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THESIS BOOKLET

HUMAN STANDING DYNAMIC BALANCING AND ELEMENTARY BIOLOGICAL SIGNAL PROCESSING

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1. Introduction

The study of biomechanics – the motion of living beings – is as old as human history itself, from the motions of everyday living, physical work, hunting, and fighting to the specific movements of sports and dance. Balancing is the intrinsic process of motor control coordination. The maintenance of balance, particularly in bipeds such as humans, is an intricate process carried out by an integrated neuro-musculo-skeletal system. Static balancing is examined in the field of posturography, whereas dynamic balancing corresponds to the study of all movements [1]. Postural balance requires non-linear control with time delays, where the central nervous system has to ensure stability and accuracy in a fraction of a second [2]. To solve this challenging task, the central nervous system creates synergistic motor strategies through learning and recalls these strategies when different balancing tasks have to be carried out [3]. These strategies have been extensively studied, both theoretically and experimentally [4–6].

Studying balancing may prove to be a fruitful endeavor as it provides insight into the organization and control of complex systems. This thesis explores four topics of study: the field of balance assessment methods, a particular balance assessment test, an open-chain kinematic model of the body, and biologically inspired signal processing.

The role of balancing tasks and tests is becoming more prominent in medicine and sports sciences as well. Training of coordination and proprioception are used not only for increasing athletic performance. These are now an integral part of skills development for children and rehabilitation programs for various orthopedic (e.g., crucial ligament tear, arthrosis, joint replacement) and neurological alterations (e.g., stroke, dementia, Alzheimer’s disease). There is also the possibility of applying these tests as diagnostic tools and research efforts are made to this end.

Besides static posturography, dynamic balancing tests are also becoming prevalent, such as the sudden perturbation test [7][8]. The PosturoMed device was invented in 1995 and was introduced to the clinical biomechanics literature by Müller et al. in 2004 [7]. The device is widely used in Europe to train athletes, provide rehabilitation, therapeutic, and balance assessment methods. The platform is a solid metal plate (12 kg, 60 cm × 60 cm) manufactured with anti-slipping surface that is suspended on eight 15 cm long identical steel springs. This allows the platform to freely move along the horizontal plane. The participant is standing on the platform and the device provides an unstable condition to challenge balance. A release mechanism can also provide a sudden perturbation to elicit a balance recovery response motion. Recovery time, damping factor and muscle activation timing and level can be measured to assess the balancing effectiveness [3,9,10].

Traditionally for balance assessment, the human body is modeled with a single point (the center of mass, or the center of foot pressure), a single or double inverted pendulum, or a multi-segment model of the body [11]. Naturally, increasing the complexity of the body model increases the accuracy and sensitivity of the method. Conversely, this makes it more difficult to implement such assessments in clinical practice due to the increasingly specific and costly instruments and the expertise to operate such equipment. Therefore, it is sensible to choose a model that is sophisticated enough to obtain the necessary and correct conclusion from a balance assessment test and at the same time has simple enough measurement requirements.

The study of motion and motor control involves the measurement and analysis of signals from multiple modalities, such as positional data, joint angles, muscle activation via EMG-signals, cortical activation via EEG-signals, and pulse via pulse oximeter or electrocardiogram. The multiple modalities and the different physical units or dimensions make it difficult to consider these signals simultaneously and extract valuable information. Furthermore, these data are temporal in nature and also have a strong spatial dependence. Better mathematical and computational tools are needed to analyze such data. One effective computational tool for spatio-temporal data that has emerged recently is the spiking neural network (SNN), also called the third generation of artificial neural networks, in which the processing units (neurons) of a SNN behaves similarly to a biological neuron [12].

2. State of the art and research questions

Dynamic balancing assessments

Numerous different balancing tasks, devices and measures have been used in the research of balancing, and many are being applied in clinical or athletic settings. However, I could not find in the literature a broad overview of the measurement methods applied in the area of standing dynamic balancing.

