DRIFT-FREE POSITION ESTIMATION FOR PERIODIC MOVEMENTS USING INERTIAL UNITS

Nora Millor, Pablo Lecumberri, Marisol Gómez, Alicia Martínez-Ramírez, Mikel Izquierdo

Abstract— **Latest advances in microelectromechanical systems have made inertial units (IUs) a powerful tool for human motion analysis. However, difficulties in handling their output signals must be overcome. The purpose of this study was to develop the novel "PB-algorithm" based on polynomial data fitting, splines interpolation and the wavelet-transform, one after the other, to cancel drift disturbances in position estimation for periodic movements. High-accuracy position measurements from an optical system (Vicon Nexus 1.0) were used to validate the proposed method and comparison with another drift-correction algorithm was provided. Results indicate the accuracy with respect to the Vicon's reference signal (Euclidean Error (EE) lower than 54.62 x 10^{-3}m and correlation coefficient higher than 0.968). A reduction of the Root-Mean-Square-Error (RMSE) of 68.74% was obtained when the proposed two-step method was compared with a Modified-Band Limited Fourier Linear Combiner (BMFLC). All methods were applied to data from the 30-s Chair Stand Test (CST), which is one of the most used clinical tests dealing with lower body strength assessment, falls prediction and gait disorders in older adults. The relevance of this study is that after cancelling drift disturbances, and obtaining an accurate Z-position estimation, it is possible to evaluate the sit-to-stand and stand-to-sit transitions from the whole test.**

***Index Terms*— Accelerometer, drift-problem, human movement analysis, wavelets, splines, 30-s chair stand test.**

I. INTRODUCTION

INertial units (IUs) comprising accelerometers, gyroscopes and, in some cases, magnetometers have become an innovative non-invasive solution not only to assess sports-related performance [1] but also as a clinical source of functional capacity assessment [2-5]. This is of special interest when dealing with frailty or with Parkinson disease since patient's displacement to a clinic or an institution to make the measurements is often inadvisable [6-8]. Indeed, expensive and sophisticated measurement tools such as force platforms or vision systems are being confined to making experiments in laboratories.

One of the main limitations of IUs is that their outputs are relative data sets (i.e. angles between segments and their acceleration or velocity), while standard technologies directly provide absolute and relative body segment position/and orientation in a fixed reference frame. In fact, finding 3-D segment position, absolute angles and complete kinematics is the major difficulty when using body-fixed inertial sensors [9-11]. In this regard, one of the most common problems is the drift effect, an encumbering noise that arises when integrating the acceleration signal to obtain velocity or position, which can even hide the real outcome.

Through the literature different methods can be found to partially solve this problem: aided sensors or sensing systems data fusion [11-14] wavelet analysis [15;16], Fourier-based filters [17-21], band-pass filtering [22] and polynomial data fitting [23]. Generally they tend to use the aid of an externally referenced sensor or prior knowledge of the motion as well as complex linear and adaptive filtering or other data processing to estimate displacement from the acceleration signal. The present study develops a new method to cancel the drift effect based on the use of a single IU and jointly considering different processing methods. In particular, polynomial data fitting [23], spline interpolation and wavelet transform were employed one after the other. The idea is to obtain an accurate estimation of the Z-position signal without any restriction (i.e. previous knowledge of acceleration, velocity and/or position at reference points [23]) other than the movement's periodicity. This way, inertial technology arises as a powerful tool to measure activity during mobility related activities in a noninvasive manner.

The 30-s chair stand test (CST) is one of the most used clinical tests dealing with lower body strength assessment in older adults [24-26]. Moreover, this test has been reported to

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be a good falls predictor [27] and to have a high correlation to gait and other activities performance [28;29], especially in older frail population [30-32]. The relevance of this study for 30-s CST users lies in its enabling automatic cycle's counting and subsequent definition of the movement's phases. Secondly, the current 30-s CST’s output information would be improved by automatic analysis of kinematic and kinetic variables describing the movement's performance from IU´s data recordings. In addition, to the best of the author´s knowledge, drift-canceling methods have not been deeply tested with long duration and wide movement amplitudes as the ones of the 30-s CST.

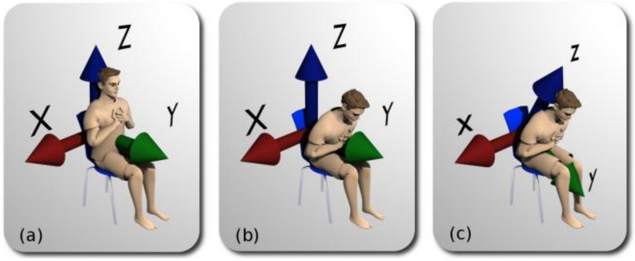

Fig. 1: Changes in global and IU's local Cartesian reference axes when the subject is trying to stand up at the beginning of the 30-s CST. The first figure, (a), depicts the initial position; global and local reference axes coincide. When the subject changes position, the global axis remains unchanged (b) whereas the IU's local reference axis rotates with the physical device (c).

