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Wearable Systems with Minimal Set-up for Monitoring and Training of Balance and Mobility

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Abstract— **With the objective to release solutions which can be easily manageable by their final users, including older users, we worked to design methods and devices which rely on a minimal set-up for monitoring and rehabilitation of balance and mobility. A single inertial sensing unit, typically worn on the trunk, was hence engineered to accomplish for activity monitoring and event detection (including fall detection), tremor rejection, instrumented clinical tests (e.g. stabilometry, Timed-Up and Go), and sensory biofeedback (audio, visual or tactile). The sensing unit is wirelessly connected with a processing unit, which can in turn act as a gateway to remote applications or caregivers. Promising results were obtained, which may pave the way to novel intensive and pervasive neurorehabilitation strategies.**

I. Introduction

INERTIAL tracking technologies are becoming widely accepted for the assessment of human movement in both clinical practice and scientific research. They favourably compare to commercial movement analysis systems in terms of cost, size, weight, power consumption, ease of use and, most importantly, portability, while showing, at the same time, a similar reliability [1]. This makes movement data collection no longer confined to a laboratory environment and opens new and promising opportunities for an ecological and intensive measurement of balance and mobility in real-life conditions. This objective requires a mature technology but also appropriate methods for managing the (on-line or off-line) processing, compression and mining of inertial data.

The use of accelerometers in gait and balance evaluation is supported by theoretical arguments and results of prior studies (e.g. see [2],[3]). An increasing number of studies make use of accelerometers to characterize human gait or classify physical activities. Only a few studies, nevertheless, have employed accelerometers to investigate balance control during standing [4],[5] or have extensively compared information from force plate and accelerometer measures [6],[7]. We recently worked on designing prototypes, protocols, and signal analysis techniques with the aim to release smart wearable systems with a minimal set-up (i.e. a single sensing and processing unit) which can account for reliable estimates of balance and mobility functions by minimizing information loss compared to more complex systems.

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Postural instability, gait disturbances and falls are a leading cause of morbidity and mortality among older adults [8], especially among patients suffering from a neurodegenerative disease like Parkinson's disease (PD). While much is known at the present about the multi-factorial nature of gait disturbances and falls, there are still many questions regarding the best therapeutic means of improving these impairments and thus reducing fall risk.

The use of laboratory-based biofeedback has been offered in the past as an instrument for training that enables an individual to learn how to change physiological activity or behavior for the purposes of improving performance. Inertial sensors provide the mean for developing wearable biofeedback platforms that are suitable for home-based training and rehabilitation.

Based on our previous laboratory-based studies [9],[10], we hypothesized that deficits in postural control can be positively influenced by sensory Bio-Feedback (BF)-based dynamic balance training and that this training can be offered directly in patients' homes.

This paper presents a survey of some of the research issues we addressed, in the Biomedical Engineering Group of the University of Bologna, in the field of wearable systems for monitoring and training of balance and mobility.

II. Methods

A. *Study 1: Accelerometer-based estimate of anticipatory postural adjustments*

After proving that accelerometers can reliably detect characteristics of anticipatory postural adjustments (APAs) before step initiation [11] we investigated whether accelerometers can be used to characterize subtle step initiation deficits in subjects with early-to-moderate, untreated PD [12] which may then degenerate later on in the disease in start hesitation and motor blocks. Eleven PD (UPDRS III=29±1.0/108) and 12 age-matched healthy control subjects were asked to take two steps moving from a force plate (AMTI OR6-6). Postural adjustments were compared from center of pressure (COP) and from acceleration of the trunk at the center of mass level (MTx, 49A33G15, XSens).