Dynamic balancing is broadly defined as the controlling process taking place under non-static conditions. In the current thesis, the investigation is restricted to balancing that is taking place in upright stance under dynamic conditions. Hence, the operational definition of *standing dynamic balancing* is a) the maintenance of standing balance during a continuous perturbation or under dynamic environmental conditions, b) the recovery of standing balance following a sudden perturbation or c) a combination of these. Standing dynamic balance includes both postural control as it aims at maintaining or recovering a balanced standing position and equilibrium control as it must create reactions to destabilizing forces from the perturbation.

Research question 1: How can standing dynamic balance assessment methods be classified with regards to the balancing tasks and devices being used?

Balance assessment with the PosturoMed device

Already existing measurement protocols in clinical practice obtain data by tracking the platform motion to calculate measures of balancing performance. Parameters used to quantify balance recovery effectiveness include the end time of balancing, the damping factor, the distance travelled in the directions parallel and perpendicular to the perturbation.

Previously used metrics measured the effectiveness of the balance recovery motion. It could be supposed that the shape of platform trajectory (the execution of regaining balance) contains information regarding the balancing abilities of participants. Based on our review of the literature, no previously existing parameters had been developed to characterize the shape of platform motion trajectory following the sudden perturbation. In order to address this gap, the following research question can be posited:

Research question 2: What parameter can effectively characterize the platform trajectory during balance recovery following a sudden perturbation? How can the measures for effectiveness and platform trajectory be used to characterize the recovery action?

Open kinematic chain models of the human body

It is well established in the literature that balancing involves several common coordination strategies. In standing balance, the ankle-hip strategy approach distinguishes three strategies, i.e., the ankle-dominant, the hip-dominant, and the ankle-hip mixed strategies [13]. The applied biomechanical model is chosen with regards to the studied strategies to be detected, e.g., to show the presence of the ankle strategy or another coordination pattern for a specific movement.

Notably, most kinematic chain models are restricted to a single plane (either AP or ML), and few works model the body in all directions to investigate coordination [11]. However, the interplay between the perturbed and non-perturbed directions can be significant in the case of perturbed standing. In order to capture this co-ordinational effort, a biomechanical model is needed that is capable of capturing the motion in the perpendicular direction and also the active joint torques that arise to execute such maneuvers.

For this reason, I proposed studying the application of an open chain model that specifically considers all spatial dimensions and is easy to construct, using the Denavit-Hartenberg convention.

Research question 3: Can a conventional open-chain kinematic model of the standing human body describe motion and estimate joint torques accurately to detect balancing strategies?

Biologically inspired signal processing

In a spiking neural network (SNN), information travels between the processing units in the form of binary spiking events. SNN systems are thus inspired by the information processing solutions of the biological brain. Real world measurements provide analog (continuous or discrete) real-value temporal signals, therefore it is necessary to implement an encoding method to convert the analog values to spike events to provide input to such systems. This analog-to-spike encoding can compress the data size of the signal considerably [14] since the spike train is a binary value series. Ultimately, a correct spike encoding could lead to better information preservation along with input data reduction and compression [14–18]. It is extremely important to generate the spike train input to the SNN such that the task-relevant information content of the signal is preserved.

Each encoding method has a unique way of extracting information from the input signal. The issues here are what information is lost and what is preserved and thus how effective was the encoding. In general, studies on SNNs start by assuming that the encoded spike train is already available as input to the system. Little has been published on the specific effects of encoding methods on the spike train information content and the reconstructed signal, or in fact on the rationale behind the selection of a particular encoding algorithm. Few are the studies that considered optimizing the encoding step separately. At the same time, the SNN community has not settled on any encoding method selection and optimization methodology with regards to temporal data.

Research question 4: How can temporal spike encoding be optimized to retain the highest amount of information?

Research question 5: Is there a temporal spike encoding algorithm that can be recommended as a general-purpose encoding?

Research question 6: How can the widely used BSA encoding be optimized for information retention?

3.Main contributions

This section provides a summary of the dissertation in the form of the stated main contributions, with background explanation and practical applications.

