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Gait Dynamic Stability Analysis and Motor Control Prediction for varying Terrain Conditions

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***Abstract*— This work presents the gait dynamic stability modelling for different walking terrains adopted by the motor. The sensory-motor transitional gait assessment is difficult in clinical environment in case of disorders. The aim of present study was to model and analyse dynamic stability thresholds for gait transitional phases. Experimental data were collected from four healthy subjects while walking on a force platform placed at ramp and level ground walking tracks. The rate-dependent variations in the center of pressure (COP) and ground reaction forces (GRF) were modelled as motor output and input responses. Finite difference and non-linear regression algorithms were implemented to model gait transitions. Dynamic stability estimation for ramp and level ground walking were performed by analysis in time and frequency domains. Our investigation provided interesting results; 1) the overdamped motor output response acts as a compensator for instabilities and oscillations in unloading phase and initial contact, and 2) prediction of ramp ascend walking as the least stable gait than ramp descend for healthy subjects.**

Keywords—dynamic; stability; gait; transient; frequency domain; ramp walk; model.

I. INTRODUCTION

Walking is an essential daily living activity in human's life that becomes vital in case of gait impairments. The gait transitional phases are more critical while performing level ground and ramp walk activities. The neuromotor is the part of human brain that controls the stability. The dynamic stability of gait depends on the center of pressure (COP) and its rate dependent variations [1, 2]. The COP is defined as the path on the foot plantar surface, where all the external forces act [3]. While important advances have been achieved on gait static stability in the last decades, only a few research works have focused on the analysis of gait dynamic stability. Still, the neuromuscular response thresholds involved in balance control are largely unknown [4]. Some of these works have proposed to use the rate of change in the COP or center of mass (COM) acceleration a_{COM}, as neuromuscular motor responses to achieve dynamic stability. However, the correlation in the COP and the COM along with motor adaptation to gait transitional balance at different walking terrains, which remain unknown, are investigated in this work.

Ageing, motor disorders and pathologies are main factors for gait impairments and fall risk [5]. The study by Heinemann revealed that about 75% of people over 65 years old have weight-bearing lower limb problems and also fall is the leading cause of accidental deaths in old age [6]. In normal conditions, two third of body weight lies at two third of body height [7]. The successful negotiation between body and environment reduces the chances of injuries due to fall risk. In relation to this, the ankle-foot, seen as the end-effector, plays a key role in the negotiation of balance during walking. Previously, the COP has been used to distinguish gait abnormalities, establishing a rehabilitation index and for evaluation of foot orthoses [3]. Under pathological conditions, the rate of change in the COP assesses impairments threshold clinically [1, 8]. The time derivative of the COP stands as an important measure, describing the motor output response to compensate instabilities [9].

Only few works have studied the prediction of gait transitions in relation to gait dynamic stability. These works have used the first order negative exponential model, widely applied for gait stability analysis in loading phase, and where time constant and gains were estimated from time domain a_{COM} [2, 4, 5, 10]. Prediction of the COP and the GRF rate dependant variations in loading phase have been studied using the sample entropy algorithm [11]. The Savitzky Golay filter has been used to compute the COP velocity and analyze dynamic stabilities for four-foot conditions [8]. The study of the gait transitional stability for inclined surfaces has not shown relevant progress. However, analysis of this stability is critical to understand and predict slip and fall risks. In this work, we analyze the dynamic stability of gait transitional phases, gait unloading and effects of vibrations at the initial contact event. This investigation is performed for different terrain conditions, particularly for ramp walk activities, which require a complex neuromotor control. Furthermore, motor transient responses are modelled to estimate instability thresholds both in time and frequency domains.

II. METHODS

The experimental protocol consisted of an array of 12 cameras connected to the Qualisys motion capture system with AMTI force platforms (BP 400600-2000) shown in Fig.1. The operating frequencies were 400fps and 1200Hz respectively. The force plate data was captured using 64 channel analogue output board (PCI-DAC6703) and synchronized with motion markers using Qualysis software (QTM) and Oqus cameras. The experiments were performed with four healthy subjects (ages 20±1; foot length 27±1cm; weight 72±7kg, heights

175±7.5cm) and having no previous impairment history. Four trials were conducted for each subject at user self-selected normal walking speed for level ground (8m), ramp ascend and ramp descend (5.7m) walk. The ramp inclination was 5° from ground level. The experiments were performed with the consent of ethical approval from the University of Leeds.

Each subject was instructed to look forward straight and perform three rhythmic steps before making contact with force plate almost in the middle. The motion data, captured from each subject, was exported as AVI file at 400fps. The rate dependant variations were measured using ImageJ, which is an advanced open source image processing software applied for biomechanical analysis [13, 14]. After selecting the desired region of interest and pre-processing steps, the GRF vector edges were detected from the Kymograph plot, which is an image analysis technique for single plane time-displacement motion. Here, this technique was applied to macroscale motion analysis as shown in Fig. 2(b-d). The finite difference algorithm was applied to the COP and the GRF vector paths extracted by kymograph (see Table 1). The rate of change in the GRF was normalized with body mass to obtain vibrations signals i.e. ($'a_{COM}$ =*GRF/mass*) for respective subjects. The measurements and stability analysis was made for left foot considering symmetry in healthy subjects.

