Gait & Posture 67 (2019) 147–150

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Short communication

Clinical validity of novel postural stabilization experimental indices based on hyperbolic transformation

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ARTICLE INFO

Keywords:
Postural stabilization
Balance
Hyperbolic coordinates
Charcot_Marie_Tooth disease
Multiple sclerosis

ABSTRACT

Background: Postural stabilization is the function which allows an individual, after a transitional movement, to recover balance in a quiet erect posture. An experimental method has been proposed (Rabuffetti, 2011) and proved valid for the assessment of balance disorders in individuals with neurological diseases. It would seem that the two original indices were not fully independent since their concurrent distribution was confined by a hyperbolic boundary.
Research question: A methodological advancement involving non-linear transformation techniques is required to overcome the limitations of the original approach.
Methods: A hyperbolic transformation is applied to the original indices related to the mechanics of the stabilization (instability at beginning of stabilization and time rate of stabilization), thus defining two novel indices (Instability and Promptness). These novel indices may be related to different functional domains concerning, respectively, peripheral force capacity and central nervous motor control. The validity of these novel indices is quantified by their correlation with clinical scales in an already validated group of patients with Charcot-Marie-Tooth disease (N = 47) or Multiple Sclerosis (N = 20).
Results: The novel indices generally improved validity compared to the original indices (+66% of indices show a statistically significant concurrent validity on a clinical scale). Moreover, Instability was more related to the Charcot-Marie-Tooth group (9 out of 12 valid correlations), and Promptness to the Multiple Sclerosis group (4 out of 5, when also considering statistical trends), in accordance to the, respectively, more peripheral and more central nature of the two neurological diseases.
Significance: The novel postural stabilization indices support a clinical application for two reasons: 1) they have shown improved validity, compared to the original indices, in two groups of patients affected by neurological pathologies of different nature, 2) they are more closely related, compared to the original indices, to different functional domains.

1. Introduction

Instrumental posturography [1] provides an objective assessment of balance that cannot be obtained by clinical tests [2], however "... *An overriding concern is the lack of ecological validity in posturography experiments. (...) Virtually all studies focus on erect standing, while in daily life more dynamic balance skills are required* " [3]. Accordingly, in order to address the limitations of current balance measures, the need for more challenging tasks that mimic postural control demands in daily-life has been highlighted [4].

The study of balance recovery following external perturbations has been undertaken with full control over the perturbation features [5]. Alternatively, postural transitions have been assumed as self-induced perturbations of balance [4]. Methods to study postural stabilization following postural transitions have been proposed [6–10] and have supported clinical and ergonomic studies [11–13].

In a previous method [8], the stabilization following transitional movements (sit to stand, step forward and bending) was quantified by three independent parameters: the instability rate at the instant in which the macroscopic transition ends and stabilization begins (Y0), an asymptotic instability rate reached after the stabilization (Y_{inf}), and a time related to the Y0-to- Y_{inf} transition (T). In particular, T was the

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https://doi.org/10.1016/j.gaitpost.2018.09.024
Received 29 November 2017; Received in revised form 10 September 2018; Accepted 25 September 2018

