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# Comparison of Different Motion Capture Setups for Gait Analysis

## Validation of spatio-temporal parameters estimation

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***Abstract*—Inertial measurement units (IMUs) are increasingly used in gait analysis because of their portability, low cost and long-distance measuring. The aim of this study focused on the comparison of 2 different inertial sensors setups and algorithms respect to a reference measure system for the estimation of gait spatio-temporal parameters. (a) A marker stereo photogrammetric system (Optitrack) was used as reference gold-standard. Two IMU setups were adopted for the comparison of different algorithms: (b) a single sensor positioned on the trunk, and (c) 2 sensors positioned on the heels. Three healthy subjects performed gait trials at 3 different self-selected speeds: (α) normal, (β) slower than normal, (γ) higher than normal. Data analysis considered signals that had been registered simultaneously by the three setup instrumentations. Among the IMUs signals, acceleration and angular velocity were considered and used for gait parameters estimation. Signal post-processing was performed through algorithms analyzing signals with respect to the local sensor axes, avoiding cumbersome pre-processing. The absolute errors among the spatio-temporal gait parameters obtained by the 3 setups were evaluated.**

**Overall, IMUs allowed an accurate parameters estimation, at all the performed velocities. A consistent correspondence was confirmed by the comparison of estimated spatio-temporal parameters. However, for most of them, the trunk configuration revealed smaller errors with respect to the heels configuration. This may be explained by a better identification of gait events guaranteed by the trunk IMU algorithm. The results demonstrated the suitability and accuracy of the trunk IMU setup and algorithm for the estimation of spatio-temporal parameters during gait. Besides, the trunk IMU setup requires the use of only one sensor instead of two.**

***Keywords—IMUs; stereo photogrammetric system; gait events; spatio-temporal parameters; validation***

## I. Introduction

Motion analysis has become a valuable test for the quantification of locomotion impairments, as well as in the assessment of activities of daily living. In particular, it has been used to investigate different situations, ranging from the analysis of changes caused by aging [1], to the description of orthopaedic [2, 3] and neurological [4, 5] pathologies, to evaluate the locomotion alterations due to obesity [6, 7] or even to assess sport performances [8-10].

In recent years, the use of Inertial Measurements Units (IMUs) constantly increased because of their low cost, compactness and portable characteristics [11-13]. IMUs-based systems had been verified both to assess spatio-temporal gait parameters and joint kinematics [6, 14]. Compared with traditional laboratory-based equipment, such as multi-camera motion capture or instrumented mats, inertial sensors allow to overcome limitations concerning the amount of recorded data and the lab constraints [15]. The possibility to measure gait trial outside the laboratory environment may avoid some technical drawbacks and it might allow an extended analysis of motion performance in various conditions and activities.

A variety of spatial and temporal parameters were identified to quantitative describe human gait [17-19]. The principal challenge in using inertial sensors is the development of a robust algorithm for gait events identification and for the compensation of drift errors due to the integration process [20, 21]. Several solutions [21-23] have been proposed for the positioning of sensors on specific human segments to obtain reliable signals, especially for the sensors on the feet. One other fundamental aspect is the variability of gait patterns between subjects and the alteration caused by pathologies. This requires accurate and repeatable methods and algorithms for the investigation of both healthy and pathological subjects. Based on IMU configurations, different strategies and approaches have been proposed for signal processing [18-19, 22]. Other crucial aspects are an operator-independent positioning of the sensors and a reduced time of preparation.

The focus of the present pilot study is the comparison of two different inertial sensors systems setups and algorithms for the estimation of spatio-temporal parameters [22, 24]. More specifically, (a) a stereo photogrammetric system was used as reference gold-standard. Two IMU setups, (b) a single sensor on the trunk and (c) 2 sensors on right and left heels respectively, were deployed. Results from IMU configurations were compared with the one obtained using the stereo photogrammetric system. Three young healthy subjects were tested at 3 different gait speeds. Differences in spatio-temporal gait parameters, obtained with the different setups, were evaluated, with the attempt to identify the best and more suitable IMUs configuration and algorithm between those considered.

## II. Materials and Methods

### A. Subjects

Three young healthy individuals (two females and one male, age: 26 ± 1 years, BMI: 22.0 ± 4.5 kg/m$^2$) participated in the study after giving their informed consent. None of them reported musculoskeletal, neurological or other gait diseases.

### B. Instruments

Mo-cap instrumentation included two Optitrack bars V120 Trio as the reference optoelectronic system, and 3 MTx Xsens inertial sensors (IMU).

