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Robotic dynamic posturography: a validation study using IMU and force platform data

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Abstract. This paper details the development and preliminary validation of an automated system designed for the dynamic assessment of human balance. The system comprises a novel two-axis robotic perturbation device integrated with wearable inertial measurement units (IMUs) and a force platform for capturing postural responses. The design process, component selection, integration challenges, and preliminary validation results on healthy subjects are presented, demonstrating the system's potential for clinical applications.

Keywords: Dynamic Posturography, Balance Assessment, Automated Perturbation, Wearable Sensors, Inertial Measurement Units, Biomechanics

1 Introduction

Maintaining balance is a complex sensorimotor process crucial for daily activities. Objective assessment of dynamic balance control, particularly in response to external perturbations, provides valuable insights into neuromuscular function and fall risk, especially in clinical populations. Traditional methods often rely on manual perturbations or complex, expensive systems based on platform shifting/tilting [1−3]. Few studies have covered direct force perturbations applied on the body of subjects [4−8]. That may depend on safety reasons as well as on the increased difficulty in regulating interaction forces between the human body and external systems, especially when short-lasting (impulsive) interactions are taken into account. On the other hand, direct stimulation allows to replicate typical conditions of balance perturbation, as those coming from interaction with the environment. In addition, shifting from the base of support to the lower/upper body, it is possible to greatly expand the possibility of trial customization, in terms of direction, point of application and magnitude of the perturbation imparted, besides the possibility to exert multiple stimulations at the same time in different body districts.

This paper shows the outcomes of a research project aimed to develop a cost-effective, automated, and reliable system for applying controlled perturbations and measuring the subsequent postural response, thereby facilitating dynamic posturography in various settings. Previous works showed preliminary results collected with manual [9]

and semi-automatic versions of a patented perturbation device [10−13]. In this paper, the outcomes of the trials conducted with a fully automated device are shown. The project was structured into three phases and corresponding milestones, that will be discussed in the following sections:

- design and realization of a fully automated/robotic perturbation device capable of delivering well-defined and repeatable stimuli;
- identification and integration of a suitable postural response detection system with the perturbation device;
- validation of the complete system through field testing and data collection.

2 Methods

2.1 Perturbation System Development

The design of the automated Perturbation Generation and Analysis System (aPGAS) was built around the architecture of an Automatic Perturbator (AP) device described in the literature [11,12]. This device is based on a tubular electric linear motor (GD160Q, NiLAB GmbH, Austria) with 100 mm stroke that is controlled by Model Predictive Control (MPC) action to allow accurate impulse control of each stimulation imparted. Closed-loop feedback is allowed by a uniaxial load cell (UMM 50 kgf-ranged load cell, Dacell Co. Ltd., Korea) rigidly connected between the rod end and a polyethylene interface used to contact the human body. An optical sensor (Q4XTULAF400-Q8, Banner Engineering Corp., USA) is mounted integral with the motor frame and used to monitor the actuator stroke and to allow appropriate control switching between idle, approach, strike and return phases. Additional details about the control logic are provided in the references [10,12].

In previous works [12,13], AP operation was handled by a human operator, who had to maneuver the device close to the trunk of a standing subject and to press a button to generate the disturbance. The latter was set as a square force signal with constant magnitude (40−100 N) lasting 100−250 ms. The stability and robustness of force impulse control, as well as the selection of direction and point of application of the perturbation, depended on the ability of the operator him/herself. To overcome limitations due to the effects of untrained operators, a fully automated solution has been developed. An initial market analysis for 6-degree-of-freedom (DOF) robotic arms revealed that commercially available systems meeting the project's stringent payload and structural rigidity requirements exceeded the budget constraints. Consequently, the design focus shifted towards identifying the essential DOFs for applying perturbations to subjects with varying anthropometry. This led to the selection of a 2-axis Cartesian positioning system.