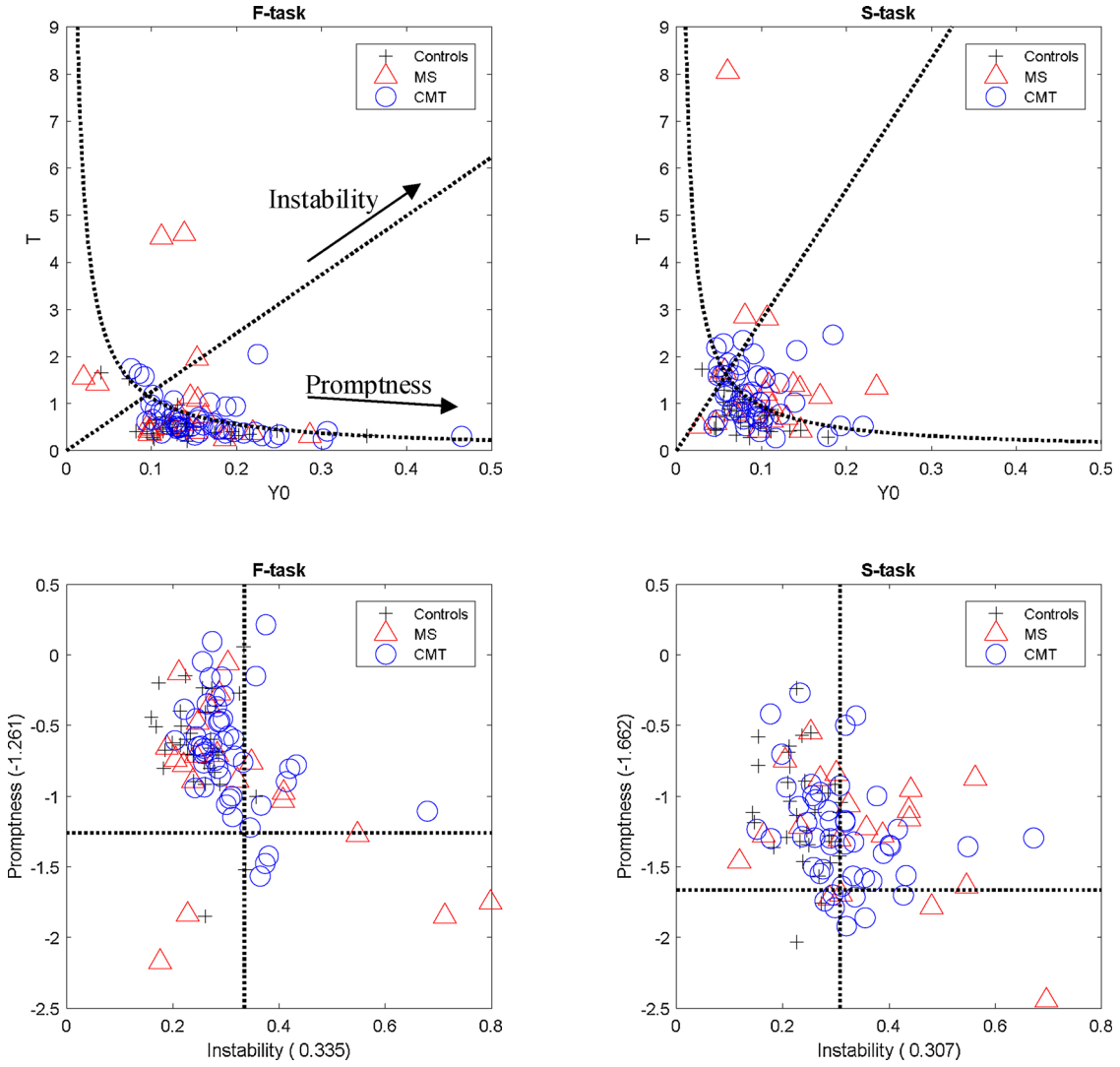

Fig. 1. Scatter plots of Y_0 versus T (upper plots) and of corresponding Promptness vs. Instability (lower plots) for F-task (left plots) and S-task (right plots). The three experimental groups are: controls (+ marker), MS (triangle marker) and CMT (circle marker). The dotted lines of the Instability/Promptness plot (marking respectively the normal 95th and 5th percentiles) are transformed also in the Y0/T plot as, respectively, hyperboles and lines departing from the origin.

time constant of the negative exponential function fitting the instability profile from Y0 to Y_{inf}. The application of this method to healthy subjects [8] and to patients with neurological pathologies [11,12], supports the proposal that the observed indices are not independently distributed: the distribution of (Y0, T) samples was apparently confined by a hyperbolic boundary. In particular, it was observed that patients may have exceeded the boundary identified in healthy data. In order to better focus on this aspect, a compound index I, product of Y0 and T, was introduced to quantify the stability/instability level. This instability index proved its validity in discriminating between healthy individuals and groups of patients, and, even more relevant for a possible clinical use, the indices were partially related to clinical test scores [11,12]. No interpretation was proposed on the differences between different Y0-T pairs with the same I value.