B. *Study 2: Accelerometer-based stabilometry*

We investigated whether it is feasible to use accelerometers similarly to force plates to quantify body sway [13]. Postural performance during quiet standing (QS) and voluntary trunk sway (TS) was assessed in five young and healthy subjects using a force plate (BERTEC 4060-08) and four accelerometers (MTx, 49A33G15, XSens). Subjects wore the sensing units via Velcro belts laterally on the right thigh and on the posterior trunk, at the level of L5, T10, and C7. By means of single- (SS) and double segment (DS) models of the body we computed accelerometry-based estimates of COP with the four accelerations used one at the time in SS, and with three different couples of accelerations in DS. In order to assess and quantify the relationship between COP and accelerations, we performed a linear regression analysis between the COP signal and the acceleration signals at the four different measurement sites, during QS and TS trials.

C. Study 3: Accelerometer-based tremor estimation and filtering

Tremor, which is a common symptom of several disorders of the central and peripheral nervous system, including PD, may mask the underlying postural stabilization process and, in turn, affects postural measures and leads to biased results in stabilometry. We proposed a new method for tremor removal based on Hilbert–Huang transformation (HHT) [14]. We compared the effectiveness of linear low-pass filters (LPF) and HHT-based filtering on a set of postural parameters extracted from acceleration signals.

We examined the quiet standing of 20 PD subjects, with and without tremor ('tremor at rest' item of UPDRS III=3.35±2.5/20), and 20 age-matched healthy control subjects. Subjects were wearing at L5 a triaxial accelerometer (McRoberts Dynaport Micromod; sample rate = 100 Hz, range = ±2 g).

D. Study 4: Sensitivity of accelerometer-based measures of postural sway to early, untreated PD

Abnormalities of postural sway associated with untreated PD have not been reported, yet. Although not clinically apparent, we hypothesized that spontaneous sway in quiet stance is abnormal in people with untreated PD [15].

We examined 13 subjects, recently diagnosed with PD (UPDRS III=28.1±11.2/108), who were not yet taking any anti-parkinsonian medications and 12 healthy, age-matched control subjects. Postural sway was measured with a linear accelerometer (MTx, 49A33G15, XSens) at L5 and compared with traditional forceplate (AMTI OR6-6) measures of sway. Subjects stood for two minutes under two conditions: eyes open (EO) and eyes closed (EC).

E. Study 5: Feature selection for accelerometer-based posture and TUG analysis in Parkinson's Disease

We investigated the sensitivity to PD-related postural instability of a broad set of 175 measures computed from acceleration signals, including postural acceleration, postural displacement, and tremor measures (see Fig.1) [16]. Twenty early-mild PD (UPDRS III=26.6±7.1/108) and 20 age matched healthy control subjects, wearing an accelerometer at L5, were tested in five conditions characterized by

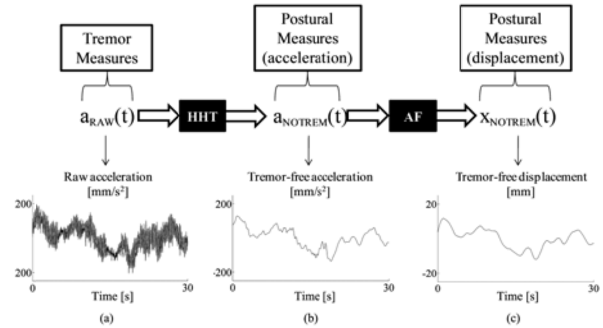

Fig. 1. Schematic representation of the different processing stages of the acceleration signals. (a) Raw acceleration is filtered by the HHT [14], obtaining (b) tremor-free acceleration; then the anthropometric filter (AF) is applied to get (c) tremor-free displacement

different degrees of sensory and attentional perturbation. Different testing conditions were considered in order to identify those sensory and attentional demands that, in QS, are more capable of disclosing postural differences between PD and control subjects. Conditions include manipulations of the visual and peripheral somatosensory input, and a dual task paradigm challenging attentional and cognitive resources of subjects.

