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# Is the Limit-Cycle-Attractor an (almost) invariable characteristic in human walking?

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ABSTRACT

*Background:* Common methods of gait analyses measure step length/width, gait velocity and gait variability to name just a few. Those parameters tend to be changing with fitness and skill of the subjects. But, do stable subject characteristic parameters in walking exist? Does the Limit-Cycle-Attractor qualify as such a parameter?.
*Research question:* The attractor method is a new approach focusing on the dynamics of human motion. It classifies the fundamental walking pattern by calculating the Limit-Cycle-Attractor and its variability from acceleration data of the feet. Our hypothesis is that the fundamental walking pattern in healthy controls and in people with Multiple Sclerosis (pwMS) is stable, but can be altered through acute interventions or rehabilitation.
*Methods:* For this purpose, two investigations were conducted involving 113 subjects. The short-term stability was tested pre and post a 15 min passive/active MOTOmed (ergometer) session as well as up to 20 min afterwards. The long-term stability was tested over five weeks of rehabilitation once a week in pwMS. The main parameter of interest describes the velocity normalized average difference between two attractors (δM), which is an indicator for the change in movement pattern.
*Results:* The Friedman's two-way ANOVA by ranks did not reveal any significant difference in δM. However, the conventional walking tests (6 min.10 m) improved significantly ($p < 0.05$) during rehabilitation. Contrary to our original hypothesis, the fundamental walking pattern was highly stable against controlled motor-assisted movement initiation via MOTOmed and rehabilitation treatment. Movement characteristics appeared to be independent of the improved fitness as indicated by the enhanced walking speed and distance.
*Significance:* The individual Limit-Cycle-Attractor is extremely robust and might indeed qualify as an (almost) invariable characteristic in human walking. This opens up the possibility to encode the individual walking characteristics. Conditions as Parkinson, Multiple Sclerosis etc., might display disease specific distinctions via the Limit-Cycle-Attractor.

## 1. Introduction

Gait is the primary human way of locomotion. No wonder the modern quantitative scientific endeavor to understand the mechanism behind the central movement trait began as early as the nineteenth century [1]. Since then, important advancements in measurement techniques (digitizing systems, force plate etc.) and analysis (quantification of segmental movement etc.) have been achieved. To a certain extent, those advancements allow identification of alterations in movement pattern after training and rehabilitation. Analyzed parameters in that context are mostly step length, step width, gait velocity and gait variability to name just a few [2,3]. The disadvantage of these parameters persists in their selected information content calculated out of tiny parts of step cycles (step length etc.) or in over-averaging of multiple cycles (gait velocity). Important information of continuous locomotion is not accessible in this way. With the development of the chaos theory [4], new promising approaches dealing with the dynamics of human movement appeared in gait analysis. Here, however, lie some methodological problems. In general, chaos theory is based on fully deterministic systems, which are in principle describable

*Abbreviations:* 5WRI, 5 weeks rehabilitation investigation; 6MWT, 6-min walking test; 10MWT, 10-m walking test; ANOVA, Analysis of Variance; EDSS, Expanded Disability Status Scale; f, fixed hands; fMRI, functional magnetic resonance imaging; MS, Multiple Sclerosis; nf, non-fixed hands; PP, primary progressive; pwMS, people with Multiple Sclerosis; RR, relapsing-remitting; SP, secondary progressive; STI, short-term investigation; D, absolute variability of walking data relative to the respective attractor; δM, average distance between 2 attractors, indicating a change in movement pattern; δD, states changes in walking regularity between two measurements

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by the underlying differential equations. For human movement, the respective equations are unknown. That is where the embedding theorem [5] comes to the rescue providing smooth attractors from observational data. An attractor "is a set of states (points in the phase space), invariant under the dynamics, towards which neighbouring states in a given basin of attraction asymptotically approach in the course of dynamic evolution" [6]. Building on this approach, the Lyapunov exponent λ can be used as a parameter for quantifying stability of motion [7]. However, human movement dynamics always contain some kind of (stochastic) fluctuations, which make the correctness of the resultant numbers of λ questionable. It was shown even by adding white noise that λ can be calculated for Hénon, Lorenz and Rössler systems with errors below 10 % (for an embedding dimension up to three) [8]. Still the situation remains problematic since a 10 % error might undermine the significance of a statement. In addition, white noise might not be the (only) source of disturbance. Disruption in the form of a "random walk" [9] is another possible complication preventing or greatly reducing an adequate accuracy of calculating λ. We assume that this might be the reason why those approaches are only capable to analyse human locomotion on a group level, but lack the sensitivity to give decisive data on individuals.