The aim of this study was to develop a novel two-step processing method (i.e. polynomial data fitting followed by baseline estimation) to cancel drift disturbances in position estimation for periodic movements. High-accuracy position measurements from an optical system (Vicon Nexus 1.0) were used to validate the proposed method and to compare its performance with another drift-correction algorithm [17].

II. MATERIALS AND METHODS

A. Subjects

Seven healthy subjects (5 males and 2 females, age: 22 ± 5 years, body mass: 68.5 ± 8.6 kg, height: 1.7 ± 0.1 m) volunteered to participate in this study. All of them were thoroughly informed about the experimental procedure, the purpose, nature and possible risks associated with the study, as well as the right to finish their participation at their will. Subsequently, subjects gave their written informed consent to participate.

These experimental procedures were approved by the Institutional Review Committee of the Public University of Navarra, and Department of Health Sciences of the Government of Navarra, according to the Declaration of Helsinki.

B. Testing Procedures

The 30-s CST consists in standing up and sitting down from a chair with arms crossed across the chest as many times as possible within 30 seconds. All trials were performed in a laboratory with the same chair and ambiance conditions. The chair was backless to permit full visibility of the marker tracker by the optical system during the task performance. Each subject was asked to perform two sets of the 30-s CST under two different conditions. The first one, called self-adjusted-test (SA-test), was carried out after the command “slow but comfortable velocity performance”, while the second one, called high-speed test (HS-test), obeyed the command “as fast as possible”. There were two minutes of resting time between both trials in order to let the subject recover from the first performance. The reasoning behind this methodology is that during the self-adjusted trial the movement performance is expected to be different from the high-speed one. In fact, trunk angular displacements were assessed to be lower during the high-speed trial [33], raising the impact of geometrical errors [34]. Similarly, smoother displacements were detected when carrying out the 30-s CST for the self-adjusted conditions compared to the fast ones. Therefore, the HS-task is regarded as an extreme scenario in terms of position estimation’s difficulty.

C. Instrumentation

An IU integrating 3 accelerometers, 3 gyroscopes and 3 magnetometers (MTx, Xsens Technologies B.V. Enschede, Netherlands) attached over the L3 region of the subject’s lumbar spine provided the kinematic data recorded in each trial at a sampling rate of 100 Hz. MTx combines itself nine individual MEMS sensors to furnish accurate 3D orientation as well as other kinematic data such as: 3D acceleration, 3D rate of turn (rate gyro) and 3D earth-magnetic field. A detailed description of the MTx’s calculation methods can be found elsewhere [1]. Optical motion analysis system (Vicon Nexus 1.0) was used as truth-reference and it was time synchronized with the MTx to compare both signal results.

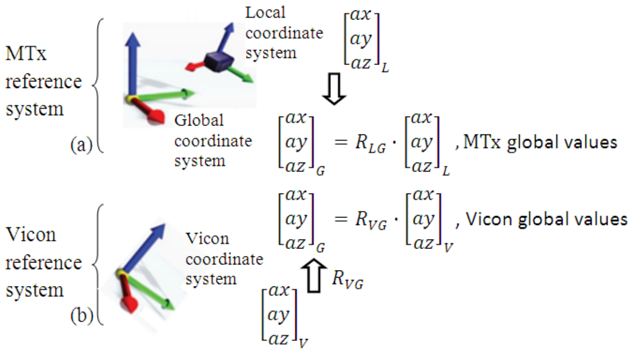

Fig. 2: Reference systems changes to obtain the global values from MTx and Vicon. Subindexes “L”, “G” and “V” refer to the MTx local, global and Vicon local coordinate systems respectively and R_{LG} and R_{VG} to the rotation matrices to change coordinates from the first indicated reference system to the second one.

The IU provided linear acceleration and rate of turn in a sensor-fixed Cartesian reference frame (xyz). Before the beginning of the test, with the subject sitting on the chair and his back in upright position, the sensor-fixed reference frame was aligned with the Earth-fixed global reference frame (XYZ), whose Z axis lies on the vertical pointing upwards, its X axis lies on the lateral direction and its Y axis on the anterior-posterior direction (Figure 1). Orientation data consisting in the Euler angles (in XYZ or roll-pitch-yaw order) defined the rotation that aligned the global axis to the sensor-fixed reference frame at each time instant. Then, linear acceleration in the global reference frame was obtained from the acceleration and orientation data provided by the IU (Figure 2A). Furthermore, optical data were also collected using a 100Hz six-camera Vicon system (Vicon Motion System, Oxford, UK), in order to check the new method's accuracy [35]. Specifically, in our study, a Vicon Nexus 1.0 was employed, using only three from the six available cameras. They were previously calibrated similarly to [36] and the data from the two systems were time-synchronized through sync pulses in order to compare both of them in an off-line analysis with Matlab (Math Works, Massachusetts, USA). One 4 mm Vicon reflective marker was placed on the MTx to acquire its three dimensional position for subsequent comparisons.

D. Signal Processing

Drift effect correction.

