability of injures to bones, muscle, joints;

Easy to integrate with wireless devices and cloud technologies: the most advanced inertial sensor trackers are able to process data in real time feedback to coaches by means of a wireless connection with a mobile device (smartphone or tablet) or a web platform (cloud).

Detect absolute orientation: all inertial sensors detect gravity force: this provide a reference for orientation. Sometime magnetometers are also used to get geographical orientation (tracking the Earth magnetic field, as done by compasses). This can be used situations needing contextual awareness;

Not very suitable for position tracking: contrary to GPS trackers, inertial sensors are currently not very precise for position tracking. However, this is a very active research area (it is for example relevant to indoor positioning) and many progresses are continuously done. Probably in the near future a number of viable technique will be available.

Conclusions

Inertial sensor technology is a very new paradigm in sport performance tracking. It greatly expands the possibility allowed by traditional GPS trackers and it is certainly attracting a lot of attentions and interest. The possibility of obtaining detailed information on the technical aspects of the athletic performances is one of the most interesting factor. The other relevant possibility is related to injuries prediction and prevention. A lot of scientific research exists on these topics but, up to date, very few commercial products that effectively implements these findings are available.

It can be foreseen however that the demand for this technology will widely increase in the next few years, along with the awareness and confidence in using it. This trend will also be backed by the fact that inertial sensor trackers will be generally less expensive than high speed GPS trackers.

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Performance Assessment of the TalentPlayer Inertial Tracking Technology

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Introduction

In recent years the use of sport tracking technologies has become very common, especially in elite sports. It allows to evaluate the volume and intensity of athletes' physical effort and provides useful insights to enhance training sessions effectiveness. Most tracking solutions currently available on the market are based on GPS technology. They allow to track athlete position, speed, direction and to compute many other figures, usually related to energy expense and metabolic power.

GPS technology has however some drawbacks: devices can only be used outdoor and their performances depend on sky visibility; they tend to be bulky due to the large batteries required to power the receiver; and if high quality data (i.e. affected by lower errors) is desired, expensive high-end solutions have to be used. To overcome all these issues, **TalentPlayer has developed a new technology entirely based on inertial sensors**. This technology provides **the same information of high-quality GPS trackers**, with a number of advantages: motion is directly measured instead of being computed, devices are smaller and lighter, they **can also be used during indoor sessions,** and **they are considerably cheaper than high-end GPS trackers**, yet providing similar performances.

However, since inertial trackers are a very new technology, it is important to thoroughly assess their performances.
The aim of this paper is to test the TalentPlayer inertial tracker and to evaluate its performances, by using direct measurements and methods recommended by the International Federation of Association Football (FIFA), that has recently issued a standard for evaluating Electronic Performance and Tracking Systems (EPTS) performances [1].
The tests confirm that **TPDev devices performances match those of high-quality GPS** in terms of errors on speed and distance.

TPDev inertial tracking device

The TPDev inertial tracker is a small wearable electronic device (Fig. 1) integrating a 6 degree-of-freedom MEMS inertial sensor, able to provide acceleration and rotational data along the 3 axes. It is designed to be worn on the lower leg, by means of an elastic band or a specifically designed shin guard, and it can acquire **acceleration and rotation data** with a rate of **600 samples per second**. Data is analysed in real-time by the device, using proprietary mathematical models taking into account the cinematic, dynamic and energetic features of the motion. This allows to obtain the **instantaneous athlete's speed, acceleration, distance and change of directions, and to derive the most common metabolic figures**. Acquired data are stored in the device memory and can be downloaded by a smartphone or tablet via Bluetooth. Data can be browsed immediately on the mobile device, or can be uploaded in the TalentPlayer web platform for storage and subsequent analysis.

The TPDev device is very small and lightweight, so it can be worn easily and without interference with the athlete's motion. The **battery and memory allow up to 4 hour of data acquisition**.

Figure 1 – The TPDev tracking device, the elastic band and the shin guard for wearing it, and a screenshot of the web platform.

Testing methodology

Tests performed were aimed at assessing the TPDev accuracy (errors) in speed and distance. Errors on distance were measured directly, while errors on speed were evaluated by following the methodology described in the FIFA standard [1]. FIFA methodology consists in using video motion analysis as a reference and comparing the speed data obtained by the tracker under test with data from the video. Data time series are firstly resampled at the same rate, then aligned by evaluating the cross correlation. Finally, the sample-to-sample difference is taken, and the error distribution is drawn.