Feature selection was implemented to identify the subsets of measures that better characterize the distinctive behavior of PD and control subjects. It was based on different classifiers and on a nested cross validation, to maximize robustness of selection with respect to changes in the training set. The classifiers that we considered in this study are some of the most popular classifiers, namely the linear and quadratic discriminant analysis, Mahalanobis classifier, logistic regression, K-nearest neighbors, and support vector machines.

A similar methodology was used for feature selection on a set of 56 temporal, coordination and smoothness measures computed from acceleration signals during an instrumented Timed-Up & Go (TUG) test carried out on the same population [17]. A wrapper feature selection was implemented for different classifiers with an exhaustive search for subsets from 1 to 3 features. A leave-one-out cross validation (LOOCV) was implemented both for the feature selection and for the evaluation of the classifier, resulting in a nested LOOCV.

F. Study 6: Neurorehabilitation potentials of a wearable BF system

Within the activities of the EU-funded SensAction-AAL project we advanced in the design and validation of a previous portable prototype of an Audio-BF (ABF) system for balance and mobility [18].

Augmentation of sensory information, such as during ABF of the trunk acceleration, has been shown to improve postural control [19]. By means of quantitative electroencephalography (EEG), we examined the basic processes in the brain that are involved in the perception and cognition of auditory signals used for ABF [20]. ABF and Fake ABF (FAKE) auditory stimulations were delivered to

10 healthy naive participants during quiet standing postural tasks, with eyes-open and closed. Trunk acceleration and 19-channels EEG were recorded at the same time. Advanced, state-of-the-art EEG analysis and modeling methods were used to assess the possibly differential, functional activation, and localization of EEG spectral features (power in α, β, and γ bands) between the FAKE and the ABF conditions, for both the EO and the EC tasks.

Based on the observation that physical therapy may have a positive effect in neurodegenerative disorders such as Progressive supranuclear palsy (PSP) and PD, and considering the promising results of the ABF training in patients with peripheral vestibular deficits [9],[10], we hypothesized that PSP and PD deficits in postural control may also be influenced by ABF-based posture and dynamic balance training.

To this aim, a first uncontrolled intervention study, with a 6-week intervention to improve posture and dynamic balance was conducted in a 1:1 setting three times per week for approximately 45 minutes in a geriatric rehabilitation center in southern Germany [21]. Assessments were performed within 1 week before the beginning of the intervention (T1), within 1 week after the last training session (T2), and 4 weeks after the completion of the intervention (T3). The intervention involved 8 PSP patients (median age 66 years).

In a second study run in Tel Aviv, 7 patients with PD were recruited for a similar 6-week intervention program [22]. The training was individualized to each patients needs and was delivered using the ABF system. The training was focused on improving posture, sit-to-stand abilities, and dynamic balance in various positions. Non parametric statistics were used to evaluate training effects.

III. Results

A. Study 1: Accelerometer-based estimate of anticipatory postural adjustments

APAs measured from the peak COP displacement toward the swing leg and the peak trunk acceleration toward the stance leg were smaller in untreated PD compared with control subjects [12]. The magnitude of APAs measured from peak COP displacements and accelerations were correlated.

Reduced APAs are a specific, primary symptom of PD, responsible for severe balance and mobility problems [23]. In this study, we found small peak APAs in subjects with mild PD, even though the velocity and length of their first steps were not slower or smaller than steps of control subjects. These results are consistent with separate, interacting motor programs for neural control of APAs and the step itself [23],[24]. Early PD may affect the supplementary motor cortex, responsible for APAs before it affects the primary motor cortex and other areas responsible for generating force for stepping [25].

These results suggest that quantitative analysis of step initiation from one accelerometer on the trunk could provide useful information for the characterization of patients in early stages of PD, when clinical evidence of start hesitation may not be detectable. Ambulatory monitoring of step initiation is also promising for monitoring patient progression in the home environment, and eventually providing feedback for preventing freezing of gait episodes.