Z-position signal, obtained through double integration of the Z-acceleration, was used to detect the subject's up and down positions and hence automatically obtain the number of complete sit-stand-sit repetitions during the 30-s CST. However, the raw Z-acceleration signal provided by the IU has to be treated as previously mentioned. Firstly, the coordinate reference system needed to be changed from local to global. Secondly, the gravity acceleration component, roughly estimated as 9.8 m/s^2, had to be removed (Figure 3).

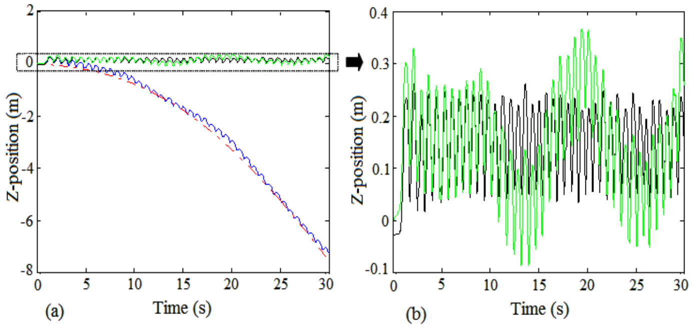

Fig. 3: Figure (a) shows the Z-position signal (blue line) gravity error correction (green line), and the Vicon reference signal (black line). Red line is the tendency line based on fourth level polynomial estimation that tracks the gravity error, Part (b) shows the corrected and reference signal enlargement.

Finally, relative position was obtained through double integration of the acceleration data (Figure 4A), assuming resting initial conditions. However, this straightforward process was hindered by noise in the acceleration signal as well as by approximation errors due to numerical integration. This drift effect that occurs for various reasons (e.g., vibration or environmental temperature fluctuations) can, in practice, make the position or velocity signals became unusable within several seconds. Therefore, an added step to solve this problem is needed. Here, a new method based on polynomial curve adjustment and splines approximation is proposed. In doing so, we will be able to achieve a correct Z-position overcoming the drift error problem.

Our correction method first tries to estimate the drift caused by a small DC bias in the Z-acceleration signal principally due to assuming a gravity component of 9.8 m/s^2. This gross approximation leaves a small continuous component which gives rise to a quadratic component in the double-integrated signal. Here, a fourth order polynomial was used to obtain the estimation parameters from the position signal, without incurring in over-fitting. Then, the derivative of the estimated polynomial was employed to adjust the velocity signal and get the position signal through integration (Figure 4B).

However, some baseline fluctuations can still be observed after removing the polynomial estimation of the drift component so a second step is needed to correct them. In this case, local maxima and minima position signal information and one of the following assumptions, were used:

1. Hypothesis 1: "Subjects reach the same position when they make contact with the chair each cycle". Therefore, differences in the minimum values of the Z-position signal are due to baseline drift. This baseline is estimated as a cubic spline passing through the minima (with a tolerance of 5 mm) and minimizing the differences between movement ranges in different standings (Figure 5A).
2. Hypothesis 2: "Subjects reach the same vertical position when they get to the upright position". In this case the baseline drift causes the variation of the maximum peaks from the Z-position. The baseline is then estimated as the signal in the 0-0.25 Hz frequency range with minimum distance to the Z-position maximum points (Figure 5B). Here, low frequency interpolation of the maxima series was employed. The condition of zero initial velocity is imposed to reduce inaccuracies in the first samples' estimation.
3. Hypothesis 3: "Subjects don't always get to the same upright or sitting positions; instead, they reach different maximum and minimum peaks each cycle." In this case baseline drift is assumed to be common to both maxima and minima series of peaks and of low frequency. Firstly, two cubic splines are used to interpolate the maxima and minima series respectively. Secondly, the wavelet analysis was used to extract the common low frequency component. In this case a wavelet analysis of 15 levels using a fourth order Coiflet was applied to both

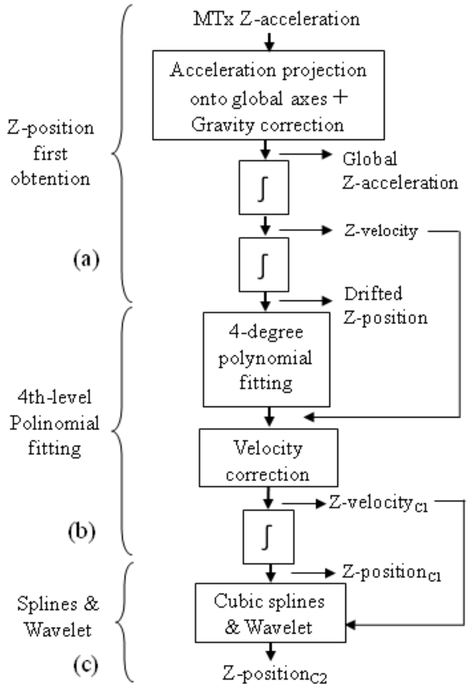

Fig. 4: Z-position free-drift obtaining algorithm: double integration process, part (a), first correction (C1), part (b). and second correction (C2), part (c).

interpolation signals and, the mean of the coefficients up to level 7 is used to synthesize the low-frequency baseline estimation (Figure 5C).