Our tests were carried out on a 100.0 m linear track that was accurately measured by means of a measuring tape and checked against other references (maps, GPS). The length was found to be correct within few centimetres (i.e. 10^{-2} m, or 0.01%). Two athletes were enrolled and instructed to run and walk the entire track length. Subjects had an age ranging from 30 to 40 and a height ranging from 1.70 m to 1.85 m. The runs were recorded with a high-speed camera, acquiring High Definition video (1920 x 1080 pixels) at 100 frames per second, and positioned in the mid-point, at about 90° with respect to the track (see a frame in Fig. 2).

The TPDev was attached to the athlete's lower shank by means of an elastic band. A total of 4 runs and 3 walks where performed and recorded. The TPDev and the camera acquired independently and simultaneously these runs.

Video recordings were analysed by using the Kinovea motion analysis software [2][3] in order to extract instantaneous speed data.

Figure 2 – A frame of the recorded video showing the measuring grid, the speed trajectory and the athlete while running (yellow circle).

The data series from the TPDev and the camera were then resampled at 10 Hz (10 samples per second), aligned by using the cross correlation, and subtracted in order to get the error. In addition to this, for each run, the overall error on the track length obtained by the TPDev, was directly calculated comparing the run distance provided by the device with the known track length (100.0 m).

Results

Speed data acquired by the TPDev is shown in Fig. 3. The four runs and three walk sequences can be clearly distinguished. Peak speed ranged from 6.45 m/s (23.2 km/h) of the fastest run to 2.11 m/s (7.59 km/h) of the slowest walk. The distance provided by the device for each run can be directly compared to the ground truth (i.e. 100.0 m), and so the absolute and relative error can be directly calculated, as shown in Table 1.

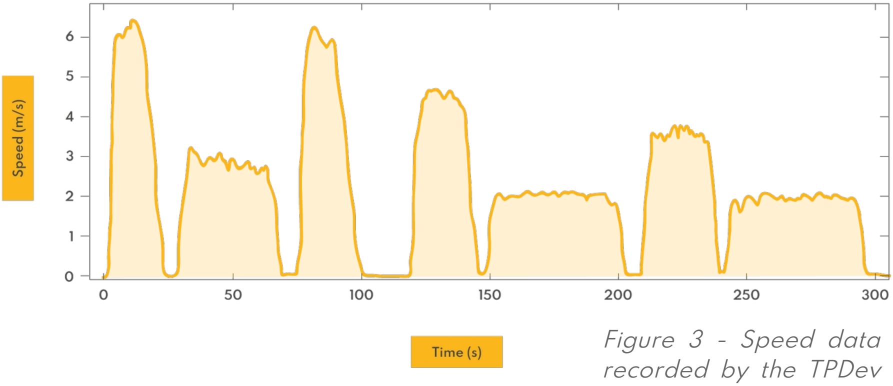

Figure 3 - Speed data recorded by the TPDev for the 7 test runs.

As it can be seen, the maximum error is 2.61 m (or 2.61%), while the average error over all runs is -0.66 m (or -0.66%).
Figure 4 shows instead the comparison of speed data from the video analysis and the TPDev device, both resampled at 10 Hz.

DISTANCE ERROR				
NAME	TPDev dist. (m)	Ref. Dist.	Error (m)	Error (%)
Run 1A	102.11	100.0	2.11	-2.11
Walk 1A	101.52	100.0	1.52	-1.52
Run 2A	101.79	100.0	1.79	-1.79
Run 1B	99.02	100.0	-0.98	0.98
Walk 1B	100.83	100.0	0.83	-0.83
Run 2B	97.39	100.0	-2.61	2.61
Walk 2B	101.96	100.0	1.96	-1.96
			Average err.	**-0.66**

Table 1 - Evaluation of the TPDev error on distance.