B. Study 2: Accelerometer-based stabilometry

We obtained [13] root mean square errors between measured and estimated COP which are comparable with the accuracy of the force plate: 1.1±0.1 mm (QS) and 6.0±1.1 mm (TS) with the SS model using the thigh acceleration, and 0.9±0.06 mm (QS) and 4.6±0.6 mm (TS) with the DS model using the combination of thigh and L5 accelerations. In addition, model parameters in QS were well in line with values from anthropometric tables disclosing interesting developments for the proposed methodology. Lastly, we found a very good correlation ($0.90<r<0.98$) between the performance measures computed from measured and accelerometer-based COP. Such high correlations are important since performance measures computed from the COP have proved able to distinguish conditions [26] or discriminate between people with and without balance disorders [27].Based on these results we can conclude that accelerometers could be used to provide information similar to force-plates to assess postural performance.

C. Study 3: Accelerometer-based tremor estimation and filtering

HHT can be used to effectively remove tremor artifacts from accelerometer-based postural parameters in those trials of PD, which are most affected by this non-stationary symptom of the disease [14]. We compared the performance of HHT and a linear filter showing that LPF and HHT-based filtering lead to similar results when subjects do not have tremor. However, some postural parameters (mean velocity, frequency-domain parameters, and jerk) are strongly affected by high-frequency tremor components; thus, inefficient tremor suppression may mask the underlying postural performance. Using LPF, cutoff frequency and the order of the filter must be accurately set to avoid misleading results and interpretations. On the other hand, HHT is a very powerful tool for signal analysis, capable of handling nonlinear and nonstationary signals.

On the basis of these results HHT-based filtering can be recommended as an efficient and robust tool for tremor removal that allows the preservation of local dynamics without sacrificing frequency bandwidth (see Fig.1). Further, the results obtained using HHT (and not LPF) closely match the classification of different PD phenotypes with distinct clinical patterns, benign (tremor-dominant) and malign (bradykinesia, rigidity, and gait and posture disabilities), which may disclose in the future different neurorehabilitation strategies [28].

D. Study 4: Sensitivity of accelerometer-based measures of postural sway to early, untreated PD

The key findings of this study [15] are: 1) postural control is affected in subjects with untreated PD; 2) acceleration-based parameters are able to distinguish between the two groups as well as COP parameters.

One of the parameter that best discriminated postural sway between untreated PD and control subjects was JERK of the lower trunk. JERK, the relative smoothness of postural sway can be interpreted as a measure of dynamic stability, reflecting the amount of active postural corrections. It is not likely due simply to changes in postural tone or movement speed clinically apparent in untreated PD because it did not correlate with the Motor UPDRS or its rigidity or bradykinesia subcomponents. It is possible, however, that increased JERK reflects increases in axial rigidity at the trunk that is not measured in the UPDRS but can be shown to be increased in early-to-moderate PD using sensitive torque measures [29]. The JERK increase in our subjects was not due to resting tremor because we low-pass filtered the acceleration signals at 3.5 Hz to eliminate parkinsonian resting tremor that ranges from 4 to 7 Hz and JERK did not correlate with Motor UPDRS tremor. Previous studies of patients with Parkinson's disease [30] reported statistically significant abnormalities of JERK measures in handwriting likely related to a reduced capability to coordinate the finger and wrist and by reduced control of wrist flexion.

Root mean square and the frequency dispersion of postural sway in the EO condition also discriminated sway in untreated PD subjects compared to controls subjects.

E. Study 5: Feature selection for accelerometer-based posture and TUG analysis in Parkinson's Disease

We found the appropriate combination of measures that could best discriminate between early-mild PD subjects and CTRL subjects [16]. Results revealed that feature selection procedures based on different classifiers were comparable in terms of accuracy in discriminating between PD and CTRL subjects (5% of misclassification rate). Therefore in similar circumstances, attention should be focused on the feature selection procedure rather than on building new or complex classifiers. We obtained good classification results with only three measures, showing that several redundant or irrelevant features were in the dataset. Selected measures included a tremor-related measure, a postural measure in the frequency domain, and a postural displacement measure. The proposed feature selection hence is useful to: 1) optimize the experimental protocol and reduce the cost of data acquisition; 2) reduce the computational costs; 3) improve clinical understanding of the results; 4) help in data visualization; and 5) improve classification accuracy.

