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Assessing Standing Balance using MIMO Closed Loop System Identification Techniques

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Abstract: Human standing balance is a complex of systems, like the muscles, nervous system and sensory systems, interacting with each other in a closed loop to maintain upright stance. With age, disease and medication use these systems deteriorate, which could result in impaired balance. In this paper, it is demonstrated that multi-input-multi-output closed loop system identification techniques (MIMO-CLSIT) can be used to assess the underlying systems involved in standing balance and guide possible therapeutic options. In this study, mechanical and sensory perturbations were combined and applied simultaneously using a Balance test Room. The results demonstrate the value of MIMO-CLSIT to assess the underlying systems involved in standing balance and therefore to improve diagnosis of impaired standing balance.

Keywords: Closed-loops, Perturbation, MIMO, System identification, Diagnosis

1. INTRODUCTION

Impaired standing balance is a significant problem in elderly and is one of the main causes and risk factors of falling (Lin et al. 2012; Muir et al. 2010; Rubenstein 2006). These falls could result in serious injuries and finally in death (Cummings et al. 1985). In combination with the increasing population of elderly and the increased average life expectancy, falls and impaired balance are a huge socio-economic problem (Hartholt et al. 2012).

Standing balance is the ability to maintain an upright position and to counteract disturbances, such as gravity. To keep the body upright, several systems interact in a closed loop to control each joint, like the ankles and hips, resulting in a multi-segmental system. The central nervous system receives information about the velocity and position of all body segments from the sensory systems, such as the visual, vestibular and proprioceptive system, and force-related sensory information from tactile sensors and Golgi-tendon organs. In the CNS, this information is integrated based on the reliability and a motor command is sent to the muscles. The muscles contract and generate a corrective torque around each joint to keep the body in an upright position (Engelhart et al. 2014a). The human balance control could be compared to robot stance control, in which typically zero moment point compensation is used. However, flexible sensory integration is not included, resulting in instability of a robot in situations in which a human is able to maintain standing balance (Peterka 2009).

With age, disease and medication use, the underlying systems deteriorate (Horak et al. 1989; Konrad et al. 1999; Sturnieks et al. 2008). As the underlying systems interact with each other in a closed loop, they can compensate for each other's deterioration. This makes it difficult to detect underlying changes in standing balance and underlying causes of impaired standing balance using current descriptive clinical balance tests (Pasma et al. 2014). Therefore, a new method is required to detect the underlying changes in standing balance at an early stage resulting in a specific diagnosis of impaired standing balance and therefore a possibility to apply targeted interventions to improve standing balance.

Previous research already showed that it is possible to describe underlying mechanisms involved in standing

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balance using perturbations and multi-input-multi-output closed loop system identification techniques (MIMO-CLSIT) (Boonstra et al. 2013; Engelhart et al. 2014b; Peterka 2002). In those studies, several systems were perturbed one by one during quiet stance, while the subject kept his balance. The reaction of the human body was measured by the joint angles and torques and related to the perturbation using non-parametric system identification methods, which shows to be the most robust way to estimate balance behaviour (Engelhart et al. 2015).

In this paper, we show it is possible to apply multiple mechanical and sensory perturbation signals simultaneously to the human body and therefore to detect underlying systems involved in standing balance in one test using MIMO-CLSIT. The design of a custom-made device, the Balance Test Room (BalRoom), is introduced, which is used to apply the several perturbations simultaneously during standing balance.

Figure 1: The Balance Test Room (BalRoom) set up consisting of support surfaces and a visual scene to apply sensory perturbations and rods on hip and shoulder level to apply mechanical perturbations to the human body.

2. METHODS

2.1 Apparatus

The BalRoom is a custom-made device (MotekforceLink, the Netherlands and University of Twente, the Netherlands) to study standing balance. The BalRoom consists of three modules applying perturbations simultaneously during standing balance (Figure 1).