Reference systems unification.

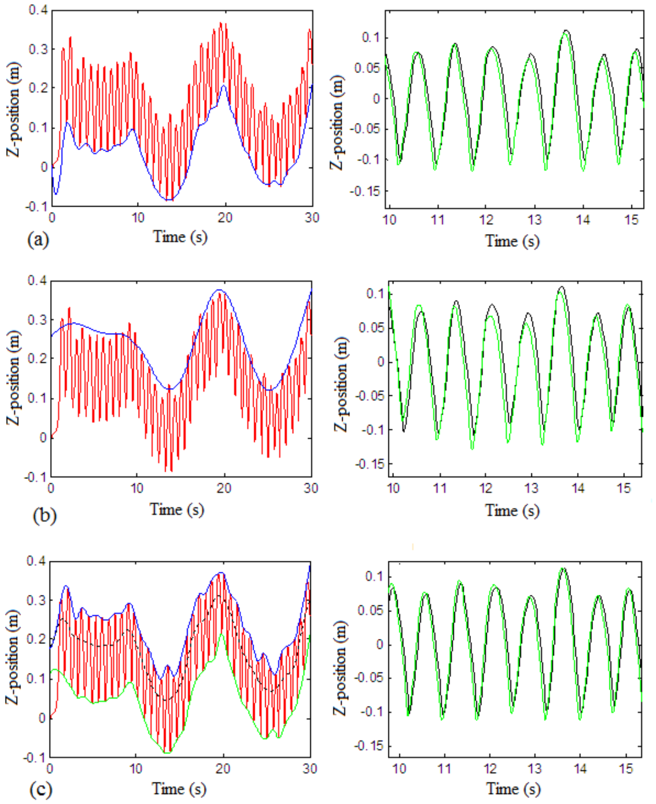

Fig. 5: Final drift effect correction under different conditions from one subject performing the high speed test. The left side shows the drifted Z-position signal (red line) along with the estimated baseline (blue line in (a) and (b), black dotted line in (c)). The blue and green lines in (c) are the spline-based interpolation of maxima and minima respectively. The right side shows the corrected Z-position (green line) with the reference Vicon Z-

Vicon reference system had to be changed to the global axes used by the MTx. To this purpose, some calibration measures from the Vicon system collected after each measurement were used to obtain the rotation matrix needed to make the coordinates change (Figure 2B)). This arrangement makes it possible to compare the trajectory reconstructed from IU's data and the one provided by the Vicon system.

Statistical parameters for comparisons.

Comparisons were done based on parameters such as the Euclidean error (EE), (1.1), similarly to [35], and accuracy, defined as the percentage of the whole signal without error. Furthermore, statistical parameters such as the root mean squared error (RMSE), (1.2), and the correlation coefficient (r) were also obtained to check our method's accuracy:

$$EE = \left\| \sum_{n=1}^{N} Zposition_{Vicon}(n) - Zposition_{MTx}(n) \right\| \qquad (1.1)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{n=1}^{N} Zposition_{Vicon}(n) - Zposition_{MTx}(n)} \qquad (1.2)$$

Modified-BMFLC vs PB- algorithm

The method reported in the present study was compared to a recent Modified-BMFLC drift-correction algorithm [14]. The 30-s CST meets the quasi-periodic motion requirement for this drift-correction algorithm to be applied. In the literature there are other methods to correct the drift effect, but this was probably the first one which tried to cancel it when obtaining the position from the acceleration signal. Firstly, as in [17], the cutoff frequency and the order of the high-pass filter were selected according to the 30-s CST conditions. A fourth level filter was chosen and the cutoff frequency was set at the movement's fundamental frequency. Finally, in order to achieve a good BMFLC algorithm performance, 200 intermediate sub-frequencies were selected between the movement's fundamental and tenth harmonic frequencies.

III. RESULTS

A. *Number of full stands*

The mean and standard deviation of the number of full stands was 12±3 and 29±6 repetitions for the SA-test and the HS-test, respectively.

B. *Vicon reference signal vs hypothesis 1,2 and 3*

Z-position obtained from the present two-step IU's data processing method provided the same number of full stands as that reported by the Vicon system. A maximum error of the order of 0.002 m was observed when calculating the difference of both trajectories (1.1), (Figure 6).

Table 1 shows the values of the EE, RMSE and the correlation coefficient (r) of each 30-s CST task in the sagittal plane (i.e. the one where the up and down trajectory is principally located). Mean EE and RMSE values were always lower than 21.58 x 10^{-3} m and 27.80 x 10^{-3} m, respectively. The correlation coefficient was always greater than 0.96. Moreover, since the HS-test represents an extreme scenario for vertical trajectory assessment, better accuracy was obtained at SA-test performance (mean EE of 13.85 x 10^{-3} m and a coefficient of correlation of 0.99).