As far as TUG is concerned [17] the resulting selected features allow obtaining a good accuracy (7.5% of misclassification rate) in the classification of PD. Interestingly the traditional TUG duration was not selected in any of the best subsets.

Results suggest that quantitative analysis of balance and mobility using a single accelerometer and a simple test protocol may provide useful information to characterize early PD subjects. This protocol is potentially usable to monitor the disease's progression and hence personalize neurorehabilitation.

F. Study 6: Neurorehabilitation potentials of a wearable BF system

Healthy participants [20] gained advantage by ABF in reducing their postural sway, as measured by a reduction of the root mean square of trunk acceleration during the ABF compared to the FAKE condition. EEG outcomes supported the idea that ABF for postural control heavily modulates (increases) the cortical activation in healthy participants. The sites showing the higher ABF-related modulation are among the known cortical areas associated with multi-sensory, perceptual integration, and sensorimotor integration, showing a differential activation between the EO and EC conditions.

Both PSP [21] and PD [22] patients well accepted the wearable ABF device and no adverse events occurred.

In the PSP group a significant improvement in the Berg Balance Scale was observed (T2 vs. T1, $p=0.016$), which remained significant at the 4-week follow-up (T3 vs. T1, $p=0.008$). Significant improvement of the PD questionnaire was demonstrated. No significant changes were found in the TUG, the Five Chair Rise Test, and in specific clinical scales

In the PD group a significant improvement of balance, as assessed by the Berg Balance Scale, was observed (improvement of 3%, $p=0.032$), and a trend in the TUG (improvement of 11%, $p=0.07$). In addition, the training appeared to have a positive influence on psychosocial aspects of the disease as assessed by the PD quality of life questionnaire (PDQ-39) and in the level of depression as assessed by the geriatric depression scale.

IV. Discussion

A wearable accelerometer attached to a patient's belt seems a practical yet inexpensive alternative to forceplate measures of postural sway because it is an unobtrusive and accurate measure of postural control that can be used in a variety of settings. We proved its suitability for early clinical trials and for monitoring the effects of treatment of tremor, balance disorders and gait disabilities in subjects with PD. Further studies are needed to determine the reliability and sensitivity of accelerometry-based measures of postural sway. Longitudinal studies of postural sway are also needed to determine if acceleration parameters might be sensitive descriptor of disease progression and hence useful in clinical trials of neuroprotective interventions.

Preliminary evidences of the neurorehabilitation potential of wearable ABF are encouraging but further work is needed to investigate larger populations and to personalize the sensory feedback in order to implement home-based training strategies for patients with PD, a cohort which does not yet have sufficient or therapeutically valid options for improving postural instability and alleviate gait disturbances.

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References

[1] S.L. Whitney, J.L. Roche, G.F. Marchetti, C.C. Lin, D.P. Steed, G.R. Furman, M.C. Musolino, and M.S. Redfern, "A comparison of accelerometry and center of pressure measures during computerized dynamic posturography: A measure of balance," *Gait Posture*, vol. 33, pp. 594-599, 2011.

[2] K.M. Culhane, M. O'Connor, D. Lyons, and G. M. Lyons, "Accelerometers in rehabilitation medicine for older adults," *Age Ageing*, vol. 34, no. 6, pp. 556-560, Nov.2005.

[3] R. Moe-Nilssen, "A new method for evaluating motor control in gait under real-life environmental conditions. Part 1: The instrument," *Clin. Biomech.* (Bristol, Avon), vol. 13, no. 4-5, pp. 320-327, June 1998.