3.1 Dynamic balancing assessments

In order to investigate RQ1, I carried out a systematic review of the literature in 2017 according to the PRISMA guidelines [19] which had been published in full detail in [P1]. This review aimed at creating a comprehensive catalogue of dynamic balance assessment methods and determining which methods have a good discriminative ability on various populations. I proposed a structural framework for classifying the identified methods (see Table 1).

Table 1. A structural framework of dynamic balance assessment methods

Movement constraints	**Sudden perturbation**	**Continuous perturbation**	**Dynamic condition**
Unconstrained (freely on the ground)	• Simulated forward fall • Pull/push/hit perturbation • Sudden load on hands	• Force plate with visual feedback • Haptic perturbation	• Leg swinging • Objective functional reach tests
Translational movement allowed	• Sudden horizontal translation perturbation with controlled stop • Sudden horizontal platform perturbation with free oscillation • Treadmill	• Continuous horizontal oscillating platform perturbation	• Horizontal platform with free oscillation
Rotational movement allowed	• Sudden platform rotation perturbation	• Continuous platform rotation perturbation	• Balance boards

These findings resulted in my first main contribution:

Main contribution 1: Standing dynamic balance investigations can be classified according to the allowed movement directions (unconstrained, translation allowed, or rotation allowed) together with the applied intervention (sudden perturbation, continuous perturbation, or dynamic condition without perturbation).

Related publications: [P1]

Practical applications:

The current contribution aims at providing guidelines on the selection of balancing devices and tasks for various populations both for research and clinical practice. A researcher who may wish to study the balancing capabilities of a specific group, e.g., PD patients, should collect the relevant examples of balance assessments from the literature and clinical practice and place them in the classification framework provided here (Table 1). This informs the decision to select either a well-established balance assessment approach to obtain comparable measurement data or novel research avenues by utilizing a previously unused approach.

3.2 Balance assessment with the PosturoMed device

Main contribution 2: Considering the sudden perturbation test on the horizontally oscillating platform, let the following term define the directional ratio:

$$R = \frac{S_x}{S_y},$$

where S_x is the traveled path of the platform in the perturbation direction, and S_y is the traveled path of the platform in the direction perpendicular to the perturbation. The balance recovery strategy can be characterized by coupling together the platform trajectory, as quantified by the directional ratio, and the effectiveness of the balance recovery, as quantified by the damping ratio. The directional ratio

shows a consistent difference for lateral perturbations between bipedal and unipedal stances in the healthy young population, even when the effectiveness of balance recovery is similar.

Related publications: [P2-P7]
Background:

I carried out an investigation to develop and examine parameter(s) to characterize the platform trajectory following the sudden perturbation. Our earlier work [P2] with figure skaters showed that platform trajectories can exhibit various shapes. The most important aspect was to what degree the motion stayed in the direction of the initial perturbation. In some cases, the medial-lateral perturbation was turned into an anterior-posterior motion by the participant. This led to the development of the directional ratio which proved to be uncorrelated with the damping ratio, and thus it may contain new information.

To further validate the new parameter, I performed the sudden perturbation balance test on a group of healthy, young participants [P5]. Our study found that platform trajectories differ between single-leg and bipedal stance recoveries while reaching similar performance levels in a healthy, young adult population. In later works, the formula for the directional ratio was modified to result in a 0-1 ratio number which yields a better distribution [P9, P10].

Practical applications:

Further research avenues open up utilizing the directional ratio of the platform motion. Different balance recovery motion strategies (Figure 1) can be distinguished using together the mode of execution (as characterized by the platform's path) and the effectiveness of the balance recovery (as characterized by the damping factor). The applied balance recovery strategies may depend on stance types and the balancing capabilities of the participant. This methodology might reveal whether a training protocol improves balancing performance, changes the recovery action, or achieves both.

