Assessment of gait direction changes during straight-ahead walking in healthy elderly and Huntington Disease patients using a shank worn MIMU

D. Trojaniello-*IEEE Student Member*, A. Cereatti, A. Ravaschio, M. Bandettini and U. Della Croce

***Abstract*— The aim of this study was to propose and comparatively evaluate four methods for assessing stride-by-stride changes of direction of progression, during straight walking using measurements of a magnetic and inertial unit placed above the malleolus. The four methods were evaluated by comparing their estimate of the gait changes of direction of progression with that obtained from an instrumented gait mat used as a gold standard. The methods were applied to the data obtained from the gait of both healthy subjects and patients with Huntington Disease, the latter characterized by a jerky swing phase. The results showed that the errors associated to the best estimates of the gait direction changes were about 10% of its range of variability for the healthy subjects and increased to about 30% for the patients, both walking at comfortable speed when the range of variability is the largest. Additional testing on gait at various radius of curvature should be carried out to fully validate the MIMU-based estimates.**

I. Introduction

Physiological gait requires the capability of holding the programmed direction of progression. The control of the direction of progression is provided by the vestibular system in conjunction with inputs from the visual and somato-sensory systems. The ability of maintaining a pre-planned straight path is compromised in those subjects who suffer from vestibular deficits [1]. Deviations from straight gait can also be induced by blindfolding healthy subjects undergoing a galvanic stimulation [2]. Even gait disorders not involving vestibular dysfunctions, such as Huntington disease (HD), also known as "drunken gait", are characterized by staggering from side to side, with lateral swaying, and stride-by-stride lateral deviations from forward direction [3,4]. The clinical tests generally adopted to assess the changes of direction during straight walking (GDC) such as the Babinski-Weil test routinely applied to subjects with vestibular deficits [5] or the tandem gait test used in the HD assessment [6], do not provide a stride-by-stride quantitative GDC estimates. Other tools such as clinical scales only provide scores of abnormal deviations during tandem gait (Unified Huntington's Disease Rating Scale, UHDRS [7]) or moderate to marked deviations along a straight path (Tinetti balance assessment scale - gait section [8]). An accurate and objective GDC estimate would therefore be useful in clinical contexts.

Research partially supported by the V-TIME project funded by the European Commission under the 7th Framework Program, grant #278169.

D.T., A.C., U.D.C. are with the POLCOMING Department, Information Engineering Unit, University of Sassari, Italy and with the Interuniversity Centre of Bioengineering of the Human Neuromusculoskeletal System (corresponding author e-mail: dtrojaniello@uniss.it).

A. R. and M.B. are with Department of Neurosciences, University of Genoa, Italy (e-mail: aravaschio@gmail.com).

In instrumented clinical gait analysis, a quantity that could be used to properly estimate the GDC is the direction of progression (DoP). Its stride-by-stride changes can assess the ability of a subject of maintaining a straight path. Recently, Miranda et al [5] proposed a simple method for quantifying the GDC during the Babinski-Weill test in healthy subjects. However, they provided only an evaluation of the overall GDC (from the start to the end of the path). Other studies used stereo-photogrammetry or floor markers to evaluate deviations from a straight path [9,10].

In recent years, several methods based on magnetic and inertial measurement units (MIMU) for the estimate of turning parameters [11-13] have been proposed. They are designed to analyze curved paths, and are mostly based on the angular velocity signals recorded on the trunk and, therefore, do not allow for a proper estimation of the GDC along straight paths.

The aim of this preliminary study is to propose and evaluate four methods for estimating the GDC while walking along a straight path using a single MIMU attached above the ankle. The methods were applied to the gait of healthy elderly subjects and subjects with HD. Simultaneous measurements from an instrumented gait mat were used as a gold standard.

II. Material and Methods

A. Instrumentation

One MIMU (Opal^{TM}, APDM, Inc, APDM, Inc) was attached to the subject's shank about 20 mm above the lateral malleolus (Fig. 1). The performance of the MIMU (spot check) was tested according to the guidelines proposed by [14]. The MIMU measures accelerations, angular velocities and local magnetic field with respect to the axes of a local frame (LF) aligned to the edges of the unit housing. An estimate of the LF orientation with respect to the global frame (GF) was provided by an on-board Kalman filter. An instrumented gait mat (GAITRite^{TM} Electronic Walkway, CIR System, Inc) acquiring at 120 Hz (length: 9 m, spatial resolution accuracy: ±12.7 mm; temporal accuracy: ±1 sample) was used for validation purposes. The dedicated software (PKMAS, ProtoKinetics, LLC) returned all temporal and spatial gait parameters, including the DoP defined as the angle of the vector joining the heel footprint of two consecutive heel strikes of the same foot (degrees) with respect to the mat midline. Stride-by-stride DoP changes were used as GDC reference values. The MIMU and the instrumented mat were synchronized (±1 sample).

