Towards behavioral based sensorimotor controller design for wearable soft exoskeletal applications

Imran Mahmood, Uriel Martinez-Hernandez, and Abbas A. Dehghani-Sanij

Abstract—**This study presents the assessment of ankle-foot gait abnormalities and estimation of neuromuscular control for maintaining gait dynamic stability and avoid falls. Control signals are modelled as the rate of change in the body COM acceleration as an input and the COP velocity as an output. Experiments show that the toe foot condition is least stable than inverted and normal walk at loading phase. However, the overdamped motor output response, equally stable for the three undamped input instabilities, shows the robustness of our proposed motor controller. Results show that our novel neuromotor inspired controller, based on behavioral I/O signals, is robust and suitable for the assessment of exoskeletal stability and control of wearable soft robotic applications.**

I. Introduction

Locomotion is the result of combined efforts between exoskeletal and sensorimotor system, which is essential to perform daily living activities. An impairment in the exoskeletal or sensorimotor systems may result in serious outcomes such as gait instability. Assessment of gait stability and balance have been studied with four foot abnormalities; toe walk (equinus, plantigrade) and turning outside foot towards in and vice versa (inversion, eversion) [1,2]. These studies showed that untreated foot abnormalities result poor balancing, activity avoidance, high metabolic cost, skeletal deterioration and fall risk. The rate dependent variation in the body center of pressure (COP) or the center of mass (COM) were used to assess the gait dynamic stability for foot abnormalities [3, 4].

In this study, the neuromuscular dynamic stability thresholds are modelled in terms of rate dependent variations in the whole body COM and the COP signals. A disturbance in the COM acceleration is modelled as motor input, while the COP velocity is modelled as motor output, which corresponds to the muscular response via spine [5,6]. The correlation between two signals was used to determine an exoskeletal model (plant) and the neuromotor behavioral estimation (controller) as shown in Fig.1 (a, b). Our proposed controller has the ability to diagnose fall condition and generate preventive moment at the ankle-foot joint using a wearable soft actuator as a peripheral skin. This work mainly assess the I/O's stability thresholds with vibration disturbances, experiences at loading phase, and the corresponding strategy for stability adopted by the motor. Here, the plant is modelled using aforementioned I/O signals, while the motor controller is proposed using the affine parameterization method. This modelling approach has been successfully implemented for activities like level ground walk and ramp walk [5, 6].

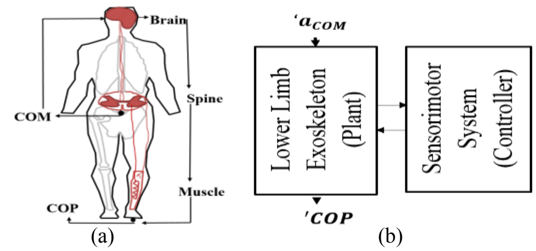

Fig. 1. (a) Neuromuscular feedback control loop, (b) Corresponding SISO linear time invariant system modelling.

II. Methods

A. Experimental Protocol

The Qualysis motion capture system, operated with 12 cameras, was used to record level ground walk with 4 healthy subjects that performed normal walk, toe walk and inverted walk. For toe and inverted walk, subjects were asked to pretend they had these foot abnormalities, similar to the visual gait analysis procedure adopted for the neurologic exam in clinical and lab environments [1, 7]. Four trials were conducted with each subject. All data were recorded at 400 fps and 1200Hz using AMTI force plates. The group means data for testing subjects was in following range: age 31±4y, height 175±1.6cm, weight 83±8kg.

B. Data Processing and Finite Difference Algorithm

After preprocessing the desired features in the QTM, the data were exported as AVI file and analyzed further using the ImageJ software. The rate dependent variations in the COP and a_{COM} were computed using the GRF vector position and magnitude respectively. The built-in velocity plugin was used to apply the finite difference algorithm over the kymograph traced the GRF vector position and magnitude. The rate of change in GRF was normalized to find $a_{COM}(= GRF/m)$. The finite difference algorithm was implemented using Eq. (1) in anterior-posterior and vertical directions for GRF trace out. The algorithm was implemented for loading phase of gait with optimum window size of 150frames suitable for all foot conditions. The results are shown in Fig. 2(a,b) for toe walk.

$$V_{COP_{AP}} = \frac{d_{xi}}{d_{ti}} = \frac{|X_{i+1} - X_i|}{|t_{i+1} - t_i|} \quad (1)$$

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Imran Mahmood, Uriel Martinez-Hernandez and Abbas A. Dehgani-Sanij are with the Institute of Design, Robotics and Optimisation (iDRO), and the School of Mechanical Engineering at the University of Leeds, Leeds, LS2 9JT, UK. (emails: mnim, u.martinez, a.a.dehghani-sanij@leeds.ac.uk).