Based on an analysis of the testing setup requirements to accommodate individuals with heights ranging from 1.50 m to 1.80 m, the system specifications were defined: a vertical travel range of 600 mm and a medio-lateral travel range of 600 mm. Crucially, the vertical axis required sufficient rigidity to withstand the reaction forces generated by the impulsive perturbation without significant deflection. High precision

electromechanical axes with screw drives (LEJS40T6B-600B-R5B21 and LEJS63T7A-600B-R5B21, SMC, Japan), driven by AC servo actuators with integrated brakes and absolute encoders, were selected. The positioning system has been designed to select and reach any point of interest with the required accuracy and stability, prior to application of the perturbation. Brakes are used on each linear axis to fix the position of the corresponding sliding cart during the perturbation phase, in which the AP driven by the tubular motor is controlled to interact with the body of the patient according to the specifications of the application. During that period, no speed or torque control is enabled on the linear axes to avoid electromagnetic interference with the instrumentation used to record the postural response. Brakes are designed to engage also during power supply losses, for safety purposes. The completed device is shown in Fig. 1.

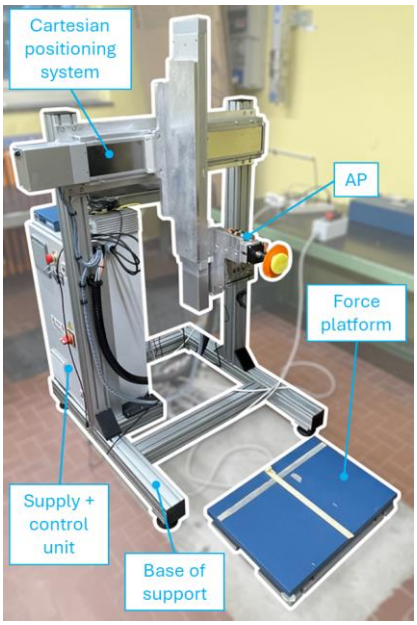


Fig. 1. The complete automated perturbation system (aPGAS).

2.2 Postural Response Detection System

Center of Pressure (CoP) estimation is standard in most of the applications centered on human motion analysis, both in static and dynamic conditions. For this reason, a force platform (BMS400600, AMTI, USA) was still included in the current setup (Fig. 1). Nonetheless, CoP-based measurements do not allow to gather information about other aspects that seem relevant in the study of postural response. In particular, we focus on muscular activity and body kinematics. Therefore, a review of wearable sensor technologies suitable for postural response characterization identified two primary candidates: surface electromyography (sEMG) technology [14−16] and inertial measurement units (IMUs) [17−20].

A wireless sEMG system (miniWave, Cometa, Italy) was initially evaluated. Preliminary tests were conducted by the authors on 20 healthy subjects by using eight sensors to record activity from key postural muscles in the pelvic region and lower limbs. However, only two muscles (tibialis anterior, gastrocnemius) showed significant activity in terms of RMS values of rectified EMG signals, indicating limited efficacy of sEMG for comprehensively capturing the postural response in this application. Low RMS values may be due to the limited impulse provided (4−10 Ns) selected for safety purposes and to avoid evoking step responses that would compromise CoP estimation. To confirm this hypothesis, implementation of sEMG in the measurement setup could be considered in the future for increased impulse levels.

Subsequently, a wireless IMU system comprising three units and a receiving base (WavePlus, Cometa, Italy) was considered. Each IMU's enables wireless measurements of triaxial acceleration, angular velocity and magnetic field. Preliminary laboratory tests confirmed the IMUs' sensitivity to simulated postural perturbations representative of the final application. Extracted parameters, including maximum anteroposterior acceleration, overall RMS acceleration, trunk inclination, and hip joint angles, demonstrated good robustness and reliability across repeated trials.

Comparative analyses favored IMUs over sEMG due to their potential to capture more relevant kinematic information characterizing the overall postural response (Fig. 2). Furthermore, IMU implementation was deemed less cumbersome and more suitable for dynamic posturography in less structured environments, aligning with the technology's intended application areas. All necessary software for integrating the selected IMU system with the perturbation device was developed and tested.



Fig. 2. A dynamic posturographic trial carried out with aPGAS.

3 System validation and results

Validation of the complete automated system has been performed on a sample of 15 healthy subjects (28.5±3.7 years, 1.76±0.07 m height, 24.3±3.7 kg/m^2 Body-Mass-Index), integrating the IMU sensors in the measurement setup. Two sensor placements at pelvis (L5 vertebra) and thigh segments (Fig. 2) have been considered. Tests were conducted using two distinct impulse intensity levels (4 and 10 Ns), applied at the interscapular level in anteroposterior direction. To assess impulse accuracy and repeatability, a force impulse (FI) parameter was estimated by windowing the perturbation signal measured by the load cell. Subjects received different instructions to pre-condition their postural control system, allowing assessment of the sensitivity of the identified indices to varying postural sets. In particular, the following conditions were achieved:

- REO: resting condition, eyes opened;
- REC: resting condition, eyes closed;
- SEO: stiff condition, eyes opened.