Figure 1. The MIMU attached above the subject's ankle.

B. Subjects

The study included ten healthy elderly (E) subjects (six females, four males, mean ± *sd*; age: 68.7 ± *5.8* y.o., BMI: 24.3 ± *1.5*) and ten HD patients (three females, seven males, mean ± *sd*; age: 54.2 ± *11.9 y.o.*, BMI: 23.6 ± *4.3*) enrolled from the outpatient Movement Disorders Clinic of the University of Genoa. Disease severity was determined by means of the UHDRS. The inclusion criteria were patients who had (1) a confirmed diagnosis of HD and (2) the UHDRS score relative to the gait and tandem walking greater than or equal to 1.

C. Acquisition protocol

Subjects were asked to walk back and forth for about one minute along a 12-meter walkway with the instrumented gait mat placed two meters from the starting line where they stood with their feet together for a few seconds after the beginning of the MIMU acquisition. Subjects walked wearing their shoes both at self-selected, comfortable speed (V1) and higher speed (V2) (i.e. maximum walking speed). In between acquisitions subjects could take a rest.

D. Gait Direction Changes estimation

The MIMU raw signals, proper acceleration and angular velocity, were expressed in the GF using the quaternion provided by on-board Kalman filter. The gravity contribution was then removed from the acceleration signals obtaining the acceleration ($^{G}a(t)$). Gait cycles were isolated using the algorithm proposed in [15].

By integrating $^{G}a(t)$ within the j^{th} gait cycle using 30% of the stance time as zero-update timing (ZUPT) [16], an estimate of the velocity variation $^{G}\hat{v}(t)_j$ from the cycle initial value $^{G}v(0)_j$ was obtained as in (1):

$$^{G}\hat{v}(t)_j = {}^{G}v(t)_j - {}^{G}v(0)_j = \int_{jZUPT_i}^{jZUPT_f} {}^{G}a(t)_j\,dt \qquad (1)$$

and the mean velocity variation for each gait cycle was then computed as in (2):

$$^{G}\bar{v}(j) = avg(^{G}\hat{v}(t)_j) \qquad (2)$$

during (i) the swing phase (*Method 1*) and (ii) the entire gait cycle (*Method 2*). The $^{G}\bar{v}(j)$ is then projected on the horizontal plane and the angle between $^{G}\bar{v}(j)$ and $^{G}\bar{v}(j+1)$ is obtained and used to define the GDC of the gait cycle *j*+1 with respect to the previous cycle (Fig. 2). The GDC was also estimated (iii) as the angle between the mean unit vector of the angular velocity $^{G}\bar{\omega}(t)_j$ during the swing phase of two consecutive strides (*Method 3)* and (iv) by computing the displacement $^{G}s(j)$ along the three directions obtained with a further integration of $^{G}v(t)_j$ throughout the gait cycle (*Method 4*). A summary description of the methods is reported in Table II.

TABLE II SUMMARY OF THE FOUR GDC ESTIMATION METHODS

Method	**Vector**	**Time interval**
M1	$^{G}\bar{v}(j)$	Swing phase
M2	$^{G}\bar{v}(j)$	Gait cycle
M3	$^{G}\bar{\omega}(t)_j$	Swing phase
M4	$^{G}s(j)$	Gait cycle

E. Data analysis

An estimate of the GDC range, determined as the interval between minimum and maximum GDC as obtained from the instrumented gait mat, was computed for both E and HD groups.

The error, defined as the difference between the MIMU-based and the instrumented gait mat GDC estimates, was determined for the tested methods. For each subject, the GDC mean absolute error (*mae*) was calculated.

III. RESULTS

The mean and standard deviation values of the gait speeds V1 and V2 for both E and HD subjects are reported in Fig. 3. The mean and standard deviation values of the GDC ranges for both E and HD subjects and for both gait speeds are shown in Fig. 4.