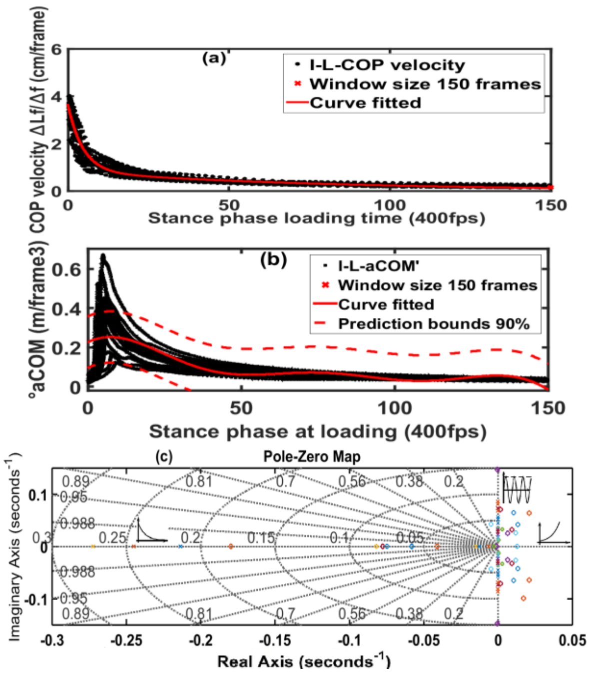

Fig. 2. (a) COP velocity, (b) $'a_{COM}$ for inverted walk in loading phase, (c) Frequency domain pole-zero map for stability analysis.

III. Results

The average speed variance was found by ANOVA test with p>0.05 for three walking conditions. The Spearman's correlation was found to be between 0.9 and 1 for both inter-trial and intra-trial variance using SPSS. The I/O signals were modelled using curve fitting toolbox from MATLAB and non-linear least square regression methods with maximizing the coefficient of determinant (R^2). Based on the impulsive nature signal, the COP velocities (output) were modelled as the sum of exponents, while vibration signals $'a_{COM}$ (input) were modelled as the sum of sinusoids. The standard deviation in modelling coefficients is not significant (<1%) from mean motor output signals, however, for input vibration signals it is significant w.r.t peak gain (>50%) and insignificant w.r.t frequency component (<2%). The mean time domain signals were transformed to frequency domain by Laplace assuming each as a single-input and single-output (SISO) linear time invariant system. The Bode plot was applied for establishing the mean stability margins mentioned in Table (1).

TABLE I
GAIT DYNAMIC STABILITY THRESHOLDS IN FREQUENCY DOMAIN

Gait Activity	*Gait Phase*	*Gait Margin (dB)*	*Phase Margin (degree)*	*Coefficient of determinant R^2 (%)*
I-L-'COP	Loading-AP	Inf	92.663	99.86
N-L-'COP	Loading-AP	Inf	92.468	99.88
T-L-'COP	Loading-AP	Inf	94.334	99.47
I-L-'a_{COM}	Loading-AP	10.366	-60.971	58.7
N-L-'a_{COM}	Loading-AP	1.0156	-1.175	68.5
T-L-'a_{COM}	Loading-AP	0.0963	36.575	46.34
I-L-'a_{COM}	Loading-vertical	4.69×10^{-7}	84.702	96.77
N-L-'a_{COM}	Loading-vertical	8.44×10^{-7}	73.6453	87.35
T-L-'a_{COM}	Loading-vertical	1.3859	-37.800	93.08

I-inverted, N-normal, T-toe, L-loading, AP-anterior-posterior.

IV. Discussion

The COP velocity signals showed that the loading phase is the most stable gait phase with GM infinite and PM 93.2±1°. However, there were vibration disturbances generated in parallel to COP velocities both in anterior-posterior and vertical directions, where the motor responded as a compensator. A pole-zero map in Fig. 2(c) showed that the motor output response was overdamped (poles at left) to compensate undamped motor inputs disturbances (poles at the imaginary axis of s-plane). We found that the impact of the input vibrations was relatively less for a normal walk with least instability margins in both AP and vertical directions. In the sagittal (vertical) plane, toe walking was highly unstable (PM= -38°) while the inverted walk was less unstable (GM≈ 0dB). The second important direction is AP, where the inverted walk proved to be most unstable (PM= -60°). Despite toe and inverted walk abnormalities, the neuromuscular system proved to be a compensator that copes with instabilities in the range close to normal walking conditions. Falling may occur if the input disturbance exceeds the stability thresholds. The balancing approach adopted by sensorimotor may be estimated by behavioral I/O's response exhibited by the human exoskeletal system. The frequency domain analysis and estimation of motor control presented in this work extend previous studies on stability analysis in time domain [1-6].

V. Conclusion and Future Work

The dynamic stability thresholds are modelled using both with normal and pretended abnormal ankle-foot conditions during gait loading phase. The correlation between I/O showed that the motor performed as a robust controller with a wider range of balancing to cope with abnormalities. The first estimation to that controller is a SISO linear time-invariant exoskeletal/plant model with advancement towards nonlinear one.

Using this plant model, the affine parameterization theory will be applied further to the estimated motor controller. The input disturbances or vibrations help to characterize the wearable soft actuator damping requirements and behavioral based neuromotor controller, applicable to assess and prevent fall condition based on the actuation of wearable soft robotics.

References

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