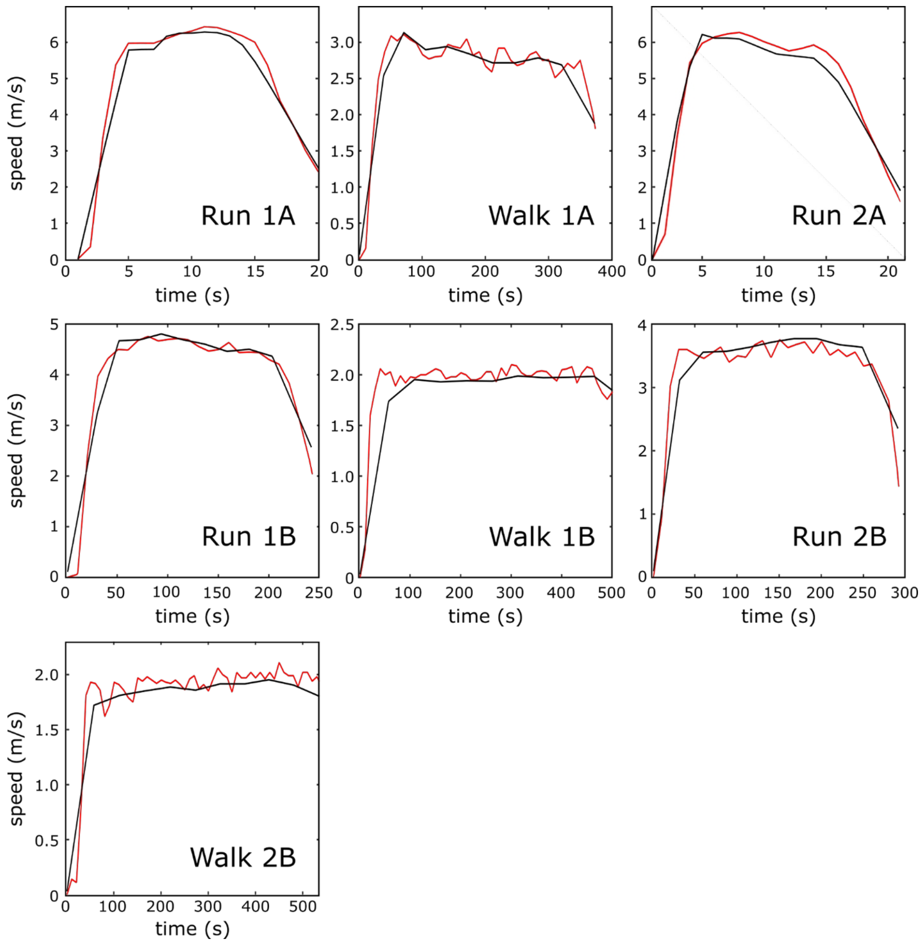

Figure 4 – Comparison of speed data obtained by the TPDev (red line) and the video analysis (black line) for the 7 test runs. Speed unit is m/s (vertical axis), time unit is seconds (horizontal axis).

The cumulative error distribution for **2383 data points**, drawn as described in the FIFA standard, gives the result shown in Figure 5. This plot shows an **average error of 0.038 m/s** with a 95% confidence level of 0.01 m/s and a standard deviation of 0.25 m/s.

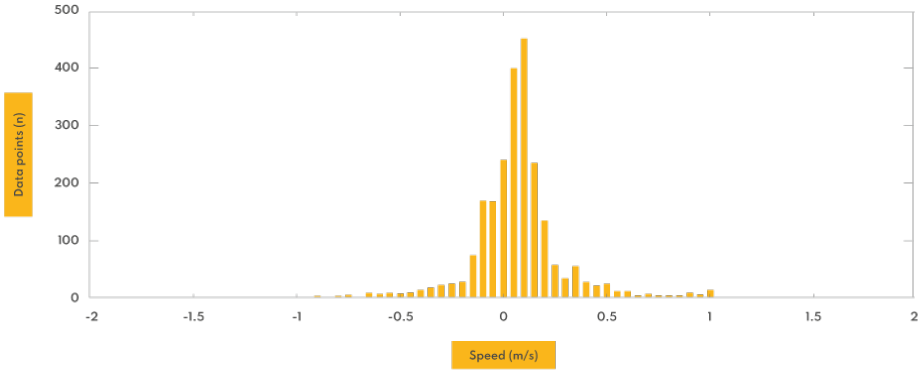

Figure 5 – Speed cumulative error histogram of the TPDev for the 7 test runs.