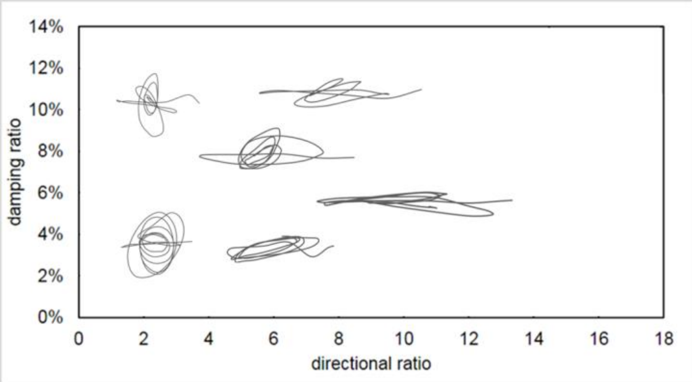

Figure 1. Various balance recovery patterns identified on the damping ratio - directional ratio plane

The improved methodology had been presented to a biomechanics audience [P4] and to orthopedic doctors and clinicians [P3]. The effects of the perturbation direction, i.e., the difference between balance recovery following medio-lateral and latero-medial perturbations have also been investigated [P6]. The connection between the body's compensatory movements and the directional ratio were also studied [P8]. Another investigation included young sailor athletes and age-matched control [20], examining the effects of visual feedback (eyes open or closed conditions) and the spring setting of the PosturoMed platform (4 or 8-spring setting).

3.3. Open kinematic chain models of the human body

Main contribution 3: An open-chain model of the standing human body based on the Denavit-Hartenberg convention that has two links (one for the upper and lower body each) and four degrees of freedom (DoF) (two single-DoF joints at the ankle and the hip levels, respectively) can estimate the torques arising in the main body joints with sufficient accuracy to detect balancing strategies.

Related publications: [P8-P11]

Background

Our goal was to demonstrate the utility and the validity of a conventional open chain kinematic model that covers all spatial dimensions. Since the target application was standing dynamic balancing, I choose to examine a two-segment model that is simple enough to capture movement related to the hip-ankle strategies (Figure 2) [P8].

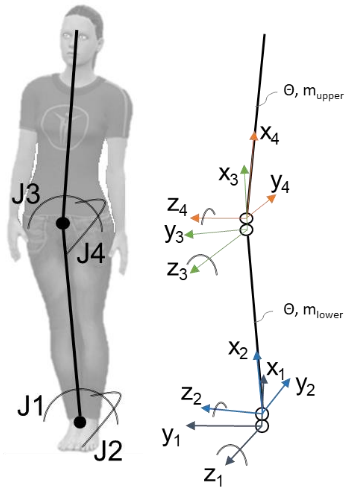

Figure 2. Inverted double-pendulum model

In order to validate the proposed double-pendulum model, I carried out validation measurements for a standing balancing task on an inhomogeneous group of healthy adult participants, comparing the indirectly *measured torques* with the *model estimated torques* arising at the ankle level [P8]. The match in signal shape was excellent in the antero-posterior direction. The estimated medio-lateral torques showed a significant scaling error compared to the indirectly measured torques. It can be hypothesized that the source of this error is that the ankle rotational axis could move during the motion recording as the participant is shifting the load distribution between their feet, thus shifting the actual rotational axis.

I have also carried out an investigation into the applicability of the double-pendulum model for the sudden perturbation test [P9, P10]. The contribution of individual joints could be estimated and visualized for the balancing motions. The four joints allowed the comparison between the ankle and hip joints as well as between the sideways and forward motion as well. These four joints can help to identify the applied coordination strategy and locate the source of a balancing deficit [P10, P11].

Practical applications

Regarding the practical utility of this contribution, the simplicity of the dynamic model needs to be emphasized: only three positions have to be tracked, i.e., the feet/ankles, the hip, and the head, using optical methods or more simply with ultrasound- or inertia-based motion sensors. Indeed, common devices that contain suitable motion sensors, e.g., smartphones, could be attached to the hip (in a pouch) and the head (on a hat) to obtain the necessary measurement data. This simplification may contribute to the broader adoption of various balancing tests and the instrumented, objective assessment of test results [8].

3.4 Biologically inspired signal processing

In order to investigate Research questions 4, 5, and 6, I carried out an investigation to provide a quantitative and qualitative analysis into different temporal spike encoding methods and to provide guidelines for the selection, optimization, and validation of encoding methods [P12]. I proposed a three-step encoding workflow. First, the encoding method is selected based on signal characteristics. Second, the encoding parameters are optimized based on error metrics between reconstructed and original signal (verification in time domain). Third, the encoding is validated by comparing the spike train to the original signal in the time/frequency domain.