TABLE I: HYPOTHESIS AND "BMFLC-ALGORITHM" COMPARISONS

Correction	30-s CST type	Euclidean Error (x10^{-3}m) Max.	Mean	SD	Accuracy (%)	RMSE (x10^{-3}m)	r
Gravity	SA-test	122.82	21.18	21.39	97.76	30.14	0.96
	HS-test	134.01	31.40	24.69	96.72	40.20	0.89
Hypothesis 1	SA-test	61.67	13.85	11.33	98.53	17.94	0.99
	HS-test	100.40	21.58	17.18	97.77	27.80	0.94
Hypothesis 2	SA-test	45.89	12.28	9.31	98.69	15.44	0.99
	HS-test	66.83	20.61	14.21	97.86	25.11	0.96
Hypothesis 3	SA-test	48.35	12.89	9.71	98.63	16.16	0.99
	HS-test	54.62	19.45	12.33	97.99	23.06	0.97
BMFLC algorithm	SA-test	173.30	34.76	38.20	96.32	17.94	0.89
	HS-test	194.10	32.81	37.12	96.58	49.68	0.84

The corrected signals showed a mean EE of 31.4 ± 24.7 x 10^{-3} m, (Table 1) after the gravity correction. Then, it was improved up to 19.5 ± 12.3 x 10^{-3} m after the second step. Accuracy differences, however, were noticed depending on the method used. Second and third procedures gave better Z-position approximations. Specifically, for the HS-test, the maximum EE decreased using the third assumption instead of the first one from 100.4 x 10^{-3} to 54.62 x 10^{-3} m. Overall, the third assumption was regarded as the more accurate due to the high variability of the maximum and minimum positions reached by the subjects during the test performance.

C. Modified-BMFLC vs. PB-algorithm

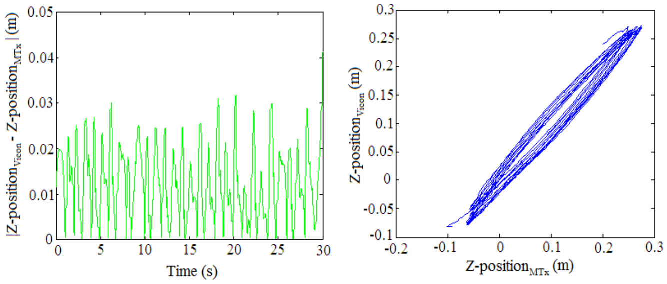

Fig. 6: Figure (a) shows the Z-position signal error after the selected correction methodology. Figure (b) shows the representation of the MTx signal vs the Vicon reference one.

Compared to the Vicon's reference signal, the modified-BMFLC algorithm showed an EE of 32.81 ± 37.12 x 10^{-3} m. and a correlation coefficient below 0.890. By using this paper's drift-correction proposal, an improvement of 40.75% and 62.90%, with respect to the BMFLC's mean EE was achieved under the HS and SA test conditions respectively.

IV. DISCUSSION

The present study is the first step to obtain a procedure to analyze the 30-s CST data. By instrumenting the test, both current parameters such as the number of performed cycles and new kinematic information could be automatically obtained.

The main result of this paper was that the new two-step processing method, or PB- algorithm, is able to cancel drift disturbances in position estimation for periodic movements facilitating the analysis of the 30-s CST using a single IU. Polynomial curve adjustment followed by splines interpolation and wavelet transform was used as an innovative method to correct the drift signal from the integrated acceleration. These results are useful for establishing movement's phases and computing kinetic parameters from 30-s CST's data. This methodology could also be used in other test involving periodic movements with little or no modification.

One of the preliminary steps of the 30-s CST evaluation is to determine the beginning and end of each up-and-down cycle from the recorded sensor's signals. In this regard, the Z-position stands as the best reference for cutting the whole 30-s signal into cycles since it is the main component of the stand-up and sit-down movement. This approach allows for the automatic recording of the number of full stands without the encumbrance of human counting error. So, once the sit-to-stand test is divided into cycles, it is possible to examine each of their phases separately in order to obtain kinematic variables related to the movement's performance.

It is know, however, that the accuracy of the displacement obtained from IU's data may be rather poor due to the inherent drift effect, mainly caused by the noise and dc bias of the acceleration signal, which grows quadratically with time. These are the reasons why IUs are seldom used alone in the measurement of displacement and different techniques are available through the literature in order to solve this problem. They range from using either aided sensors or sensing systems [11;12;13;18] to using signal analysis such as filters [22] , frequency treatment [17;21] or baseline estimation [23] to remove the sensor noise. Regarding signal analysis two techniques are typically used: adaptive filtering methods based on Fourier series and the wavelet transform. In the first case, the WFLC (weighted Frequency Fourier Linear Counter) [17;21;20] and especially, the BMFLC (Band Limited Multi Fourier Linear Combiner) are used to estimate the displacement due to a periodic motion from an accelerometer's data. In doing so, periodic signals can be modeled by series of sine and cosine components and zero phase band-pass filtering removes the unwanted noise. However, for the 30-s CST signals, better Z-position estimation was obtained when using the PB-algorithm instead of the BMFLC algorithm. The reason for this difference may be that both algorithms are tailored to different kinds of movements. While the displacements typically analyzed with the BMFLC techniques were tremors of about 0.2 mm. [17;21;26], the 30-s CST entailed up and down movements of about 30 cm. In this manner, a reduction of approximately 70 % of the RMS error was obtained with the proposed two-step processing method (Table 2). In addition, another disadvantage of the BMFCL algorithm was the fact that is specifically focused to periodic signals, something that is not always true for the quasi-periodic 30-s CST's movement. Furthermore, a large number of intermediate frequencies were needed when using the BMFLC algorithm to obtain a good Z-position approximation which makes it dependent on the input signal.