The first module consists of two support surfaces (SS), which rotate around the ankle axes. Both support surfaces are actuated independently. By these rotations a sensory perturbation to the proprioceptive system is applied (Schouten et al. 2011). The second module consists of a visual scene (VS), which rotates around the ankle axes and perturbs the visual information. Both perturbations allow to assess the contribution of the sensory systems in standing balance (Peterka 2002).

The third module consists of two rods applying pushes and pulls at the hip and between the shoulder blades. By these perturbations the leg and trunk segment will move, which makes it possible to assess the contribution of the ankle and hip joint and their coupling in standing balance (Engelhart et al. 2014b).

The BalRoom was controlled using xPC target and a custom-made Matlab interface.

2.2 Perturbation signals

To distinguish the reaction of the human body on each perturbation and therefore the contribution of each underlying system involved in standing balance, independent multisines were designed with a unique combination of frequencies (Figure 2). All excited frequencies were multiples of 0.0625 Hz resulting in a period of 16 s.

Both support surfaces rotated following a continuous position perturbation signal with increasing zero-to-peak amplitude over trials and a flat velocity spectrum with frequencies between 0.125 and 6.9375 Hz. The visual scene rotated following a continuous position perturbation signal with constant zero-to-peak amplitude of 0.03 radians and a flat velocity spectrum with frequencies between 0.0625 and 1 Hz.

Both rods moved following an independent, continuous force perturbation signal represented by zippered multisines with constant zero-to-peak amplitude of 30 Newton and consist of independent frequency contents between 0.75 and 7 Hz.

2.3 Participants

The BalRoom was evaluated on 5 healthy participants (age 25.8 ± 2.8, 3 women). All participants gave written informed consent before entry to the study.

2.4 Procedure

The BalRoom was used to simultaneously perturb the visual information by VS rotation, the proprioceptive information by SS rotation around the ankle axes and the leg and trunk segment by giving pushes and pulls using a rod at the hip and shoulder level.

During all experiments the participant wore comfortable flat shoes. The participant was instructed to stand with the arms resting along the side with both feet on the support surfaces. Three trials were presented in random order with increasing perturbation amplitude of the SS rotation (i.e. 0.02, 0.03 and 0.04 radians), while the amplitude of the other perturbations remained constant. The perturbation signals were repeated 8 times resulting in trials of 128 seconds (i.e. 8 times 16 seconds).

Before starting the recording of each trial the participant was given about 10 seconds to get accustomed to the perturbations. Between trials, the participant was offered ample resting time depending on individual needs. The participant wore a safety harness to prevent falling, which did not constrain movement and did not provide support or orientation information.

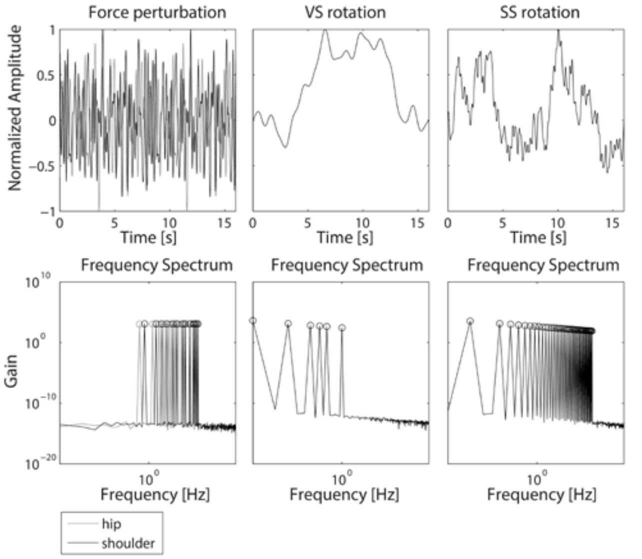

Figure 2: Normalized time signals of the perturbations of the support surfaces (SS), the visual scene (VS) and the rods applying forces at hip and shoulder level.