[4] C. Y. Cho and G. Kamen, "Detecting balance deficits in frequent fallers using clinical and quantitative evaluation tools," *J. Am. Geriatr. Soc.*, vol. 46, no. 4, pp. 426-430, Apr.1998.

[5] R. Moe-Nilssen and J. L. Helbostad, "Trunk accelerometry as a measure of balance control during quiet standing," *Gait Posture*, vol. 16, no. 1, pp. 60-68, Aug.2002.

[6] R. E. Mayagoitia, J. C. Lotters, P. H. Veltink, and H. Hermens, "Standing balance evaluation using a triaxial accelerometer," *Gait Posture*, vol. 16, no. 1, pp. 55-59, Aug.2002.

[7] R. Moe-Nilssen, "Test-retest reliability of trunk accelerometry during standing and walking," *Arch. Phys. Med. Rehabil.*, vol. 79, no. 11, pp. 1377-1385, Nov.1998.

[8] "Guideline for the prevention of falls in older persons. American Geriatrics Society, British Geriatrics Society, and American Academy of Orthopaedic Surgeons Panel on Falls Prevention," *J. Am. Geriatr. Soc*., vol. 49(5), pp. 664-672, 2001.

[9] M. Dozza, L. Chiari, and F.B. Horak, "Audio-biofeedback improves balance in patients with bilateral vestibular loss," *Arch. Phys. Med. Rehab.,* vol. 86(7), pp. 1401-1403, 2005.

[10] F.B. Horak, M. Dozza, R. Peterka, L. Chiari, and C. Wall III, "Vibrotactile biofeedback improves tandem gait in patients with unilateral vestibular loss," *Ann. NY Acad. Sci.*, vol. 1164, pp. 279-281, May 2009.

[11] L. Rocchi, M. Mancini, L. Chiari, and A. Cappello, "Dependence of anticipatory postural adjustments for step initiation on task movement features: a study based on dynamometric and accelerometric data," in *Proc. 28th IEEE-EMBS Conf.*, New York City, USA, Aug 30-Sept 3, 2006, p.1489-1492.

[12] M. Mancini, C. Zampieri, P. Carlson-Kuhta, L. Chiari, and F.B. Horak, "Anticipatory Postural Adjustments prior to step initiation are hypometric in untreated Parkinson's disease: an accelerometer-based approach," *Eur. J. Neurol.*, vol. 16(9), pp. 1028-1034, Sept. 2009.

[13] L. Chiari, M. Mancini, L. Rocchi, and A. Cappello, "Accelerometer-based analysis of postural sway," *Clin. Biomech.* (submitted).

[14] S. Mellone, L. Palmerini, A. Cappello, and L. Chiari, "Hilbert-Huang Estimate of Tremor-Free Postural Properties from Accelerometers," *IEEE Trans. Biomed. Eng.*, vol. 58(6), pp. 1752-1761, June 2011.

[15] M. Mancini, F.B. Horak, C. Zampieri, P. Carlson-Kuhta, J.G. Nutt, and L. Chiari, "Trunk accelerometry reveals postural instability in untreated Parkinson's Disease," *Parkins. Rel. Disord.*, 2011 Jun 3 [Epub ahead of print].

[16] L. Palmerini, L. Rocchi, S. Mellone, F. Valzania, and L. Chiari, "Feature selection for accelerometer-based analysis of posture in Parkinson's disease," *IEEE Trans. Inf. Technol. Biomed.*, vol. 15(3), pp. 481-90, May 2011.

[17] L. Palmerini, L. Rocchi, S. Mellone, F. Valzania, and L. Chiari, "A clinical application of feature selection: quantitative evaluation of the locomotor function," in *Lecture Notes in Communications in Computer and Information Science*, Springer-Verlag, 2011 (in press).