Discussion

Performed tests show that the TPDev inertial tracker featured a maximum absolute error of 2.6 m (2.6%) in distance measurement, with an average error of 0.66 m across various runs. This result can be considered quite good, as it is comparable to the one obtained with good quality GPS trackers, that usually features errors in the order of 3 m (strongly dependent on the environmental conditions and satellites fix status) [4]. Also, the errors in the speed measurement (0.038 ± 0.01 m/s) is comparable to most high-end GPS trackers tested and qualified by FIFA [5][6].

Conclusions

The TPDev inertial tracker has been tested to assess the quality and reliability of its data. A direct methodology was used to evaluate the error on distance and a standard methodology, proposed by FIFA and based on video motion analysis, was employed to evaluate the error on speed measurement. Results show that errors are below 3% (below 1% on average) for distance and below 1% for speed. These errors are comparable with high end GPS trackers. The TPDev tracker however keeps some advantages on GPS technology, namely the possibility of being used indoor, the smaller and lighter form factor and the lower cost. This makes TPDev a very convenient technology to use, in alternative or in addition to traditional GPS or video trackers.

References

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TalentPlayers Change of Direction Tracking Performance

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Introduction

The TalentPlayers inertial tracking technology is based on different working principles compared to common GPS trackers, but it can provide the same parameters, with the same or even better accuracy as discussed in [1] and [2]. Independently from the specific technologies, it is quite easy to assess the accuracy of a tracker on distance, speed and metabolic output. However, testing or comparing the accuracy on Change of Directions (CoD) can be quite a challenging task. This is due to the rather qualitative definition of "Change of Direction" and the difference in data reporting among the most common commercial trackers.

Figure 1 – The TPDev tracking device, the elastic band and the shin guard for wearing it, and a screenshot of the web platform.

While distance, speed, accelerations, metabolic power or energy are well defined scalar quantities, that can be precisely measured (and compared with references), CoDs even lack of a detailed and standard definition. Up to date there are no standard to tests CoD tracking performance in scientific literature or in industrial practice, and this issue is also not addressed by the FIFA testing standard for wearable tracker devices [3][4][5].

From a purely geometric point of view, a CoD is an angular deviation of the trajectory. This is a very simple quantitative definition and can be used as a starting point to evaluate tracker ability to accurately measure CoDs. However, this definition does not characterize the performance of an athlete and the related physical stress during a match or training session. In order to obtain this meaningful information, the deviation angle must also be correlated with speed, acceleration, duration of the rotational motion and cumulative imbalance between right and left deviations. This is important also because the trajectory raw data *per se* is very "noisy" and difficult to read.

The TalentPlayers technology provides both these levels of information: TPDev trackers continuously record the change in heading angle of the athlete's motion, while the TalentPlayer Web Platform correlates this information with other parameters in order to extract only the most relevant athletic information. The advantage of this approach is that the complete raw data is captured during motion, but the relevant meaningful information is extracted subsequently (*a posteriori*).
These are some of the basic parameters provided by the Web Platform:

- Number of right CoDs >30°
- Number of left CoDs >30°
- Maximum right angle
- Maximum left angle
- Average right angle
- Average left angle
- Total imbalance

During the data processing phase, deviation of the trajectory is considered a meaningful CoD if the rotation angle is greater than 15°, the instantaneous athlete speed is greater than 2 m/s and the rotation is completed in less than 2 seconds. These parameters represent a quite optimal definition of meaningful CoD, however they are configurable if desired.
Maximum and average data are computed over the continuous raw data, not from single extracted CoDs, so they are very representative of the entire athlete's rotational movements (from which, for example, accurate imbalance stress can be calculated).
Since the processing parameters can be easily modified and finetuned *a posteriori*, this document will focus on the characterization of the tracking device itself, in terms of resolution, accuracy and repeatability.

TPDev CoD performance test

The following test was designed in order to evaluate the resolution, accuracy and repeatability of the angle measurement provided by the TPDev.
Two subjects worn the TPDev tracker at their lower dominant leg by means of an elastic band. The subjects run at jogging speed a track composed by 3 segments in forward and back direction, as shown in Fig. 2.