In Fig. 5 the mean value of the *mae* and its *sd* of all four MIMU-based GDC estimation methods computed over the gait tests of E and HD subjects are reported for both gait speeds. The same *mae* values, normalized with respect to the relevant GDC ranges, are reported in Fig. 6. Three gait tests were removed from the analysis due to technical issues.

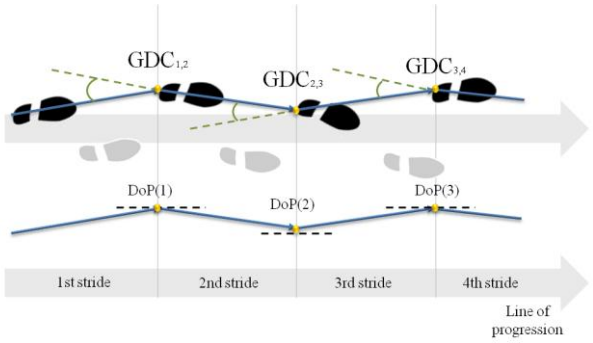

Figure 2. Changes of DoP during straight walking (GDC).

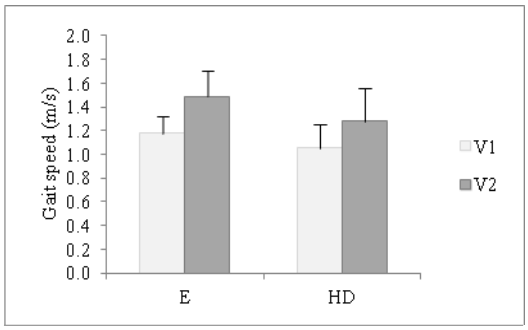

Figure 3. Mean and standard deviation values of the gait speed (as determined by the gold standard) for both the E and HD subjects groups for each gait speed trial (V1, V2).

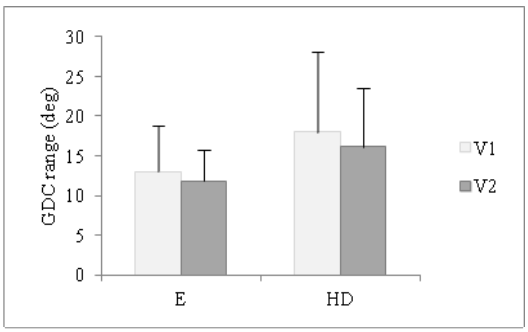

Figure 4. Mean and standard deviation values of the GDC ranges (as determined by the gold standard)for both the E and HD subjects groups for each gait speed trial (V1, V2).

IV. DISCUSSION

Wearable inertial sensors may potentially estimate changes in the direction of progression, among other key gait characteristics, when walking outdoors and for extended time opening new scenarios in the assessment of people's gait. In fact, the relationship between gait speed and direction could be a prognostic parameter to use for monitoring the rehabilitation outcome of HD patients [17]. In this study we proposed and compared four methods for a MIMU-based stride-by-stride estimation of the gait direction changes in both healthy and subjects affected by a disease known to increase the variability of gait patterns. We chose to evaluate the tested methods on groups characterized by extremely different gait features expecting to make the validation more robust than if performed on a group of healthy subjects as it is often the case in the literature on MIMU applications. For example, Schafer et al [18] proposed a method to be applied to MIMUs attached to the feet in order to determine the heading information from gait cycle patterns only on healthy subjects and without reporting errors in estimating the GDC. The best performing tested methods (*Method 1* and *Method 3*) showed *mae* values about one order of magnitude lower than the GDC range for the E subjects at comfortable speed, but even if they remain the best performing methods, their performance worsened remarkably when applied to the HD subjects at comfortable speed (*mae* of about 30% of GCD range).