*Optitrack.* Optoelectronic system configuration dealt with the combination of two V120 Trio Optitrack bars. Three cameras composed each tracking bar. The cameras detected infrared light and allowed obtaining spatial information of marker positions. The bars were self-contained and pre-calibrated. Each bar presented its local reference system centered in the middle of the instrument. The sampling frequency of 120 Hz was selected for both tools. Six passive reflective markers with a diameter of 14 mm were positioned bilaterally on selected anatomical landmarks of feet. In particular, as showed in Fig. 1A-B, markers were located on the lateral malleolus, on the toe and in correspondence of the heel. The software *Motive* enabled the data acquisition.

*IMUs.* Each IMU consists of tri-axial accelerometer, gyroscope and magnetometer. The magnetometer information were not considered for the present analysis. The inertial sensors sampling frequency was set at 50 Hz. Measurement range of the inertial sensors were set to ± 5G (corresponding to ± 49.03 m/s$^2$) for the accelerometer and ±1200 dps (corresponding to ±21 rad/s) for the gyroscope. Elastic bands were used to fix the sensor medially on the trunk, while the heel sensors were firmly secured with adhesive tape. Trunk and heel IMUs x-axes were oriented vertically downward, while z-axes were oriented in the opposite direction with respect to the gait motion. Positions and orientations of IMUs are reported in Fig. 1C. The MTx sensors were powered and were controlled by the Xbus Master. The Xbus Master sampled and sent synchronous digital data from the MTx units to the PC unit. The transmitted data were recorded by using the software *MT Manager*.

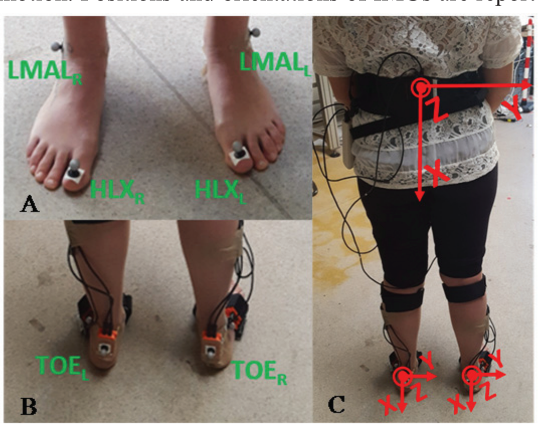


Fig. 1. A-B) Position and labeling of markers on anatomical landmarks of each foot. C) Position and orientation of 1 sensor on the trunk and 2 sensors on the heels.

### C. Protocol

Tests were conducted indoor, in a laboratory room. Spatial and temporal synchronizations were necessary in order to combine and compare data acquired with Optitrack and IMUs systems. For the spatial synchronization between the two Optitrack bars, three markers were positioned along the path and a static acquisition was performed before and after each recording session. For the temporal synchronization between Optitrack and IMUs system, the subject was required to impact the right heel on the floor before starting the gait performance. The impact entailed a spatial peak of heel marker vertical coordinate from Optitrack and a high peak of acceleration from the right heel IMU. Participants were requested to walk barefoot over a straight path of 6 meters (marked on the floor with a tape), at three different velocities: self-selected (α) normal, (β) slow and (γ) high speed.

Data acquisition was conducted simultaneously with the two different instrumentations, to register simultaneous signals and consider the same gait performance.

### D. Signal Processing and Data Analysis

Three markers were placed on the floor (2 aligned with the walking path and one outside), and their position was acquired during a static trial. The coordinates of the markers were combined to identify a Global Coordinate System (GCS). The X-axis of GCS was aligned with the direction of motion, while the Y-axis of GCS was assumed vertical with respect to the ground. Indeed, by means of rotational matrices, it was possible to move from the local frame of each camera bar to the GCS.

Only the central 3m of the 6m-path were visible from Optitrack system and hence only the corresponding steps were considered, even if the IMUs registered a larger number of steps. Different algorithms were used to determine the gait events from instrumentation setups.

*Optitrack algorithm.* Concerning video stereo-photogrammetric data, a custom analysis was developed to identify the gait events of initial and final foot contact.

Fig. 2A and 2B report the X and Y coordinate of the heel markers respectively. For the heel strikes (HS) estimation, we considered the time samples before the beginning of each plateau in the X-coordinate trajectory (marked with a blue square). All of these time instants were used as the central point of a local time window of ±8 frames. The selected time windows were reported along the Y-coordinate of the heel marker. The HS instants corresponded to the local minimum peaks of the coordinate Y inside each time interval. Fig. 2B depicts a graphic representation of HS instants, stressed by blue circles [24].