TABLE II: PB-ALGORITM Vs MODIFIED-BMFLC (% IMPROVEMENT)

30-s CST type	Correction	Euclidean Error ($x10^{-3}$m) Max.	Mean	SD	Accuracy (%)	RMSE ($x10^{-3}$m)
SA-test	Vs Hyp.2	73,51	64,65	75.62	64.34	70.15
	Vs Hyp.3	72,10	62,90	74.59	62.69	68.74
HS-test	Vs Hyp.2	65.56	37.17	61.72	37.54	49.45
	Vs Hyp.3	71.86	40.75	66.79	41.27	53.58

The term "Hyp." was used as the abbreviation of hypothesis.

In this study, polynomial curve adjustment, and baseline interpolation (i.e cubic splines and wavelet analysis) were used in an innovative method, called PB-algorithm, to correct the drift from the double-integrated acceleration signal. Firstly, the use of a fourth-level polynomial was able to correct the effect of the gravity vestige that biased the acceleration signal and which completely hid the true Z-position. Secondly, baseline interpolation from local maxima and minima yielded an even better Z-position estimation eliminating the remaining drift artifact. Three alternative hypotheses were proposed to drive the interpolation process: 1) Equal minimum values when sitting down; 2) equal maximum values when standing up and 3) maximum and minimum values affected by the same low-frequency baseline deviation. Min and max Z-position variability has been assessed from Vicon system. The average values were 1.94% and 82.21% for max. and min. Z-positions, while there was a maximum variation of 6.28% and 207.9 % for max. and min. Z-position. Therefore, the third hypothesis provides a more accurate Z-position estimation since subjects do not always get the same position either when they upright stand up or when they reach the seat. Moreover, results show it provides better results in almost every test condition. We obtained an original method to firstly obtain the drift corrected Z-position signal from the Z-acceleration and secondly to have a reference to automatically analyze the 30-s CST.

A comparison with the position provided by a Vicon system was used in the present study to check the validity of the PB-algorithm for the 30-s CST. The present results showed higher accuracy of the Z-position estimation for the 30-s CST than that obtained with the Modified-BMFLC algorithm, even for the HS-test. As reported in Giasanti et al. [34], lower accuracy in the position estimation is achieved when the movement involves greater accelerations (i.e. in high speed movements). The PB-algorithm proposed in the present study outperformed the BMLFC algorithm under both test's conditions (SA-test and HS-test).

Despite the extra processing, the use of IUs shows several advantages over optical systems. Firstly, IUs do not constrain the measurement volume and do not suffer from shadowing problems. In addition, they can be easily attached to the human body without hindering the execution of motor tasks. Finally, the results show that the PB-algorithm performs satisfactorily under different velocity conditions. This suggests that the proposed procedure could be applied to evaluate the test performance of aged or Parkinson's affected subjects with low-velocity movements without the constraint of a laboratory setting.

V. CONCLUSION

In summary, this study introduces a new perspective for analyzing periodic movements based on the position signal. Once the drift is removed, the position information obtained from IUs' data is similar in quality to the one provided by expensive laboratory-fixed instruments like optical systems. This paper presents an accurate two-step processing method, or PB-algorithm, based on considering polynomial data fitting followed by cubic splines and wavelet analysis, for drift cancellation in periodic movements with a single IU. In the case of the 30-s CST, it leads to obtaining automatically the test outcome (the number of completed cycles) as well as meaningful kinematic data for the evaluation of the movement execution as in [37]. It could also be applied to other tests dealing with stand-up or sit-down movements such as the Sit-to-Walk test, widely used in medical applications [38]. This could lead to an improvement of clinical settings as well as rehabilitation therapies and fall risk identification, which is nowadays based on parameters obtained from visual observations.