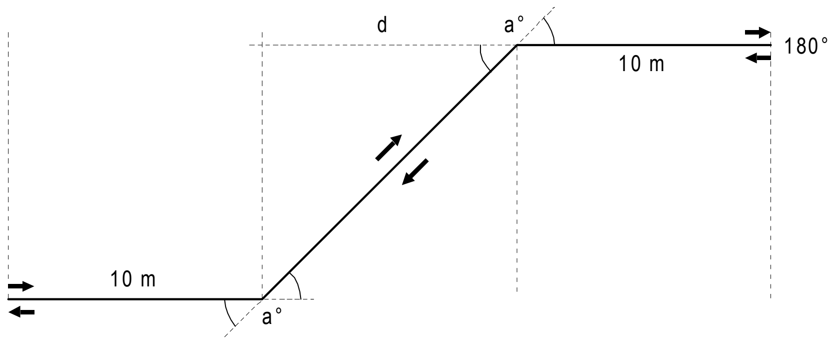

Figure 2 –Track schematic, composed by 3 segments forming 2 equal angles depending on the distance d and a 180° turn at the end.

The central segment was set at different angles during the test in order to measure smaller angles (14°) as well much greater angles (90°). Moreover, a 180° turn is performed at the end of the track in order to return back to the starting point. A complete run so implies:

- 10 m of straight trajectory
- Turn to left by a given angle
- Turn to right by the same angle
- 10 m of straight trajectory
- A 180° turn
- Turn to left by a given angle
- Turn to right by the same angle
- 10 m of straight trajectory (to starting point)

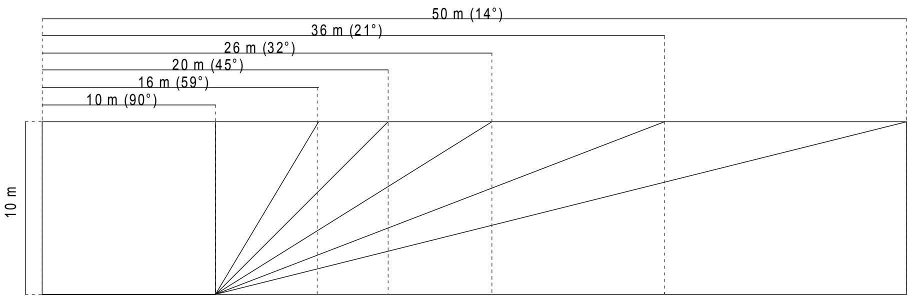

Figure 3 – Tested angles and how to geometrically obtain them by setting the distance of the second turning point. The angle is given by a = tan^{-1}(10/(d-10)), where a in the angle and d is the distance of the second turning point.

A complete run of the track provides measurements of CoD angles two times toward left and two times toward right. Test angles were chosen starting from very small (14°) so to test the device sensitivity (resolution), while various angles steps (up to 90°) where chosen to characterize its accuracy. The repetitions allow to characterize the repeatability. Figure 3 shows the construction of the track, that can be done by fixing one turning point and moving the second at the specified distance.

It must be noted that, in spite of the simplicity of this setup and test, some execution error has to be expected that adds to the result. These are due either to measurement and alignment errors on the track, either in the test execution by the athlete, that cannot perform geometrically sharp CoD and usually tends to approximate them with small arcs. Moreover, the smallest is the angle, the later the athlete will notice any error and correct its trajectory. Smaller angles also are more affected by small random movements that acts as noise with respect to the measured quantity.

Results

Figure 4 shows, as an example, the raw data acquired from one subject during the test. This is the actual data recorded by the device, that is subsequently processed by the Web Platform. As it can be seen, the trajectory raw data is very rich of information but quite difficult to interpret, so the processing step is very useful to extract only relevant CoD data.

Test results are summarized in Table 1.

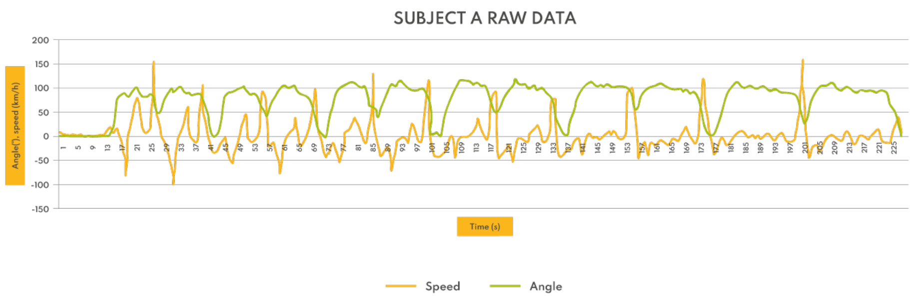

Figure 4 – Raw data of the subject A test. It can be noted that the average jogging speed was about 10 km/h (blue line), while CoD are recognizable as peaks in the trajectory curve (red line) decreasing in amplitude during the execution of the test (see Fig. 3).