2.5 Data recording and processing

The actual angles of SS rotation (i.e. motor angles), the applied torques to both support surfaces (i.e. motor torques) and the applied forces to the hip and shoulder (i.e. push forces) were available for measurement. Lower and upper body segmental movements were measured in anterior-posterior direction using two draw wire potentiometers (Celesco SP2-50, Celesco, Chatsworth, CA, United States) at a sample frequency of 1000 Hz. The leg and hip angle were calculated using goniometric and using the segment movement of the lower and upper body. The ankle and hip torque were obtained from the motor torques and push forces using inverse dynamics (Winter et al. 1990). The time series were segmented into eight data blocks of 16 seconds (i.e. the period of the perturbation signal).

2.6 Closed loop system identification techniques

MIMO-CLSIT was used to estimate the contribution of the sensory systems and the dynamics of the ankle and hip joint. To indicate the effect of the perturbations on the ankle torque, hip torque, leg angle and hip angle, Frequency Response Functions (FRFs) were estimated using non-parametric methods. The time series of the perturbations, ankle and hip torque, and leg and hip angle were transformed to the frequency domain. The periodic part of the frequency coefficients was determined by averaging over the data blocks. The Power Spectral Densities (PSD) and Cross Spectral Densities (CSD) were computed to calculate the FRFs (van der Kooij et al. 2005). Only the excited frequencies were analysed.

Sensitivity functions

The sensitivity functions were estimated using the indirect approach according to (1) (Peterka 2002; van der Kooij et al. 2005).

$$ {}^{d}S_{x}(f)=\Phi_{d,x}(f)\cdot\left[\Phi_{d,d}(f)\right]^{-1} \qquad (1)$$

In which $\Phi_{d,x}$ represents the CSD of the perturbation (d) (i.e. support surface (SS) rotation or visual scene (VS) rotation) and x, which represents the ankle torque (T_a), hip torque (T_h), leg angle (θ_l), or hip angle (θ_h), and $\Phi_{d,d}$ the PSD of the perturbation. This results in 8 FRFs; SS rotation to 1) ankle torque (${}^{SS}S_{Ta}$), 2) hip torque (${}^{SS}S_{Th}$), 3) leg angle (${}^{SS}S_{\theta l}$), and 4) hip angle (${}^{SS}S_{\theta h}$), and 5) t/m 8) the VS rotation to each torque and angle (${}^{VS}S_{Ta}$, ${}^{VS}S_{Th}$ ${}^{VS}S_{\theta l}$, ${}^{VS}S_{\theta h}$). Each FRF is represented by a magnitude and phase representing the relation between perturbation and torque or angle in terms of amplitude and time.

Joint dynamics

The MIMO approach was used to estimate the dynamics of the ankle and hip joint and their coupling according to (2) (Engelhart et al. 2014b).

$$ H_{c}=-S_{d,T}\left(S_{d,\theta}\right)^{-1} \qquad (2)$$

In which $S_{d,T}$ and $S_{d,\theta}$ are the CSD matrices between the external perturbations (d) and the corrective ankle and hip torques (T) and the leg and hip angles (θ) resulting in a two-by-two matrix (H_c). This matrix represents 4 FRFs; 1) leg angle to ankle torque ($H_{\theta l2Ta}$), 2) hip angle to ankle torque ($H_{\theta h2Ta}$), 3) hip angle to hip torque ($H_{\theta h2Th}$), and 4) leg angle to hip torque ($H_{\theta l2Th}$). Each FRF is represented by a magnitude and phase representing the relation in terms of amplitude and time.

3. RESULTS

In this section we demonstrate the application of the BalRoom by identifying the contribution of the sensory systems and the joint dynamics.

Figure 3 shows the sensitivity functions of the SS rotations to ankle and hip torques and angles averaged over 5 healthy participants by increasing the perturbation amplitude of the SS rotation. The magnitude of the sensitivity functions decreases with increasing perturbation amplitude, indicating that participants react less on the proprioceptive perturbation by using their proprioceptive information less (downweighting).