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REFERENCES

1. Martinez-Ramirez, A., Lecumberri, P., Gomez, M., and Izquierdo, M., "Wavelet analysis based on time-frequency information discriminate chronic ankle instability," *Clinical Biomechanics*, vol. 25, no. 3, pp. 256-264, Mar.2010.
2. Boonstra, M. C., van der Slikke, R. M. A., Keijsers, N. L. W., Van Lummel, R. C., Malefijt, M. C. D., and Verdonschot, N., "The accuracy of measuring the kinematics of rising from a chair with accelerometers and gyroscopes," *Journal of Biomechanics*, vol. 39, no. 2, pp. 354-358, 2006.
3. Moe-Nilssen, R. and Helbostad, J. L., "Trunk accelerometry as a measure of balance control during quiet standing," *Gait & Posture*, vol. 16, no. 1, pp. 60-68, Aug.2002.
4. Veltink, P. H. and Franken, H. M., "Detection of knee unlock during stance by accelerometry," *IEEE Transactions on Rehabilitation Engineering*, vol. 4, no. 4, pp. 395-402, Dec.1996.
5. Veltink, P. H., Bussmann, H. B., de, Vries W., Martens, W. L., and Van Lummel, R. C., "Detection of static and dynamic activities using uniaxial accelerometers," *IEEE Transactions on Rehabilitation Engineering*, vol. 4, no. 4, pp. 375-385, Dec.1996.
6. Jeon H, Kim SK, Jeon B, and Park KS, "Distance Estimation from acceleration for quantitative evaluation of parkinson tremor," *International Conference of the IEE Engineering in Medicine Biology Society*, vol. 6, pp. 393-396, 2011.
7. Fazio P, Graneri G, Casetta I, Cesnik E, Mazzacane S, Caliandro P, Pedrielli F, and Graneri E, "Gait measures with a triaxial accelerometer among patients with neurological impairment," *Neurological Sciences*, Mar.2012.
8. Yang, C. C., Hsu, Y. L., Shih, K. S., and Lu, J. M., "Real-Time Gait Cycle Parameter Recognition Using a Wearable Accelerometry System," *Sensors*, vol. 11, no. 8, pp. 7314-7326, Aug.2011.
9. Aminian, K., Trevisan, C., Najafi, B., Dejnabadi, H., Frigo, C., Pavan, E., Telonio, A., Cerati, F., Marinoni, E. C., Robert, P., and Leyvraz, P. F., "Evaluation of an ambulatory system for gait analysis in hip osteoarthritis and after total hip replacement," *Gait & Posture*, vol. 20, no. 1, pp. 102-107, Aug.2004.
10. Dejnabadi, H., Jolles, B. M., Casanova, E., Fua, P., and Aminian, K., "Estimation and visualization of sagittal kinematics of lower limbs orientation using body-fixed sensors," *IEEE Transactions on Biomedical Engineering*, vol. 53, no. 7, pp. 1385-1393, July2006.
11. Morris, J. R. W., "Accelerometry - Technique for Measurement of Human Body Movements," *Journal of Biomechanics*, vol. 6, no. 6, pp. 729-732, Nov.1973.
12. Padgaonkar, A. J., Krieger, K. W., and King, A. I., "Measurement of Angular Acceleration of A Rigid Body Using Linear Accelerometers," *Journal of*

Applied Mechanics-Transactions of the Asme, vol. 42, no. 3, pp. 552-556, 1975.