An analog method was adopted for the toe off (TO) estimation. Fig. 3A and 3B report the X and Y coordinate of the toe markers. First, the X-coordinate of the toe marker was considered (Fig. 3A). We identified the time samples before the slope change in the X-coordinate trajectory, depicted as blue triangles. All the time instants were used as the central point of a local time window of ±8 frames. The selected time windows were reported along the Y-coordinate of the toe marker. The minimum peak inside each time interval defined the TO instant. Fig. 3B reports the graphic representation of the minimum peaks and TO instants stressed by blue crossed marks [24].

*IMUs algorithm.* The signals of IMUs were used for gait events estimation. Both acceleration and angular velocity signals were used for the trunk-IMU configuration, while in the heel-IMU setup only the angular velocity was considered. To avoid noising interference, IMUs signals were filtered with a low pass 4th order Butterworth with a cut off frequency of 30 Hz.

For the IMU-trunk setup, the acceleration along the local z-axis allowed the identification of gait events. HS instants were selected as the local maximum peaks of the acceleration, while the TO instants as the minimum peaks [24]. The sign of the angular velocity along the local x-axis was used to discriminate right (negative sign) and left (positive sign) foot. Fig. 4 shows an example of the signals and the gait events calculation during gait performed at normal speed (α). HS and TO instants are stressed by circle and crossed marks respectively. Red color refers to the right foot, while the green one to the left foot. Vertical lines represent the HS instant (solid line) and TO instant (dashed line) obtained from the Optitrack system. These lines depict the gait events calculated with the gold standard method. The lines were used as comparison for the validation of gait events calculated with the IMU on the trunk.

For the IMU-heel setup, the angular velocity along local y-axis was considered from each sensor [22]. The first maximum peak was identified after each plateau with angular velocity closed to zero value. The corresponding times of these maximum peaks were assumed as the TO instants. HS instants were selected as the second maximum peaks. Fig. 5 shows an example of the signals and the gait events calculation during gait performed at normal speed (α). HS and TO instants are stressed by blue circle and black crossed marks respectively. Red color refers to the signal acquired from the right foot, while the green one to the signal acquired from the left foot. Vertical lines represent the HS instant (solid line) and TO instant (dashed line) obtained from the Optitrack system. These lines depict the gait events calculated with the gold standard method. The lines were used as comparison for the validation of gait events calculated with the IMU on the heels.

For each setup, the following spatio-temporal parameters were estimated: stride time, step time, stance time and duration, swing time and duration, single and double support time, single and double support duration, foot symmetry and limp index. Duration was expressed as a percentage of gait cycle (%GC). Foot symmetry was calculated as the ratio between step time and gait cycle, and the limp index as the ratio between right and left stance time [26].

For each subject, a total of 8 gait cycles were considered, both for normal and high velocity. At low velocity, the female subjects performed a total of 12 gait cycles, while the male subject performed a total of 8 gait cycles. Considering each speed separately, mean and standard deviation values were estimated intra and inter subjects. In addition, the mean absolute errors were calculated as the difference between averaged values obtained from Optitrack and IMUs measurement systems.

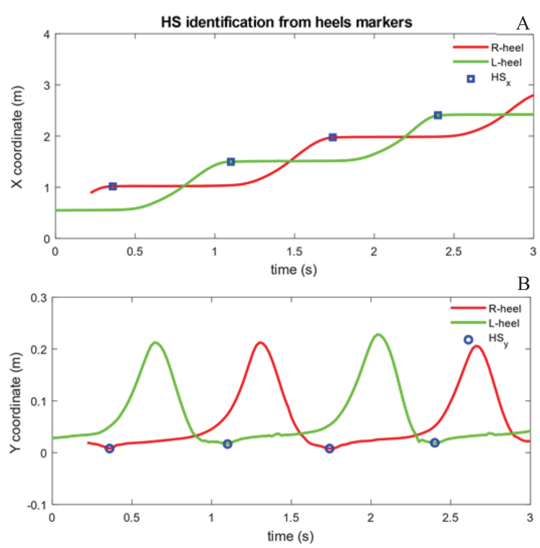


Fig. 2. Optitrack: example of heel-strike (HS) identification from (A) X coordinate and (B) Y coordinate of the heel markers. The red line refers to the right heel marker, while the green line corresponds to the left one. Blue squares and circles identify HS instants.