Our investigation utilized four artificially generated, characteristically different test signals: step-wise, periodical with noise, trended periodical, and event-like signals. I analyzed one stimulus estimation encoding algorithm: Ben’s Spiker Algorithm (BSA), and three temporal contrast encoding algorithms: Threshold-based Representation (TBR), Step-forward encoding (SF), and Moving window encoding (MW). I compared the original and the reconstructed signals via three different error metrics: coefficient of regression, root mean square error and signal-to-noise ratio.

Based on this investigation, the following main contribution can be stated regarding Research question 4:

Main contribution 4: Considering the conversion of digital signals into spike trains, the following encoding workflow (Figure 3) is recommended to maximize information retention:

- **the spike train is obtained by applying the encoding method on the original signal;**
- **the reconstructed signal is obtained by applying the corresponding decoding method on the spike train;**
- **the parameter(s) of the encoding are tuned to the extreme value of a cost function.**
- **A signal-to-noise ratio type of cost function can be recommended, where the difference of the reconstructed and the original signals are considered noise, and the signal-to-noise ratio should be maximized.**

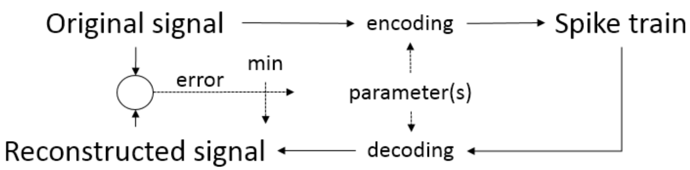

Figure 3. Recommended spike encoding optimization workflow

Relevant publication: [P12]

Practical applications

Using the proposed workflow to optimize the encoding in itself ensures that the task-relevant information is retained. This also speeds up the training of the machine learning system by reducing the parameter space.

Based on the investigation outlined above, the following main contribution can be stated regarding Research question 5:

Main contribution 5: Considering the conversion of digital signals into ternary (-1, 0, +1) spike trains, the so-called Step-Forward (SF) algorithm can provide a robust encoding solution for signals such as step signals, aperiodic signals, trended signals, and aperiodic signals containing noise and events with different amplitudes. The encoding can be optimized by following the recommendations presented in Main contribution 4.

Relevant publication: [P12]

Practical applications

The SF encoding can be recommended as a general-purpose encoding; a good choice for multimodal signals that is easy to optimize and robust to different signal characteristics. An example is shown in Figure 4.

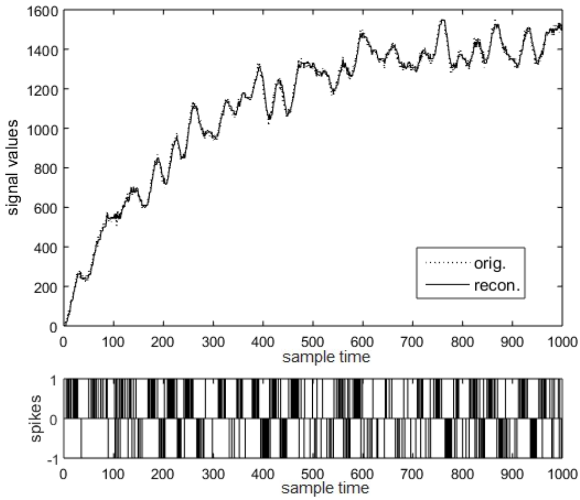

Figure 4. Exemplar signal conversion with Step-Forward encoding: original, encoded, and decoded signals

Based on the investigation outlined above, the following main contribution can be stated regarding Research question 6:

Main contribution 6: Considering the conversion of digital signals into binary (0, +1) spike trains, the Ben's Spiker Algorithm should be applied with the following considerations in order to optimize the retained information of the encoding:

- **the FIR-filter applied during the conversion shall be designed such that the frequency characteristics of the filter matches the spectrum of the information content that is desired to be retained**
- **the coefficients of the FIR-filter shall be scaled up by multiplication such that the sum of the coefficients is twice the amplitude of the input signal's**

- **the threshold type parameter of BSA shall be optimized by maximizing a signal-to-noise ratio, where the difference between the original and the reconstructed signals (calculated by a convolution of the encoded spike train and the FIR-filter) is considered noise.**

Relevant publication: [P12]

Practical applications

The BSA-encoding is especially relevant as it is a widely used encoding because it provides binary spike trains. Any effort to improve the information retention of the encoding may improve the performance of SNN systems and may speed up the training process considerably. An example is shown in Figure 5.

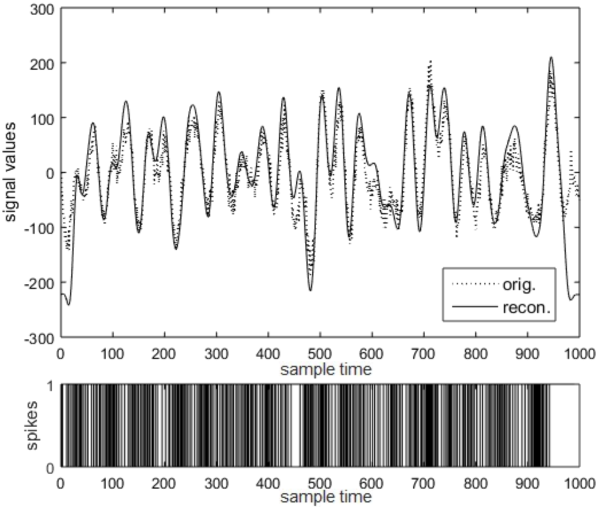

Figure 5. Exemplar signal conversion with BSA encoding: original, encoded, and decoded signals

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6. Own publications related to contributions

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[P2] **Petró Bálint**, Dr. Kiss Rita: Directional ratio: a proposed new variable of dynamic balance regain. Recent Innovations in Mechatronics, 4, 1-4, (2017)

[P3] **Petró Bálint**, Kiss Rita M: A dinamikus egyensúlyozó-képesség hirtelen irányváltoztatási tesztjének értékelési módszere (előadás, absztrakt) (Evaluation methods of the sudden perturbation test of dynamic balancing abilities (presentation and abstract)). Magyar Ortopédiai Társaság 60. Kongresszusa, 2017. június 29. – augusztus 1., Nyíregyháza, Paper A-0041. (In Hungarian)

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[P6] **Petró, B.,** & Kiss, R. M.: Effects of perturbation direction on single-leg stance balance recovery performance (presentation, abstract). Francesca Cosmi (ed.) "34th Danubia-Adria Symposium on Advances in Experimental Mechanics, University of Trieste, Italy, 2017", Trieste, EUT Edizioni Università di Trieste, 2017

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[P9] Bernadett, Kiss; **Balint, Petro**; Rita, Kiss: Analysing human balance recovery action using calculated torques of a double pendulum model (abstract). Stefan, Dan Pastrama; Dan, Mihai Constantinescu (szerk.) 35th Danubia Adria Symposium on Advances in Experimental Mechanics, Sinaia, Románia (2018) pp. 121-122.

[P10] **Balint, Petro**; Bernadett, Kiss; Rita, Kiss: Analysing human balance recovery action using calculated torques of a double pendulum model. Materials Today: Proceedings, 12(2), 431-439, (2019).

[P11] **Petró Bálint**, Kiss Rita M.: Az egyensúlyozó emberi test modellezése kéttagú, négy szabadságfokú fordított ingával (Modeling of the balancing human body with a two-link, four-degrees-of-freedom inverted pendulum). XIII. Magyar Mechanikai Konferencia, Miskolc-Egyetemváros, 2019. augusztus 27-29. (in Hungarian)

[P12] **Balint Petro**, Nikola K Kasabov, Rita M Kiss: Selection and optimization of temporal spike encoding methods for spiking neural networks. IEEE Transactions on Neural Networks and Learning Systems, 31(2), 358-370 (2020).