13. Rehbinder H. and Hu X.M., "Drift-free attitude estimation for accelerated rigid bodies," *Automatica*, vol. 40, no. 4, pp. 653-659, Apr.2004.
14. Willemsen, A. T. M., Frigo, C., and Boom, H. B. K., "Lower-Extremity Angle Measurement with Accelerometers - Error and Sensitivity Analysis," *IEEE Transactions on Biomedical Engineering*, vol. 38, no. 12, pp. 1186-1193, Dec.1991.
15. Najafi, B., Aminian, K., Loew, F., Blanc, Y., and Robert, P. A., "Measurement of stand-sit and sit-stand transitions using a miniature gyroscope and its application in fall risk evaluation in the elderly," *IEEE Transactions on Biomedical Engineering*, vol. 49, no. 8, pp. 843-851, Aug.2002.
16. Shen, S. C., Chen, C. J., and Huang, H. J., "A New Calibration Method for Low Cost Mems Inertial Sensor Module," *Journal of Marine Science and Technology-Taiwan*, vol. 18, no. 6, pp. 819-824, Dec.2010.
17. Latt, W. T., Veluvolu, K. C., and Ang, W. T., "Drift-Free Position Estimation of Periodic or Quasi-Periodic Motion Using Inertial Sensors," *Sensors*, vol. 11, no. 6, pp. 5931-5951, June2011.
18. Riviere, C. N. and Thakor, N. V., "Modeling and canceling tremor in human-machine interfaces," *IEEE Engineering in Medicine and Biology Magazine*, vol. 15, no. 3, pp. 29-36, May1996.
19. Riviere, C. N., Rader, R. S., and Thakor, N. V., "Adaptive canceling of physiological tremor for improved precision in microsurgery," *IEEE Transactions on Biomedical Engineering*, vol. 45, no. 7, pp. 839-846, July1998.
20. Tan, U. X., Veluvolu, K. C., Latt, W. T., Shee, C. Y., Riviere, C. N., and Ang, W. T., "Estimating displacement of periodic motion with inertial sensors," *IEEE Sensors Journal*, vol. 8, no. 7-8, pp. 1385-1388, July2008.
21. Veluvolu, K. C. and Ang, W. T., "Estimation of Physiological Tremor from Accelerometers for Real-Time Applications," *Sensors*, vol. 11, no. 3, pp. 3020-3036, Mar.2011.
22. Djuric-Jovicic M., Jovicic N., and Popovic D.B., "Kinematics of Gait: New Method for Angle Estimation Based on Accelerometers," *Sensors*, vol. 11, no. 11, pp. 10571-10585, Nov.2011.
23. Djuric-Jovicic M., Jovicic N., Popovic D.B., and Djordjevic A.R., "Nonlinear optimization for drift removal in estimation of gait kinematics based on accelerometers," *Journal of Biomechanics*, vol. 45, no. 16, pp. 2849-2854, Nov.2012.
24. Jones, C. J., Rikli, R. E., and Beam, W. C., "A 30-s chair-stand test as a measure of lower body strength in community-residing older adults," *Research Quarterly for Exercise and Sport*, vol. 70, no. 2, pp. 113-119, June1999.
25. Smith, W. N., Del Rossi, G., Adams, J. B., Abderlarahman, K. Z., Asfour, S. A., Roos, B. A., and Signorile, J. F., "Simple equations to predict concentric lower-body muscle power in older adults using the 30-second chair-rise test: a pilot study," *Clinical Interventions in Aging*, vol. 5, pp. 173-180, 2010.
26. Tang, H. W., Lin, P. S., Liu, H. H., Liu, S. C., Cheng, H. S., and Wong, A. M. K., "The relationships between knee extensor muscle strength and 30-s chair stand test in community-dwelling elderly of different health statuses," *Journal of Aging and Physical Activity*, vol. 16, pp. S176-S176, July2008.
27. Yuuji K, "The CS-30 test is a useful assessment tool for predicting falls in community-dwelling elderly people," *Rigakuryoho Kagaku*, vol. 23, pp. 441-445, 2008.
28. Toshimichi S, "Elderly people's stand up ability and excretion independence," *Rigakuryoho Kagaku*, vol. 22, pp. 89-92, 2007.
29. Yukiyasu M, "Relationship of a 30-second chair-stand tesst to gait performance in stroke patients.," *Rigakuryoho Kagaku*, vol. 19, pp. 69-73, 2004.
30. Baruth, M., Wilcox, S., Wegley, S., Buchner, D. M., Ory, M. G., Phillips, A., Schwamberger, K., and Bazzarre, T. L., "Changes in physical functioning in the Active Living Every Day program of the Active for Life Initiative," *Int.J.Behav.Med.*, vol. 18, no. 3, pp. 199-208, Sept.2011.
31. Foley, A., Hillier, S., and Barnard, R., "Effectiveness of once-weekly gym-based exercise programmes for older adults post discharge from day rehabilitation: a randomised controlled trial," *Br.J.Sports Med.*, vol. 45, no. 12, pp. 978-986, Sept.2011.
32. Marues, E., Carvalho, J., Pizarro, A., Wanderlay, F., and Mota, J., "The Influence of Physical Activity, Body Composition, and Lower Extremity Strength on Walking Ability," *Motor Control*, Sept.2011.
33. Janssen, W. G. M., Bussmann, J. B. J., Horemans, H. L. D., and Stam, H. J., "Analysis and decomposition of accelerometric signals of trunk and thigh obtained during the sit-to-stand movement," *Medical & Biological Engineering & Computing*, vol. 43, no. 2, pp. 265-272, Mar.2005.
34. Giansanti, D., Macellari, V., Maccioni, G., and Cappozzo, A., "Is it feasible to reconstruct body segment 3-D position and orientation using accelerometric data?," *IEEE Transactions on Biomedical Engineering*, vol. 50, no. 4, pp. 476-483, Apr.2003.
35. Giansanti, D., Maccioni, G., Benvenuti, F., and Macellari, V., "Inertial measurement units furnish accurate trunk trajectory reconstruction of the sit-to-stand manoeuvre in healthy subjects," *Medical & Biological Engineering & Computing*, vol. 45, no. 10, pp. 969-976, Oct.2007.
36. Angermann M, Robertson P, Kemptner T, and Khider M, "A High Precision Reference Data Set for Pedestrian Navigation using Foot-Mounted Inertial Sensors," *International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, Sept.2010.
37. Millor N., Lecumberri P. Gómez M. Martínez-Ramírez A. Izquierdo M., "An evaluation of the 30-s chair stand test in older adults:frailty detection based on kinematic parameters from a single inertial unit," *Journal of*

NeuroEngineering and Rehabilitation, vol. 10, pp. 86-95, 2013.

38. Dehail, P., Bestaven, E., Muller, F., Mallet, A., Robert, B., Bourdel-Marchasson, I., and Petit, J., "Kinematic and electromyographic analysis of rising from a chair during a "Sit-to-Walk" task in elderly subjects: Role of strength," *Clinical Biomechanics*, vol. 22, no. 10, pp. 1096-1103, Dec.2007.