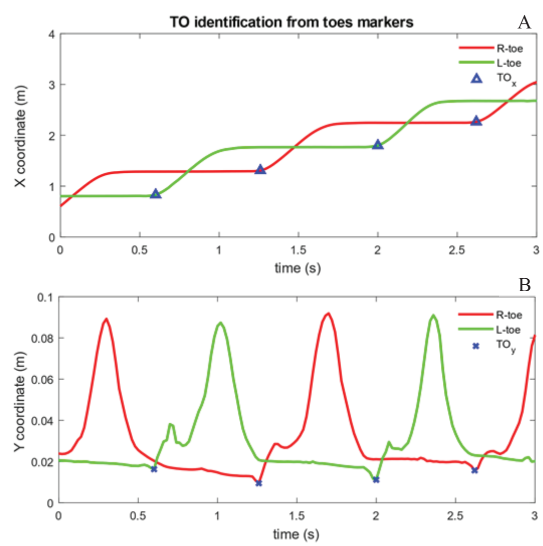


Fig. 3. Optitrack: example of toe-off (TO) identification from (A) X coordinate and (B) Y coordinate of the heel markers. The red line refers to the right toe marker, while the green line corresponds to the left one. Blue triangles and crosses identify TO instants.

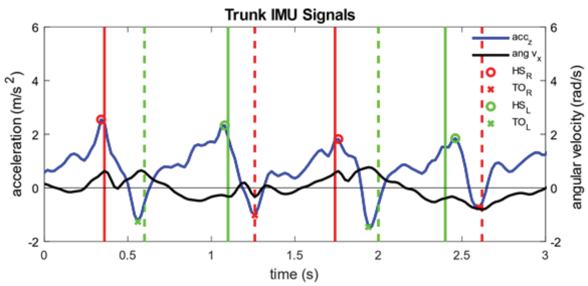


Fig. 4. IMU on the trunk: anterior-posterior acceleration (blue line) and vertical direction angular velocity (black line). Maximum and minimum peaks of the acceleration identify HS and TO, respectively. In particular, red color refers to the right foot and green color to the left one. Vertical lines represent the HS instant (solid line) and TO instant (dashed line) obtained from the Optitrack system.

For each setup, we considered the parameter values obtained from the various gait cycles collected from each subject, averaging left and right strides.

Custom Matlab® routines to process data were developed.

## III. Results

Average and standard deviation of spatio-temporal parameters are reported for the three different system setups and corresponding algorithms (Table I). Errors as average differences of spatio-temporal parameters are shown when considering one IMU on the trunk compared to Optitrack system (Table II) and two IMUs on the heels compared to Optitrack system (Table III). Data from the three velocities are described separately in all tables.

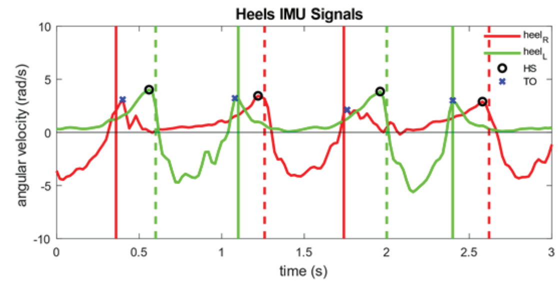


Fig. 5. IMUs on the heels: y-axis angular velocity (red line: right foot, green line: left foot). Vertical lines represent the HS (solid) and TO (dashed) obtained from the Optitrack system.

## IV. Discussion

The object of the present study focused on the comparison of different motion capture setups and algorithms for the evaluation of spatio-temporal parameters in gait analysis. Two different configurations of inertial sensors were proposed and compared with the stereo photogrammetric system, assumed as the gold standard. The gait parameters and absolute errors were estimated as the difference between IMUs and Optitrack values.

In the past, several methods were suggested for estimating initial and final contacts using lower trunk and heels IMUs [22, 24, 27-30]. In this work, the used algorithms for gait events detection were the same to the ones discussed in [22, 24]. Compared with other previous solutions [27-30], the selected strategies proposed some positive characteristics. As a first advantage, the algorithms dealt with the analysis of signals along local sensor axis, overcoming the identification of the body-segments reference systems. Moreover, these methods