In this study, a refinement of the previously published method [8] was implemented in order to identify indices that are specific for different functional domains: the two indices Y0 and T are non-linearly transformed into a new pair of indices which is expected to distribute more uniformly and to have a functional meaning. The already published data on patients with MS [11] or CMT disease [12] were reprocessed, and the validity of the novel indices was quantified by the correlation coefficient on available clinical scales.

2. Materials and methods

2.1. Participants and protocol

Previously published data sets on postural stabilization in 20 patients with MS [11] and 47 patients with CMT disease were retrieved [12]. Both data sets included pathology-specific clinical tests and postural stabilization experimental assessments. The considered transition tasks were sit-to-stand (S-task) and take-a-step-forward (F-task). Details of the experiments are available in the original articles. The normal data sets included 31 age-matched healthy subjects (31–71 years).

2.2. Data analysis and outcome parameters

The data sets included stabilization parameters according to [8]: Y_0 accounting for the residual instability as transition ends and stabilization begins; T proportional to the stabilization time.

A hyperbolic transformation, ensuring biunivocal correspondence between spaces, was applied according to the following equations.

$$Instability = \sqrt{Y_0 \bullet T} \quad (1)$$

$$Promptness = \log_e \sqrt{\frac{Y_0}{T}} \quad (2)$$

The Instability index (Eq. (1)) is associated with the hyperbole level and is related to the overall instability (actually the former I index is the square of Instability).

The Promptness index (Eq. (2)) characterises different points along a hyperbolic iso-Instability profile, with decreasing values from lower right (higher Y_0, lower T) to upper left (lower Y_0, higher T); accordingly, this index is related to the stabilization promptness.

The inverse transformation is expressed by the following equations:

$$Y_0 = Instability \bullet e^{Promptness} \quad (3)$$

$$T = Instability \bullet e^{-Promptness} \quad (4)$$

2.3. Statistical analysis

According to the original articles, the nonparametric Spearman correlation coefficient was applied. The p-value for statistical significance was set at 0.05. Non-significant trends were evident for p-values up to 0.10.

3. Results

The experimental data distributions of T vs. Y0 and Instability vs. Promptness are presented in Fig. 1.

The correlations of novel indices with already considered clinical tests are presented for the CMT group (Table 1) and for the MS group (Table 2). Already presented values concerning Y0 and T [11,12] are also included.

Table 1
Spearman correlation coefficient values between postural stabilization indices and CMT related clinical scales. First value for S-task, second value for F-task. Underlined bold for significant values (p-value < = 0.05), bold only for trends (p-value < = 0.10).

Clinical test	Y0	T	Promptness	Instability
$CMTES_{TOT}$	0.22 / 0.06	0.19 / **0.31**	-0.06 / -0.21	**0.46** / **0.48**
$CMTES_{VS}$	0.01 / 0.22	0.17 / 0.26	-0.11 / -0.01	0.23 / **0.40**
$CMTES_{SL}$	**0.27** / -0.09	**0.29** / **0.46**	-0.12 / **-0.39**	**0.58** / **0.52**
VAS pain	-0.20 / **0.29**	0.07 / -0.22	-0.13 / **0.29**	-0.03 / -0.10
MRC_{ADF}	**-0.26** / 0.14	-0.16 / **-0.51**	0.01 / **0.46**	**-0.46** / **-0.47**
MRC_{APF}	-0.24 / 0.11	-0.19 / **-0.42**	-0.01 / **0.39**	**-0.43** / **-0.46**
MRC_{KF}	0.01 / 0.17	-0.07 / -0.19	0.05 / 0.20	-0.17 / -0.09
MRC_{KE}	0.11 / 0.08	-0.15 / -0.06	0.14 / 0.06	-0.15 / -0.02
MRC_{HF}	-0.04 / 0.12	-0.04 / -0.16	0.01 / 0.14	-0.18 / -0.13

CMTES: Charcot–Marie–Tooth Examination Score (TOT: total score; VS: vibration sense; SL: strength legs); VAS: Visual Analog Scale; MRC: Medical Research Council scale for muscle strength (ADF: ankle dorsiflexors; APF: ankle plantarflexors; KF: knee flexors; KE: knee extensors; HF: hip flexors).