Figure 4 shows the averaged sensitivity functions of the VS rotation to ankle and hip torques and angles by increasing the perturbation amplitude of the SS rotation. In this case the magnitude increased with increasing perturbation amplitude, indicating that participants react more on the visual information by using their visual information more (upweighting).

Figure 5 shows the averaged joint dynamics ($H_{\theta l2Ta}$ and $H_{\theta h2Th}$) and their coupling ($H_{\theta l2Th}$ and $H_{\theta h2Ta}$) during simultaneous perturbation of the visual and proprioceptive information and the leg and trunk segment of 5 healthy participants. It is shown that the joint dynamics and their coupling remained constant by changing the perturbation amplitude of the sensory perturbations.

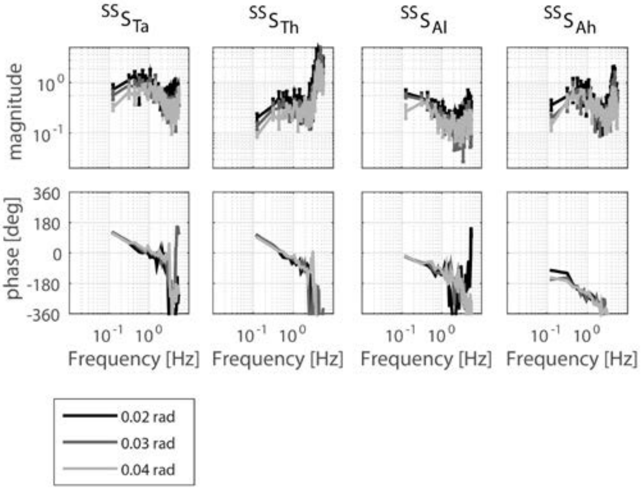

Figure 3: Averaged Frequency Response Functions of the sensitivity functions of support surface (SS) rotations to the ankle torque, hip torque, leg angle and hip angle for three conditions with increasing perturbation amplitude of the SS rotation.

4. DISCUSSION

In this study we investigated the value of MIMO-CLSIT to assess the underlying systems involved in standing balance using a novel apparatus, which can perturb the proprioceptive information, visual information, and ankle and hip segment simultaneously. Independent sensory and force perturbations were applied simultaneously, while the participant maintained standing balance. The results showed that using MIMO-CLSIT the underlying systems in standing balance can be investigated in one test. By applying multiple sensory and mechanical perturbations simultaneously, both the contribution of the sensory systems and the joint dynamics and their coupling can be assessed at the same time.

The results are according to previous studies in which the same kind of perturbations were applied one by one (Engelhart et al. 2014b; Peterka 2002). However, this is the first study in which these perturbations were applied simultaneously. Compared with Peterka (2002) increasing the perturbation amplitude of the SS rotation results in a decrease of the magnitude of the sensitivity functions of the SS rotation and an increase of the magnitude of the sensitivity functions of the VS rotation. Results of the joint dynamics and their coupling were comparable with Engelhart et al. (2014b). These results indicate that unless applying mechanical and sensory perturbations simultaneously, it is still possible to detect the contribution of the sensory systems and the joint dynamics and their coupling.

The next step is to describe the control of standing balance by a multi-segmental model consisting of the underlying systems and an ankle and hip joint, which will give physiological meaning to the measured frequency response functions using estimated model parameters. Previous studies already indicated that it is possible to describe the underlying systems by estimated parameters using balance control models in case of a single perturbation (Peterka 2002).

4.1 Application

Combining SS rotation with VS rotation makes it possible to assess the contribution of the proprioceptive and visual system in maintaining standing balance at the same time. According to the sensory reweighting hypothesis, a flexible and adaptive process of combining the sensory information based on their reliability, the results showed a decrease in sensitivity to the SS rotation by increasing the amplitude of the SS rotation accompanied with an increase in sensitivity to the VS rotation. This indicates that the proprioceptive information is weighted less accompanied with more weighting of the visual information in case of proprioceptive perturbations (Peterka 2002).