[18] L. Chiari, M. Dozza, A. Cappello, F.B. Horak, V. Macellari, and D. Giansanti, "Audio-biofeedback for Balance Improvement: An Accelerometry-based System," *IEEE Trans. Biomed. Eng.*, vol.52(12), pp. 2108-2111, Dec 2005.

[19] M. Dozza, L. Chiari, B. Chan, L. Rocchi, F.B. Horak, and A. Cappello, "Influence of a Portable Audio-Biofeedback Device on Structural Properties of Postural Sway," *J. Neuroeng. Rehabil.*, vol. 2: 13, 31 May 2005.

[20] M. Pirini, M. Mancini, E. Farella, and L. Chiari, "EEG correlates of postural audio-biofeedback," *Hum. Mov. Sci.*, vol. 30(2), pp. 249-261, Apr 2011.

[21] S. Nicolai, A. Mirelman, T. Herman, A. Zijlstra, M. Mancini, C. Becker, U. Lindemann, D. Berg, and W. Maetzler, "Improvement of balance after audio-biofeedback. A 6-week intervention study in patients with progressive supranuclear palsy," *Z. Gerontol. Geriatr.*, vol. 43(4), pp. 224-228, Aug 2010.

[22] A. Mirelman, T. Herman, S. Nicolai, A. Zijlstra, W. Zijlstra, C. Becker, L. Chiari, and J.M. Hausdorff, "Audio-Biofeedback training for posture and balance in Patients with Parkinson's disease," *J. Neuroeng. Rehabil.*, 2011 (in press).

[23] C.D. MacKinnon, D. Bissig, J. Chiusano, E. Miller, L. Rudnick, C. Jager, Y. Zhang, M.L. Mille, and M.W. Rogers, "Preparation of anticipatory postural adjustments prior to stepping," *J. Neurophysiol.*, vol. 97, pp. 4368–4379, 2007.

[24] J.V. Jacobs, J.G. Nutt, P. Carlson-Kuhta, M. Stephens, and F.B. Horak, "Knee trembling during freezing of gait represents multiple anticipatory postural adjustments," *Exp. Neurol*., vol. 215, pp. 334–341, 2009.

[25] P. Crenna and C. Frigo, "A motor programme for the initiation of forward-oriented movements in humans," *J. Physiol*., vol. 437, pp. 635–653, 1991.

[26] J.A. Raymakers, M.M. Samson, and H. J. Verhaar, "The assessment of body sway and the choice of the stability parameter(s)," *Gait Posture*, vol. 21, no. 1, pp. 48-58, Jan.2005.

[27] L. Rocchi, L. Chiari, and F. B. Horak, "Effects of deep brain stimulation and levodopa on postural sway in Parkinson's disease," *J. Neurol. Neurosurg. Psychiatry*, vol. 73, no. 3, pp. 267-274, Sept.2002.

[28] J. Jankovic, M. McDermott, J. Carter, S. Gauthier, C. Goetz, L. Golbe, S. Huber, W. Koller, C. Olanow, I. Shoulson, M. Stern, C. Tanner, and W. Weiner, and the Parkinson Study Group, "Variable expression of Parkinson's disease: A base-line analysis of the DATATOP cohort. The Parkinson Study Group," *Neurology*, vol. 40, no. 10, pp. 1529–1534, Oct 1990.

[29] W.G. Wright, V.S. Gurfinkel, J. Nutt, F.B. Horak, and P.J. Cordo, "Axial hypertonicity in Parkinson's disease: direct measurements of trunk and hip torque," *Exp. Neurol*., vol. 208(1), pp.38-46, Nov 2007.

[30] H.L. Teulings, J.L. Contreras-Vidal, G.E. Stelmach, and C.H. Adler, "Parkinsonism reduces coordination of fingers, wrist, and arm in fine motor control," *Exp. Neurol*., vol. 146(1), pp.159-70, Jul 1997.