Table I. Spatio Temporal Parameters estimation with different setups

| **Spatio-temporal parameters** | **Average Values and Standard Deviation (Mean ± SD)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | ***Normal Velocity*** | | | ***Low Velocity*** | | | ***High Velocity*** | | |
| | ***Optitrack*** | ***Trunk IMU*** | ***Heel IMU*** | ***Optitrack*** | ***Trunk IMU*** | ***Heel IMU*** | ***Optitrack*** | ***Trunk IMU*** | ***Heel IMU*** |
| Stride time (s) | 1,28±0,10 | 1,29±0,11 | 1,28±0,11 | 1,42±0,29 | 1,42±0,30 | 1,43±0,30 | 1,18±0,27 | 1,18±0,28 | 1,19±0,29 |
| Step time (s) | 0,64±0,05 | 0,65±0,05 | 0,64±0,05 | 0,71±0,14 | 0,71±0,15 | 0,72±0,15 | 0,59±0,14 | 0,59±0,14 | 0,59±0,14 |
| Stance time (s) | 0,81±0,08 | 0,82±0,08 | 0,75±0,07 | 0,93±0,22 | 0,92±0,22 | 0,87±0,23 | 0,73±0,21 | 0,74±0,18 | 0,69±0,20 |
| Stance duration (%GC) | 63,07±2,12 | 63,25±1,06 | 58,54±1,28 | 65,25±4,20 | 64,46±2,48 | 59,79±4,60 | 61,64±3,12 | 62,91±1,88 | 57,67±3,05 |
| Swing time (s) | 0,48±0,04 | 0,47±0,03 | 0,53±0,04 | 0,49±0,10 | 0,51±0,09 | 0,57±0,08 | 0,44±0,07 | 0,44±0,10 | 0,50±0,09 |
| Swing duration (%GC) | 37,32±2,26 | 36,91±0,91 | 41,60±1,61 | 34,75±4,29 | 35,97±1,97 | 40,07±4,30 | 38,19±3,00 | 36,93±1,69 | 42,31±2,87 |
| SS [a] time (s) | 0,47±0,03 | 0,47±0,03 | 0,53±0,04 | 0,50±0,10 | 0,50±0,08 | 0,56±0,08 | 0,45±0,08 | 0,44±0,11 | 0,50±0,09 |
| SS [a] duration (%GC) | 37,00±2,26 | 36,63±0,96 | 41,33±1,21 | 35,10±3,92 | 35,64±2,20 | 39,88±4,52 | 38,37±3,33 | 36,89±1,96 | 42,89±2,53 |
| DS [b] time (s) | 0,33±0,07 | 0,34±0,05 | 0,22±0,05 | 0,44±0,19 | 0,40±0,13 | 0,30±0,17 | 0,29±0,14 | 0,31±0,08 | 0,19±0,11 |
| DS [b] duration (%GC) | 25,37±4,52 | 26,17±1,82 | 16,79±3,22 | 30,49±8,59 | 28,06±3,93 | 19,85±8,60 | 23,62±5,98 | 26,14±3,38 | 15,39±5,74 |
| Foot simmetry (%GC) | 49,91±0.17 | 50,07±0,22 | 50,18±0,24 | 49,88±0,36 | 49,83±0,38 | 49,90±0,09 | 50,43±0,09 | 50,24±0,18 | 50,51±0,07 |
| Limp index | 0,96±0,03 | 1,01±0,01 | 0,96±0,02 | 1,01±0,05 | 0,99±0,01 | 0,97±0,06 | 0,98±0,03 | 0,97±0,02 | 0,97±0,01 |

[a] SS: Single Support

[b] DS: Double Support

TABLE II. SPATIO-TEMPORAL PARAMETERS ERRORS: TRUNK IMU

| Spatio-temporal parameters | Error Optitrack – Trunk IMU | | |
|---|---|---|---|
| | ***Normal Speed*** | ***Low Speed*** | ***High Speed*** |
| Stride time (s) | 0,01 | 0,00 | 0,00 |
| Step time (s) | 0,01 | 0,00 | 0,00 |
| Stance time (s) | 0,01 | 0,01 | 0,01 |
| Stance duration (%GC) | 0,18 | 0,79 | 1,26 |
| Swing time (s) | 0,00 | 0,02 | 0,01 |
| Swing duration (%GC) | 0,40 | 1,21 | 1,26 |
| SS [a] time (s) | 0,00 | 0,01 | 0,01 |
| SS [a] duration (%GC) | 0,37 | 0,54 | 1,48 |
| DS [b] time (s) | 0,01 | 0,04 | 0,02 |
| DS [b] duration (%GC) | 0,80 | 2,43 | 2,52 |
| Foot simmetry (%GC) | 0,15 | 0,05 | 0,20 |
| Limp index | 0,05 | 0,02 | 0,00 |