The CoD angles of interest were extracted from the raw data of the two performed tests (for subject A and B) and then averaged in order to be compared with the reference and to evaluate the absolute error. This error also embeds all the systematic errors that have been previously discussed. Figure 5 graphically depicts the results: it can be easily recognized that the measured angles are in good agreement with the reference (designed) ones. Also, errors are quite small and only noticeable in the case of very small angles, where systematic errors have a bigger impact.

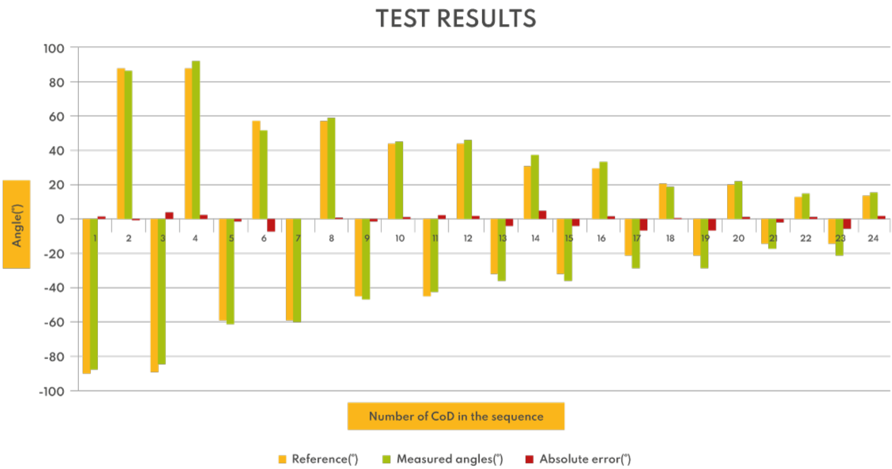

Figure 5 – Results of the test: comparison of the reference angle (blue bars) with the measured ones (red bars), and the absolute error (green bars).

Reference (°)	Subject A (°)	Subject B (°)	Tests average (°)	Absolute error (°)
-90	-83	-93	-88	2
90	99	79	89	-1
-90	-71	-99	-85	5
90	89	99	94	4
-59	-64	-58	-61	-2
59	53	53	53	-6
-59	-56	-63	-59.5	-0.5
59	61	58	59.5	0.5
-45	-47	-47	-47	-2
45	47	45	46	1
-45	-36	-48	-42	3
45	47	49	48	3
-32	-27	-44	-35.5	-3.5
32	39	37	38	6
-32	-30	-41	-35.5	-3.5
32	37	32	34.5	2.5
-21	-17	-39	-28	-7
21	25	16	20.5	-0.5
-21	-24	-32	-28	-7
21	23	21	22	1
-14	-18	-16	-17	-3
14	17	13	15	1
-14	-23	-18	-20.5	-6.5
14	18	16	17	3
			Average error	**-0.4375**

Table 1 – Numerical test results.

Conclusions

Performed tests show that the TPDev inertial tracker is able to accurately measure CoD angles with a single absolute error within few degrees and an averaged error over all the runs of about 0.43°. This last data is particularly meaningful, in fact single runs may present bigger errors due to varying conditions and execution difference with respect to the planned test, however these errors should neutralise by averaging over a number of executions. Either the single errors and the average are in any case very small and allow for a good quality tracking of the athlete activity. In particular, the very small average error implies that averaged data, that are used to compute imbalance for example, are very precise and reliable.

References

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ANNEX A

TalentPlayers Parameters List

This is a list of all parameters that can be currently obtained by TP Dev trackers. Further parameters can be calculated upon request.