The application of the perturbation of the leg and trunk segment makes it possible to investigate the dynamics of the hip and ankle joint and their coupling (Boonstra et al. 2013; Engelhart et al. 2014b).

4.2 Clinical implications

The results of this study show the value of use MIMO-CLSIT to assess the underlying systems involved in standing balance. This shows that using this technique it is possible to disentangle the underlying systems, which is not possible using current clinical balance tests. Therefore, this study shows the value of this technique in detecting the underlying cause of impaired standing balance in clinical practice. A more specific and differential diagnosis of impaired standing balance makes it possible to develop and implement targeted interventions to improve standing balance and finally reduce falling.

Furthermore, the BalRoom and MIMO-CLSIT are applicable to investigate the effect of new developed interventions. The contribution of the underlying systems can be measured before and after interventions and will show the changes in the underlying systems involved in standing balance due to the intervention. Besides, this technique can be used to monitor treatment effects.

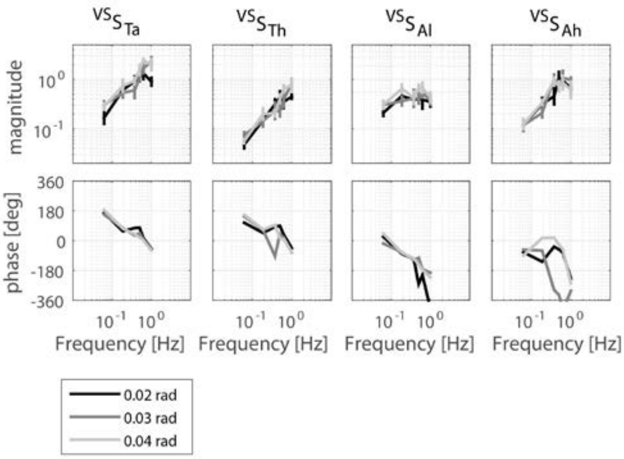

Figure 4: Averaged Frequency Response Functions of the sensitivity functions of visual scene (VS) rotation to the ankle torque, hip torque, leg angle and hip angle for three conditions with increasing amplitude of the support surface rotation.

4.3 Conclusions

In this study, mechanical and sensory perturbations were applied simultaneously to assess standing balance in one test using a novel apparatus, which can perturb the proprioceptive information, visual information, and ankle and hip segment simultaneously. The results show the possibility to apply MIMO-CLSIT to disentangle underlying systems in human standing balance, in which current clinical balance tests are lacking. Therefore, MIMO-CLSIT is an essential tool to improve diagnosis of impaired standing balance in clinical practice and to implement targeted interventions to improve standing balance. The next step is to describe the underlying systems involved in standing balance by estimating model parameters using a multi-segmental balance control model.

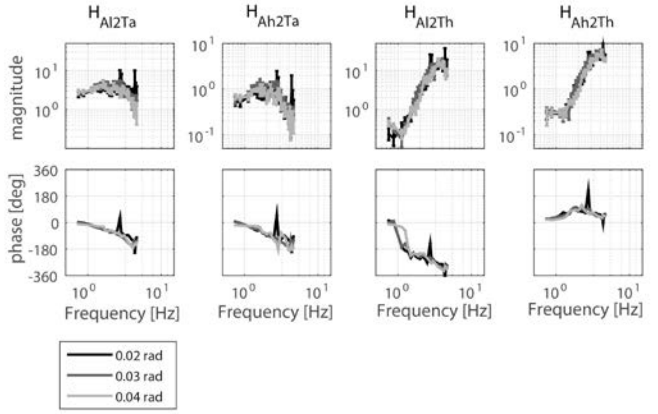

Figure 5: Averaged Frequency Response Functions of the dynamics of the ankle and hip joint ($H_{\theta l2Ta}$ and $H_{\theta h2Th}$) and their coupling ($H_{\theta l2Th}$ and $H_{\theta h2Ta}$).

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