Instructions were randomized across the sample, to limit bias on data analysis. For each instruction given, ten consecutive stimuli were imparted at low and high impulse levels, five perturbations each, with random order. A 10-seconds interval between two consecutive stimulations was ensured to avoid misinterpretation of the response data. The protocol resulted in a set of 30 perturbations for each subject. Before starting each set, AP load cell and force platform were zeroed, and IMUs were calibrated to reduce drift effects. Only accelerometer and gyroscope readings were used due to strong electromagnetic disturbances in the test area. Among all parameters tested, key values and signals extracted included: maximum Center of Pressure displacement (ΔCoP), impulse-normalized ΔCoP (ΔCoPn), CoP response duration and latency with respect to perturbation onset, maximum and RMS accelerations in anteroposterior direction, hip angles. CoP-extracted parameters were chosen to be coherent with previous studies [9,13]; maximum and RMS values of acceleration were selected as robust and concise parameters to assess signal intensity; hip angles, that are relevant to discuss lower body kinematics in response to exerted stimulations, were obtained by application of a biomechanical calibration model described in the literature [21].

The force profiles generated by the automated system demonstrated good accuracy and repeatability (Fig. 3). The FI values for the two levels tested were 3.56±0.20 Ns and 9.01±0.47 Ns across the whole sample. For each subject and condition tested, the variability of FI (assessed as percentage standard deviation) resulted always lower than 10% and 6.2% respectively for low and high impulse values. These results show the robustness of the control strategy and highlight the stability of the support provided by the positioning system. Moreover, these results are unaffected by the number of stimuli exerted, whereas trials performed with the former device handled by the operator evidenced a role of fatigue and subjective skill on test quality. Among the whole sample (30 stimuli x 15 subjects), only one perturbation was missed, likely for unexpected sway behavior from a subject preceding stimulation.

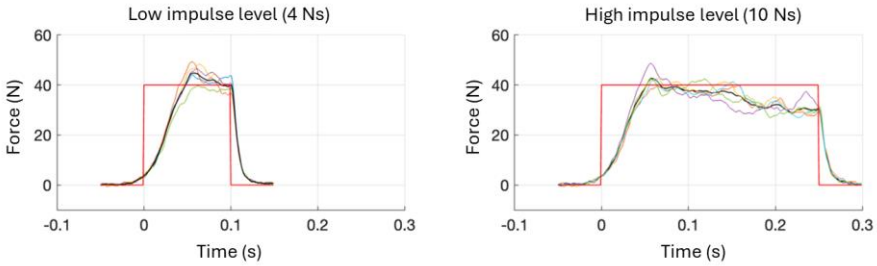


Fig. 3. Perturbation profiles exerted on a subject for low and high impulse values: red thick line is the reference force signal; black thick line is the average signal measured by the load cell over a set of consecutive perturbations shown in thin colored lines.

As expected, force platform measurements (ΔCoPn, response duration) showed good sensitivity to the different test conditions imposed by varying subject instructions (Fig. 4). As demonstrated in previous studies [9,13], the change in the center of pressure displacement (ΔCoP) remained relatively consistent across the various impulse levels examined, indicating a linear relationship between CoP displacement and perturbation impulse. Normalized CoP responses under SEO instruction exhibited greater magnitudes when subjected to lower impulse intensities. This pattern, consistent with prior research, suggests a deviation from linearity under conditions of low-intensity perturbations. As anticipated, the response duration in the SEO condition was shorter compared to other tested conditions, confirming an enhanced reactivity of the neuromuscular control system responsible for maintaining balance in scenarios requiring a stiff response. Marginal differences were observed in contrast between REO and REC outcomes, specifically concerning ΔCoP. However, more pronounced differences were evident in CoP response duration, with a modest reduction noted in response to higher impulses.