PARAMETER	UNIT	EXPLANATION
Split start	s	Star time of recording or split
Split end	s	End time of recording or split. Note: End-Start = split duration in seconds
Speed and distance		
Totale distance	m	Total distance (comprising walk)
Distance per minute	m/min	Average distance travelled in a minute
Max. speed	km/h	Maximum speed
Ave. speed	km/h	Average speed
N. of accelerations	cnt	Number of accelerations > 2 m/s^2
N. of decelerations	cnt	Number of decelerations < -2 m/s^2
Total accelerated distance	m	Distance travelled with positive acceleration (i.e. with increasing speed)
Total decelerated distance	m	Distance travelled with negative acceleration (i.e. with decreasing speed)
High acceleration distance	m	Distance travelled at high acceleration (> 2 m/s^2)
High deceleration distance	m	Distance travelled at high deceleration (< -2 m/s^2)
Max. acceleration	m/s^2	Maximum acceleration
Ave. acceleration	m/s^2	Average acceleration
Max. deceleration	m/s^2	Maximum deceleration
Ave. deceleration	m/s^2	Average deceleration
N. of sprints	cnt	Number of sprint, i.e. run at > 20 km/h
Max. sprint speed	km/h	Maximum speed during sprints
Ave. sprint speed	km/h	Average speed during sprints
Max. sprint duration	s	Maximum duration of a sprint
Ave. sprint duration	s	Average duration of sprints
Time at <6km/h	s	Time spent in speed zone 1
Time at 6-11km/h	s	Time spent in speed zone 2
Time at 11-16km/h	s	Time spent in speed zone 3
Time at 16-20km/h	s	Time spent in speed zone 4
Time at >20km/h	s	Time spent in speed zone 5
Distance at <6km/h	m	Distance travelled in speed zone 1
Distance at 6-11km/h	m	Distance travelled in speed zone 2
Distance at 11-16km/h	m	Distance travelled in speed zone 3
Distance at 16-20km/h	m	Distance travelled in speed zone 4
Distance at >20km/h	m	Distance travelled in speed zone 5

PARAMETER	UNIT	EXPLANATION
Metabolic power		
PMetabolic power	W/kg	Total metabolic power (Di Prampero-Osgnach model)
Energy spent	kJ/kg	Total energy spent (Di Prampero-Osgnach model)
Equivalent distance	m	Equivalent distance (Di Prampero-Osgnach model)
Work ratio	%	Percentage of time spent at met. power > 5 kJ/kg
Time at P.met. <10	s	Time spent in metabolic power zone 1
Time at P.met. 10-20	s	Time spent in metabolic power zone 2
Time at P.met. 20-35	s	Time spent in metabolic power zone 3
Time at P.met. 35-55	s	Time spent in metabolic power zone 4
Time at P.met. >55	s	Time spent in metabolic power zone 5
Distance at P.met. <10	m	Distance travelled in metabolic power zone 1
Distance at P.met. 10-20	m	Distance travelled in metabolic power zone 2
Distance at P.met. 20-35	m	Distance travelled in metabolic power zone 3
Distance at P.met. 35-55	m	Distance travelled in metabolic power zone 4
Distance at P.met. >55	m	Distance travelled in metabolic power zone 5
Energy at P.met. <10	kJ/kg	Energy spent in metabolic power zone 1
Energy at P.met. 10-20	kJ/kg	Energy spent in metabolic power zone 2
Energy at P.met. 20-35	kJ/kg	Energy spent in metabolic power zone 3
Energy at P.met. 35-55	kJ/kg	Energy spent in metabolic power zone 4
Energy at P.met. >55	kJ/kg	Energy spent in metabolic power zone 5
Change of Directions		
Number of CoD to right	cnt	Number of change of directions to right >30˚, at speed > 2 m/s and during < 2 sec
Number of CoD to left	cnt	Number of change of directions to left >30˚, at speed > 2 m/s and during < 2 sec
Max. angle to right	degree	Maximum angle to right
Max. angle to left	degree	Maximum angle to left
Ave. angle to right	degree	Average angle to right (taking into account only angles >15˚)
Ave. angle to left	degree	Average angle to left (taking into account only angles >15˚)
Raw data		
Vel	m/s	Instantaneous speed samples
Acc	m/s^2	Instantaneous accelerations samples (if negative = deceleration)
Dir	degree	Trajectory angle samples (positive = right, negative = left)
Pmet	W/kg	Instantaneous metabolic power (according to Di Prampero-Osgnach model, with constants chosen for ball play on grass)

TalentPLAYERS

Talent IS NOT ENOUGH