[a] SS: Single Support
[b] DS: Double Support

TABLE III. SPATIO-TEMPORAL PARAMETERS ERRORS: HEELS IMU

| Spatio-temporal parameters | Error Optitrack – Heels IMU | | |
|---|---|---|---|
| | ***Normal Speed*** | ***Low Speed*** | ***High Speed*** |
| Stride time (s) | 0,00 | 0,01 | 0,01 |
| Step time (s) | 0,00 | 0,01 | 0,00 |
| Stance time (s) | 0,06 | 0,06 | 0,04 |
| Stance duration (%GC) | 4,53 | 5,46 | 3,97 |
| Swing time (s) | 0,05 | 0,08 | 0,05 |
| Swing duration (%GC) | 4,29 | 5,32 | 4,12 |
| SS [a] time (s) | 0,05 | 0,06 | 0,06 |
| SS [a] duration (%GC) | 4,33 | 4,78 | 4,52 |
| DS [b] time (s) | 0,11 | 0,14 | 0,09 |
| DS [b] duration (%GC) | 8,57 | 10,64 | 8,23 |
| Foot simmetry (%GC) | 0,27 | 0,02 | 0,08 |
| Limp index | 0,00 | 0,04 | 0,01 |

[a] SS: Single Support
[b] DS: Double Support

avoided cumbersome pre-processing of accelerations and velocities requiring the introduction of transformations on sub-windows or the selection of operator-dependent thresholds [28]. In particular, the trunk IMU algorithm considered the acceleration along the antero-posterior direction (z-axis) for TO and HS instants selection. As a new strategy, the angular velocity along the vertical axis (x-axis) was adopted for the discrimination between right and left foot. The heels IMUs algorithms were based on the medio-lateral angular velocity (y-axis) from each foot sensor.

The average and standard deviation of gait parameters estimated by the 3 motion capture setups (Table I) were similar to those obtained by previous studies [14, 24-26]. Considering the different velocities, the step and stride time and gait phases increased at low speed, while they reduced at high speed. Between-subject variability was smaller at self-selected normal speed with respect to both higher- and slower-than-normal speeds.

Focusing on the difference between values obtained through each IMU algorithm and Optitrack system, for most parameters the average errors from the trunk-IMU (Table II) resulted lower compared with those from heel-IMUs, for all the three speeds (Table III). Moreover, for some of the proposed parameters, the range of average error of trunk IMU configuration compared with stereo photogrammetric system was close to differences already estimated in previous studies [29].

For the step and stride time, the differences resulted absent or negligible for both IMU configurations, with a maximum average error of 10 ms. For the swing and stance time, as for the single and double support time, the average differences between trunk-IMU and Optitrack underlined small errors, generally in the range 10-40 ms. Concerning the values obtained with the heel-IMU algorithm, the comparison highlighted average differences in the range 40-140 ms. Based on these discrepancies, the trunk-IMU algorithm revealed to be more accurate in the estimation of parameters that characterize specific phases of the gait cycle. For all parameters related to the duration of the gait cycle (%GC), errors were higher with both the IMU setups. In these cases, the parameters estimated with the trunk-IMU algorithm evidenced considerably smaller differences compared to the Optitrack reference. The error due to the heels IMU algorithm resulted 4 to 5 times greater than the ones obtained from the trunk IMU algorithm. This can be explained by a better identification of gait events guaranteed by the trunk IMU algorithm. Finally, negligible average errors were estimated for the limp index and the foot symmetry, revealing good results in both configurations.

Differences and comparison of results underlined how the algorithm adopted for the trunk IMU sensor disclosed to be more suitable in order to obtain an accurate and robust analysis of gait parameters.

In both cases, the different data acquisition frequency between the (a) Optitrack System and the (b) and (c) IMUs set-ups might only partly explain the discrepancy of gait events detection. In order to acquire simultaneous signals from different measurement systems, the marker was positioned on the IMU sensor. The position of the marker in correspondence of the heel without the identification of specific bony landmark could have partly influenced the HS calculations. A limitation of the study is the restricted number of subjects and gait trial repetitions since this might influence the parameters estimation. A larger number of participants can be useful to confirm the validation of the setups and algorithms. Moreover, with a greater population, statistical data analysis can be introduced.

## V. CONCLUSION

In conclusion, both IMUs configurations represent a potentially alternative tool to traditional stereo photogrammetric system for the estimation of gait spatio-temporal parameters. The easy, reproducible and user-friendly positioning of the inertial sensors on human body segments allows to analyze gait events and spatio-temporal parameters with acceptable accuracy. Inertial sensors setups might overcome limitations and constraints due to laboratory environment and reduced data acquisition volume.