Table 2
Spearman correlation coefficient values between postural stabilization indices and MS-related clinical scales. First value for S-task, second value for F-task. Underlined bold for significant values (p-value < = 0.05), bold only for trends (p-value < = 0.10).

Clinical test	Y0	T	Promptness	Instability
Falls	0.05 / 0.02	0.09 / -0.09	0.02 / 0.08	0.08 / -0.07
TUG	0.20 / -0.28	0.16 / **0.43**	0.02 / **-0.43**	0.23 / 0.29
BBS	-0.25 / 0.17	0.01 / **-0.67**	-0.18 / **0.53**	-0.11 / **-0.65**
EDSS	0.10 / -0.02	0.09 / **0.47**	-0.19 / **-0.40**	0.28 / 0.35
AssDev	-0.17 / **-0.53**	0.12 / **0.51**	-0.16 / **-0.58**	0.08 / 0.25

Falls: Number of falls in the last two months; **TUG**: Timed Up and Go Test; **BBS**: Berg Balance Scale; **EDSS**: Expanded Disability Status Scale; **AssDev**: use of walking assistive device.

4. Discussion

The method presented here is an evolution of the original approach [8] which focussed on overall instability represented by the index I. However the original approach proposed no index related to an observed phenomenon: while small instability (low Y0) can be negotiated and stabilised either with a prompt fast reaction or with a slower reaction (any T value); apparently a large instability (high Y0) is necessarily followed by a quick response and stabilization (low T) to prevent adverse events (e.g., falls). The hypothesised explanation, supported by studies on predictable balance perturbations, is that a large initial instability should be managed by a prompt active response, possibly involving anticipatory adjustments [14], while a passive, based on a stiff posture, reaction would be sufficient only for small initial instability [15].

In order to fully describe the postural stabilization features, the hyperbolic transformation of variables Y_0 and T to the variables Promptness and Instability was applied. While the Instability index is equal to the square-root of the previous index I, Promptness quantifies the interplay between Y0 and T with larger values for occurrences of large Y0 and small T. A perusal of the novel indices distribution reveals that their scattering is not confined in a sub-area of the variables' space (Fig. 1), which demonstrates how the novel indices are more likely to be independent compared to the original indices, which showed a strong interplay.

The validation of such novel indices was performed by analysing their correlation with clinical scales in two previously published datasets of patients' postural stabilization: in the CMT group the statistically significant validity of the novel indices more than doubled compared to that of the original indices, while in the MS group the figure did not change substantially (one less significant correlation, no difference when considering trends).

Interestingly, in the CMT group the validity of the Instability index was larger than that for Promptness, while in the MS group the Promptness validity was prevalent. This may refer to the different nature of the two pathologies (respectively, a peripheral and a central/

spinal neuropathy), thus making Instability and Promptness candidates for the assessment of two different functional domains: strength of the muscle system (affected in CMT) and central motor control (altered in SM).

Another observation concerns the higher (about four times) sensitivity of the indices in the F-task than the S-task. This may be explained by the irreversible nature of the F-task (while S-task is basically reversible), which is more challenging to the postural system, and suggests more focus be given to the F-task for the assessment of postural stabilization.

In conclusion, the novel postural stabilization indices a) proved to have a concurrent validity with clinical scores equal or superior, for specific pathologies, to the original indices; b) may be associated with different functional domains, while original indices were related to the stabilization mechanics; c) may provide relevant clinical information, possibly driving different therapeutic approaches.

Conflict of interest

None.

Acknowledgement

This work was supported in part by funding from the Italian Ministry of Health ("Ricerca Corrente").

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