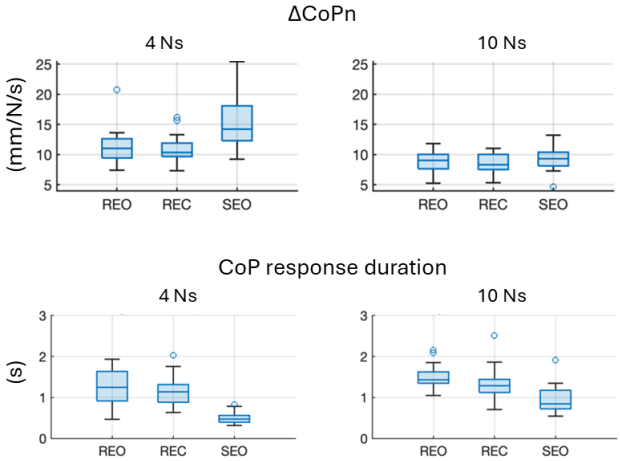


Fig. 4. Average impulse-normalized CoP displacement (ΔCoPn) and CoP response duration under different instructional sets.

Crucially, the processing of IMU signals revealed a strong correlation between parameters extracted from the IMUs and those obtained from the force platform. Specifically, the total RMS acceleration of the pelvis measured by the IMUs mirrored the behavior of ΔCoPn in discriminating between postural responses evoked under different instructions (Fig. 5, right). Analogous to CoP data, RMS accelerations exhibited a direct proportionality to the impulse magnitude. Due to the anteroposterior orientation of applied stimuli, mediolateral accelerations were consistently negligible across both low and high impulse levels (Fig. 5, left and center). Consequently, sagittal plane hip joint kinematics appear to be the dominant factor for this specific application. Nevertheless, the hip flexion-extension range remained narrow, approximating ±1.5° for low intensity perturbations and ±2.5° for high intensity perturbations, likely attributable to the brief duration and limited magnitude of the applied force profiles. While joint angles may assume greater significance with increased and multidirectional stimulation, the primary objective of this analysis was to validate the viability of the current methodological approach. The ability of the IMUs to provide additional kinematic information about the trunk and lower limbs appears particularly promising, potentially offering valuable data complementary to standard force platform measurements.

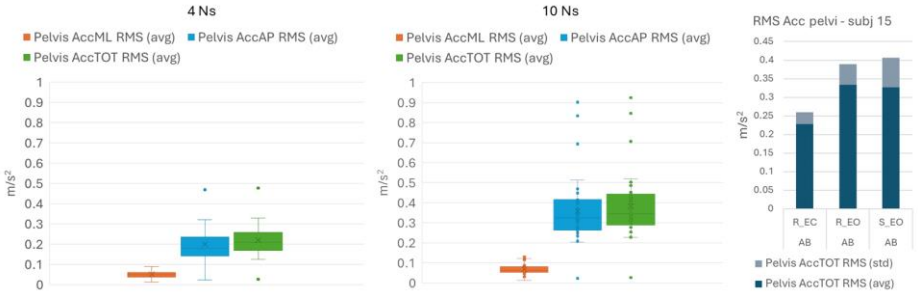


Fig. 5. RMS values of pelvis accelerations for low (left) and high (center) impulse levels averaged across all subjects, RMS values for a specific subject in the three conditions tested (right). ML = medio-lateral, AP = anteroposterior, TOT = total.

4 Conclusion

In this project, we successfully developed a novel 2-axis automated system for delivering controlled postural perturbations. Integration with wearable IMU sensors provides a robust method for quantifying dynamic postural responses. Preliminary validation on healthy subjects demonstrated the system's reliability and the sensitivity of combined force platform and IMU measures to different perturbation intensities and postural sets. The strong correlation between IMU-derived parameters (pelvic RMS acceleration) and traditional force platform metrics (ΔCoPn) highlights the potential of IMUs as a viable, potentially more portable, alternative or complement for dynamic balance assessment.

As a preliminary study focused on unveiling the potential and feasibility of the methodology presented, some limitations were highlighted too. In particular, the limited sample size of 15 healthy subjects is not fully representative of the population this

system is dedicated to. In the future, further validation on clinical populations will be necessary to assess the full potential and limitations of the methodology proposed, in particular regarding safety protocols that will be necessarily set up to allow testing on patients. The system presented clearly outperforms the former, hand-held architectures of perturbation devices in terms of repeatability and objectivity of the test performed. Nonetheless, costs and bulkiness represent critical aspects that can make adoption of such a system quite difficult in not sufficiently organized clinical environments. For this reason, the advantages of this system must be clearly assessed in a real scenario to motivate users to be interested in such technology. Future studies will strive in this direction.

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