Both the algorithms adopted with the trunk-IMU and heels-IMUs resulted suitable for the analysis of gait and parameters detection. In all participants, both acceleration and angular velocity signals showed evident and easily recognizable HS and TO events. This consideration is valid also at slower and higher speeds. The validation with stereo photogrammetric systems resulted in small and negligible differences for most gait events and spatio-temporal parameters. Comparing the two IMUs algorithms and their differences to the stereo photogrammetric system, the parameters estimation stressed a more accurate and reliable evaluation from the trunk IMU algorithm. This was due to the better identification of gait events guaranteed by the trunk IMU algorithm. Moreover, the sensor on the trunk offers the advantage to extract all the data from a single sensor.

This preliminary test represents the starting point of a deeper and larger investigation. In the future, a larger number of healthy, elderly and pathological participants will be investigated, for a more systematic testing.

## REFERENCES


[1] A: Hartmann, S. Luzi, K. Murer, R.A. de Bie, E.D. de Bruin, “Concurrent validity of a trunk tri-axial accelerometer system for gait analysis in older adults.” Gait & posture, 2009, vol. 29(3), pp. 444-448.

[2] J. Weidow, R. Tranberg, T. Saari, J. Kärrholm, “Hip and knee joint rotations differ between patients with medial and lateral knee osteoarthritis: gait analysis of 30 patients and 15 controls.” J. Orthop Res, 2006, vol. 24(9), pp. 1890-1899.

[3] R.M. Kay, S. Dennis, S. Rethlefsen, R.A. Reynolds, D.L. Skaggs, V.T. Tolo, “The effect of preoperative gait analysis on orthopaedic decision making.” Clinic orthop rel res, 2000, vol. 372, pp. 217-222.

[4] O. Sofuwa, A. Nieuwboer, K. Desloovere, A.M. Willems, F. Chavret, I. Jonkers, “Quantitative gait analysis in Parkinson’s disease: comparison with a healthy control group.” Archives of physical medicine and rehabilitation, 2005, vol. 86(5), pp. 1007-1013.

[5] U. Givon, G. Zeilig, A. Achiron, “ Gait analysis in multiple sclerosis: characterization of temporal–spatial parameters using GAITRite functional ambulation system.” Gait & posture, 2009, vol. 29(1), pp. 138-142.

[6] V. Agostini, L. Gastaldi, V. Rosso, M. Knaflitz, S. Tadano, “A Wearable Magneto-Inertial System for Gait Analysis (H-Gait): Validation on Normal Weight and Overweight/Obese Young Healthy Adults.” Sensors, 2017, vol. 17(10), 2406.

[7] P.P. Lai, A.K. Leung, A. N. Li, M. Zhang, “Three-dimensional gait analysis of obese adults.”, Clinical biomechanics, 2008, vol. 23, pp. S2-S6

[8] V. Rosso, L. Gastaldi, W. Rapp, S. Lindinger, Y. Vanlandewijck, V. Linnamo, "Biomechanics of simulated versus natural cross-country sit skiing", Journal of Electromyography and Kinesiology, 2017, vol. 32, pp 15-21.

[9] V. Rosso, G. Cinus, L. Gastaldi, "An agility test to measure performance in Para ice hockey", IEEE International Symposium on Medical Measurements and Applications (MeMeA), 2018

[10] E. Panero, L. Gastaldi, W. Rapp, “Two-Segment Foot Model for the Biomechanical Analysis of Squat.”, Journal of Healthcare engineering, 2017.

[11] P.B. Shull, W. Jirattigalachote, M.A. Hunt, M.R. Cutkosky, S.L. Delp, S. L. “Quantified self and human movement: a review on the clinical impact of wearable sensing and feedback for gait analysis and intervention.” Gait & posture, 2014, vol. 40(1), pp. 11-19.

[12] W. Tao, T. Liu, R. Zheng, H. Feng, “Gait analysis using wearable sensors. Sensors”, 2012, vol. 12(2), pp. 2255-2283.

[13] T. Liu, Y. Inoue, K. Shibata, “Development of a wearable sensor system for quantitative gait analysis.” Measurement, 2009, vol. 42(7), pp. 978-988.

[14] V. Agostini, M. Knaflitz, L. Antenucci, G. Lisco, L. Gastaldi, S. Tadano, “Wearable sensors for gait analysis.”, IEEE International Symposium on Medical Measurements and Applications (MeMeA), 2015, pp. 146-150.