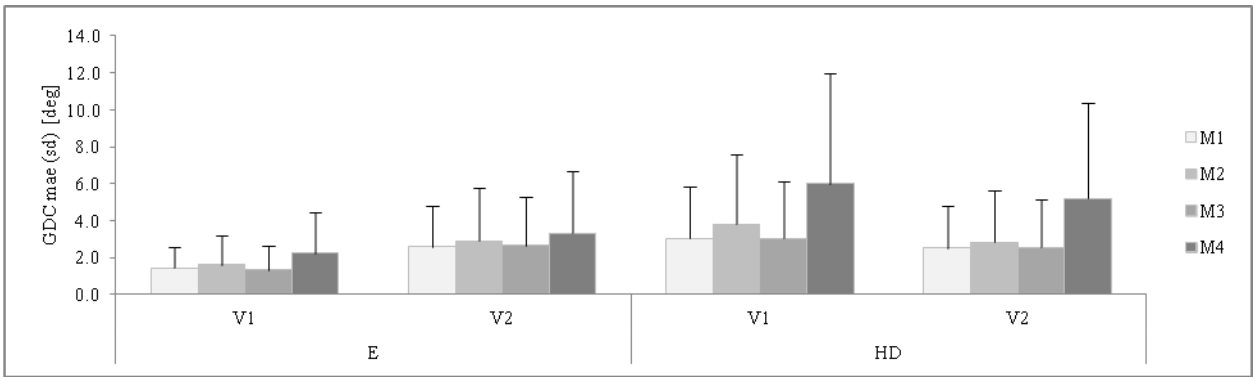

Figure 5. Average values and standard deviation over the E and HD subjects of the mean absolute error (*mae*) of the MIMU-based GDC estimates for both comfortable (V1) and fast (V2) gait speeds.

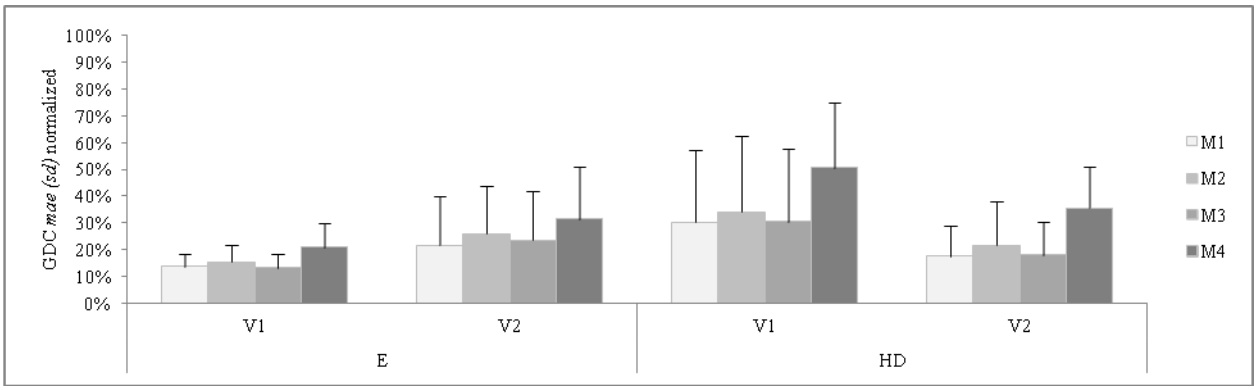

Figure 6. Average values and standard deviation over the E and HD subjects of the mean absolute error (*mae*) of the MIMU-based GDC estimates for both comfortable (V1) and fast (V2) gait speeds normalized with respect to the GDC ranges.

This might be due to the higher variability of the swing patterns typical of the HD subjects at lower speeds, consistently with the findings of other studies carried out on both healthy subjects and patients suffering of vestibular deficits [19]. As expected, lower errors in estimating GCD were found in the gait of the E group for both speeds. However, the performance of all methods (with the exception of *Method 4*), when applied to the two groups higher gait speed was very similar.

Method 1 and *Method 3* can better estimate the GCD since they only take into consideration the portion of the gait cycle that determines for the most part the direction of progression. Methods including the stance phase are more prone to instrumental errors such as the drift typical of MIMU measurements. Moreover, the "drunken gait" characteristic of HD subjects includes lateral swaying during stance, especially at lower speeds, that can increase the variability of the direction of both angular and linear velocity in stance.

Additional analysis on HD subjects aimed at investigating the influence of gait speed on the GCD estimates accuracy and at assessing the methods performance during different experimental conditions such as the tandem gait test (slowly walking in a straight line, touching the heel of one foot to the toes of the other), would be desirable. Additional information on gait progression (i.e. the DoP estimated from both foot and pelvis kinematics), a wider range of walking paths and more extended data acquisitions should also be implemented to further validate MIMU-based GDC estimates.