A new and promising non-linear approach dealing with those problems is the "attractor method" [10]. This method assumes cyclic motion to be governed by Limit-Cycle-Attractors. A supposition that is not attestable so far but is motivated by the success of its applications. Preliminary studies using the attractor method have indicated that the fundamental movement pattern can change through extreme measures - altering the physical system (weights on the feet) or affecting the control system (cognitive stress) [11]. Of special interest in that context is the population of people with Multiple Sclerosis (pwMS). Multiple Sclerosis (MS) is an inflammatory autoimmune disease with diverse types of progression and symptoms depending on the central or peripheral area of inflammation [12]. Hereby, the symptoms with the most limiting character for everyday life participation are muscle weakness and the impact of fatigue on the individual walking abilities. Previous studies have already shown that it is possible to detect motor fatigability, which is the quantifiable change in performance in pwMS [11]. Within this cohort, it is expected that walking abilities may rapidly worsen due to fatigue/motor fatigability in acute interventions; and may be improved by repeated therapy sessions during inpatient rehabilitation. That is why pwMS are of great interest for our purpose to determine how stable walking characteristics are. To verify this assumption, a study subdivided into a short-term (STI) and a 5 weeks rehabilitation investigation (5WRI) was conducted. For the STI the specialized ergometer MOTOmed (Reck GmbH, Germany) was used to test the acute influence on gait performance. The MOTOmed was chosen due to the positive instantaneous effect reported by several patients especially in regard of the passive motor-assisted mode. For the 5WRI it is known that the standard rehabilitation program positively affects the fitness and the walking capability [13]. It was to expect that these procedures regularly used in the clinical setting would evoke changes in gait of pwMS measurable by the attractor method. Therefore, our hypothesis was that both measures (short- and long-term investigations) do alter the Limit-Cycle-Attractors and the variability of movement in people with Multiple Sclerosis and healthy controls.

## 2. Methods

### 2.1. Subjects

In the short-term investigation (STI), 61 subjects (34 female, 27 male) with an average age of 51.2 ± 9.7 years were included. The healthy controls consisted of 21 participants (6 female and 15 male), which were not age matched with an average age of 32.2 ± 12.6 years. The velocity on the treadmill was of course faster for healthy controls with 3.7 ± 0.5 km/*h* compared to 1.9 ± 0.9 km/h in the pwMS. The

**Table 1**
Subject data.

| | STI | | 5WRI |
|---|---|---|---|
| **health status** | MS | Healthy | MS |
| **N** | 61 | 21 | 31 |
| **age** [years] | 51.2 ± 9.2 | 32.2 ± 12.6 | 48.5 ± 10.4 |
| **sex** [female_male] | 34_27 | 6_15 | 23_9 |
| **height** [cm] | 172.1 ± 7.6 | 173.1 ± 6.7 | 169.6 ± 7.8 |
| **weight** [kg] | 70.6 ± 11.5 | 70.9 ± 9.3 | 75.8 ± 14.0 |
| **velocity** [km/h] | 1.9 ± 0.9 | 3.7 ± 0.5 | 3.3 ± 1.2 |
| **holding rail** (No. of people) | 40 | 0 | 31_both |
| **Disease duration** | | | |
| first manifestation [years] | 16.1 ± 9.7 | n.a. | 13.3 ± 9.4 |
| first diagnose [years] | 12.2 ± 8.8 | n.a. | 9.0 ± 7.9 |
| **EDSS** | 4.6 ± 1 | n.a. | 3.1 ± 1.3 |
| **disease course** (RR_SP_PP) | 24_28_11 | n.a. | 22_3_5 |

STI short-term investigation, 5WRI 5 weeks of rehabilitation investigation.
MS multiple sclerosis, RR relapsing-remitting, PP primary progressive.
SP secondary progressive, EDSS Expanded Disability Status Scale.
n. a. not applicable.

31 pwMS participating in the 5WRI were age matched to the pwMS in the STI (48.5 ± 10.4 years). Admittedly, the duration since the first manifestation of MS and the Expanded Disability Status Scale (EDSS) in the cohort of the STI was slightly higher than in the 5WRI. Both may be related to the higher proportion of the secondary progressive (SP) type of MS in the STI. For further details, check Table 1. The pwMS included in both investigations had a definite MS diagnosis according to the McDonald criteria [14]. Moreover, only subjects able to walk without walking aid for at least 5 min on a treadmill and without any relapse within the last three months before measurements were included. All subjects were informed about the study purpose in advance and had enough time to give their written informed consent. The local ethic committee in accordance with the declaration of Helsinki gave the ethical approval for both investigations. Participants of the STI were recruited from the inpatients of the Kliniken Schmieder Konstanz from January 2015 to January 2016 and patients for the 5WRI from April to July 2016. The control group was assembled from local citizens from March to June 2015 and participated voluntarily. Exclusion criterion for the healthy controls was any preexisting neurological or orthopedic disease.

### 2.2. Experimental design

In a first session, the participants were informed and familiarized with the devices. For all measurements on the treadmill they were secured by a safety belt independently of their health status.

The design of the STI was cross-sectional based on a pre-/post-intervention protocol. The measurements of the passive and active mode intervention were within the same week, but with at least 48 h in between. Passive mode means that the electrically driven ergometer moves the subject's legs. Active mode implies that the subjects had to drive the ergometer by themselves. For the control group both conditions were measured on the same day with one hour break. During the break the controls were advised not to be physically active. For both groups, the acceleration of the feet was recorded over one minute pre and post the 15 min ergometer trial. In order to check how long a possible effect of the passive mode on gait would last; the participants were also tested after a 10 min and a 20 min seated break.

The 5WRI was designed as a longitudinal prospective cohort study during a five weeks stationary rehabilitation intervention, which is on