[15] A. Muro-De-La-Herran, B. Garcia-Zapirain, A. Mendez-Zorrilla, “Gait analysis methods: An overview of wearable and non-wearable systems, highlighting clinical applications.” Sensors, 2014, vol. 14(2), pp. 3362-3394.

[16] L. Gastaldi, S. Pastorelli, M. Caramella, U. Dimanico, “Indoor motion analysis of a subject wearing prosthesis for adaptive snowboarding.” WIT Transactions on Biomedicine and Health, 2011, vol. 15, pp. 361-372.

[17] F. Kluge, H. Gaßner, J. Hannink, C. Pasluosta, J. Klucken, B:M: Eskofier, “Towards Mobile Gait Analysis: Concurrent Validity and Test-Retest Reliability of an Inertial Measurement System for the Assessment of Spatio-Temporal Gait Parameters.” Sensors, 2017, vol. 17(7), 1522.

[18] A. Peruzzi, U. Della Croce, A. Cereatti, “Estimation of stride length in level walking using an inertial measurement unit attached to the foot: A validation of the zero velocity assumption during stance.” J. Biomec, 2011, vol. 44(10), pp. 1991-1994.

[19] D. Trojaniello, A. Cereatti, U. Della Croce, “Accuracy, sensitivity and robustness of five different methods for the estimation of gait temporal parameters using a single inertial sensor mounted on the lower trunk.” Gait & posture, 2014, vol. 40(4), pp. 487-492.

[20] R. Takeda, G. Lisco, T. Fujisawa, L. Gastaldi, H. Tohyama, S. Tadano “Drift removal for improving the accuracy of gait parameters using wearable sensor systems.” Sensors, 2014, vol. 14(12), 23230-23247.

[21] A. Rampp, J. Barth, S. Schülein, K.G. Gaßmann, J. Klucken, B.M. Eskofier, “Inertial sensor-based stride parameter calculation from gait sequences in geriatric patients.” IEEE transactions on biomedical engineering, 2015, vol. 62(4), pp. 1089-1097.

[22] S. Misu, T. Asai, R. Ono, R. Sawa, K. Tsutsumimoto, H. Ando, T. Doi, “Development and validity of methods for the estimation of temporal gait parameters from heel-attached inertial sensors in younger and older adults.” Gait & posture, 2017, vol. 57, pp. 295-298.

[23] Z. Wang, R. Ji “Estimate spatial-temporal parameters of human gait using inertial sensors.” Cyber Technology in Automation, Control, and Intelligent Systems (CYBER), 2015, pp. 1883-1888.

[24] W. Zijlstra, A.L. Hof, “Assessment of spatio-temporal gait parameters from trunk accelerations during human walking.” Gait & posture, 2003, vol. 18(2), pp. 1-10.

[25] F. Buganè, M.G. Benedetti, G. Casadio, S. Attala, F. Biagi, M. Manca, A. Leardini, “Estimation of spatial-temporal gait parameters in level walking based on a single accelerometer: Validation on normal subjects by standard gait analysis”, Computer methods and programs in biomedicine, 2012, vol. 108.1: pp. 129-137.

[26] L.N. Veilleux, M. Raison, F. Rauch, M. Robert, L. Ballaz “Agreement of spatio-temporal gait parameters between a vertical ground reaction force decomposition algorithm and a motion capture system.” Gait & posture, 2016, vol. 43, pp. 257-264.

[27] R.C. González, A.M. López, J. Rodriguez-Uría, D. Alvarez, J.C. Alvarez, “Real-time gait event detection for normal subjects from lower trunk accelerations.” Gait & posture, 2010, vol. 31(3), pp. 322-325.

[28] J. McCamley, M. Donati, E. Grimpampi, C. Mazzà “An enhanced estimate of initial contact and final contact instants of time using lower trunk inertial sensor data.”, Gait & posture, 2012, vol. 36.2, pp. 316-318.

[29] M.V. Avolio, S. Mammolito, G. Spingola, “A system for estimating Spatio-Temporal Gait Parameters and Pelvis Kinematics”, Int. Conf. Biomedical Engineering and Science, 2015

[30] J. B. Lee, R.B. Mellifont, B.J. Burkett, B. J., “The use of a single inertial sensor to identify stride, step, and stance durations of running gait.” Journal of Science and Medicine in Sport, 2010, vol. 13(2), pp. 270-273.




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