REFERENCES

[1] L. Borel, C. Lopez, P. Péruch, and M. Lacour, "Vestibular syndrome: a change in internal spatial representation.," *Neurophysiol. Clin*., vol. 38, no. 6, pp. 375–89, Dec. 2008.

[2] L. R. Bent, B. J. McFadyen, V. F. Merkley, P. M. Kennedy, and J. T. Inglis, "Magnitude effects of galvanic vestibular stimulation on the trajectory of human gait.," *Neurosci. Lett*., vol. 279, no. 3, pp. 157–60, Feb. 2000.

[3] S. Palliyath, M. Hallett, S. L. Thomas, H. K. Lebiedowska. "Gait in patients with cerebellar ataxia". *Mov Disord*., vol. 13(6), pp.:958-64, Nov 1998.

[4] C. Wider, "Huntington's disease: clinical and aetiologic aspects," *Schweizer Archiv F Neurologie Und Psychiatrie*, pp. 378–383, 2006.

[5] C. S. Miranda, C. P. Stefani, M. M. Morimoto, M. E. P. Piemonte, and C. B. Pereira, "Assessment of gait deviation on the Babinski-Weill test in healthy Brazilians.," *Arq. Neuropsiquiatr*., vol. 71, no. 9A, pp. 615–20, Sep. 2013.

[6] H. Brožová, J. Stochl, J. Klempíř, M. Kucharík, E. Růžička, and J. Roth, "A sensitivity comparison of clinical tests for postural instability in patients with Huntington's disease.," *Gait & Posture*, vol. 34, no. 2, pp. 245–7, Jun. 2011.

[7] Huntington Study Group. Unified Huntington's Disease Rating Scale: reliability and consistency. *Mov. Disord.,* 1996;11:136–142.

[8] Tinetti, M.E.; Williams, T. Frankin; Mayewski, R. "Fall risk index for elderly patients based on number of chronic disabilities". *American Journal of Medicine,* 80 (3): 429–434, 1986

[9] K. Jahn, M. Strupp, E. Schneider, et al. "Differential effects of vestibular stimulation on walking and running." *Neuroreport*, vol. 11, pp. 1745-1748, 2000.

[10] N. Deshpande, A. E. Patla "Postural responses and spatial orientation to neck proprioceptive and vestibular inputs during locomotion in young and older adults". *Exp. Brain. Res.*, vol. 167, pp. 468-474, 2005.

[11] P. Crenna, I. Carpinella, M. Rabuffetti, et al. "The association between impaired turning and normal straight walking in Parkinson's disease" *Gait & Posture*, vol. 26, iss. 2, pp. 172-178, Jul 2007.

[12] M. El-Gohary, S. Pearson, J. McNames, et al. "Continuous Monitoring of Turning in Patients with Movement Disability", *Sensors,* vol. 14, pp. 356-369, 2014.

[13] A. Salarian, C. Zampieri, F. B. Horak, P. Carlson-Kuhta, J. G. Nutt, and K. Aminian, "Analyzing 180° turns using an inertial system reveals early signs of progression of parkinson's disease," C*onf. Proc. Int. Conf. IEEE Eng. Med. Biol. Soc*., vol. 2009, pp. 224–227, 2009.

[14] P. Picerno, A. Cereatti, and A. Cappozzo, "A spot check for assessing static orientation consistency of inertial and magnetic sensing units" *Gait & Posture*, vol. 33, no. 3, pp. 373–378, Mar. 2011.

[15] D. Trojaniello, A. Cereatti, G. Paolini, et al. "Temporal gait parameters determination from shank-worn mimu signals recorded during healthy and pathological gait," *Conf. Proc. XXIV ISB* 2013

[16] A. Peruzzi, U. Della Croce, and 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. Biomech*., vol. 44, no. 10, pp. 1991–1994, Jul. 2011.

[17] Quinn L, Rao AK "Physical therapy for people with Huntington disease: current perspectives and case report," *Neurology Report,* 26: 145–153, 2002.

[18] B. Schafer "Determination of heading information from gait cycle pattern using stride length estimation with reduced IMUs on right and left foot," *Conf. Proc. IPIN*, 21-3, 2011.

[19] R. Dickstein, S. Ufaz, A. Dunsky, S. Nadeau, N. Abulaffio "Speed-dependent deviations from a straight-ahead path during forward locomotion in healthy individuals", *Am. J. Phys. Med. Rehabil.,* vol. 84(5), pp. 330-7, May 2005.