TABLE1. Finite difference algorithm.

Parameter	Actuate Value	Average Value
Rate of change in COP in AP	$V_{COP_AP} = \frac{d_{xi}}{d_{ti}} = \frac{\lvert X_{i+1} - X_i \rvert}{\lvert t_{i+1} - t_i \rvert}$	$V_{COP_AP} = \frac{d_{xi} + d_{x_sum}}{d_{ti} + d_{t_sum}}$
Rate of change in COP in ML	$V_{COP_ML} = \frac{d_{yi}}{d_{ti}} = \frac{\lvert Y_{i+1} - Y_i \rvert}{\lvert t_{i+1} - t_i \rvert}$	$V_{COP_AP} = \frac{d_{yi} + d_{y_sum}}{d_{ti} + d_{t_sum}}$
Rate of change in GRF along Y-axis	$'GRF_{sagittal} = \frac{d_{zj}}{d_{tj}} = \frac{\lvert Z_{j+1} - Z_j \rvert}{\lvert t_{j+1} - t_j \rvert}$	$'GRF_{sagittal} = \frac{d_{zj} + d_{z_sum}}{d_{tj} + d_{t_sum}}$
Rate of change in GRF in AP	$'GRF_{AP} = \frac{d_{xj}}{d_{tj}} = \frac{\lvert X_{j+1} - X_j \rvert}{\lvert t_{j+1} - t_j \rvert}$	$'GRF_{AP} = \frac{d_{xj} + d_{x_sum}}{d_{tj} + d_{t_sum}}$

Initial conditions $d_{x_sum}=0$; $d_{y_sum}=0$; $d_{z_sum}=0$.

The finite difference algorithm was implemented to determine the average rate of change. The averaging method can smooth the noise, however, the signal diminishes at gait unloading phase. The diminishing effect is compensated by a windowing technique. The one way ANOVA test was performed and proved the interclass stance time variance was insignificant i.e. p>0.05 (p=0.94 for ramp ascend, p=0.99 for ramp descend and p=0.93 for normal walk). Results from multiple trials also showed that, windows sizes of 100 and 50 frames, were the optimal for loading and unloading phases respectively. Exception was made for vertical a_{COM} signals as it takes most of the stance time to get stable. The modelling assumptions included: 1) the analysis performed along force

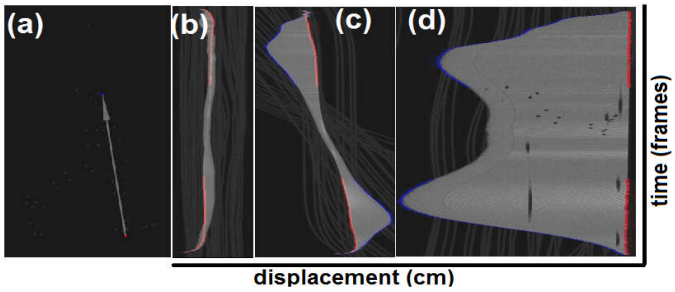


Figure 2 (a) GRF vector position and magnitude in stance phase (blue – GRF position, red – COP position), Kymograph plot in (b) AP, (c) ML, (d) vertical directions for Ramp ascending walk.

plate coordinate system i.e. X-axis for anterior-posterior (AP), Y-axis for medial lateral (ML) and Z-axis stands for vertical, 2) the neuromotor control was considered as a three degrees of freedom system i.e. AP, ML, Vertical directions, 3) In the finite difference algorithm, the initial values were assumed in the range to mean for all 16 trials, 4) the inertial effects were modelled as discrete and forced vibrations in sagittal plane.

A. Modelling Scenarios

The motor inputs ($'a_{COM}$) and controlled outputs ($'COP$) were modelled at gait transient phases i.e. loading and unloading. Each phase was modelled and analysed in multiple directions. The following abbreviations were used:

- A-L-COP velocity: Ramp ascending, loading phase COP velocity.
- D-L-COP velocity: Ramp descending, loading phase COP velocity.
- A-U-COP velocity: Ramp ascending, unloading phase COP velocity.
- D-U-COP velocity: Ramp descending, unloading phase COP velocity.
- N-L-COP velocity: Level ground walk at normal speed, loading phase COP velocity.
- N-U-COP velocity: Level ground walk at normal speed unloading phase COP velocity.
- A-L-$'a_{COM}$: Ramp ascending, loading phase rate of change in COM acceleration/vibration.
- D-L-$'a_{COM}$: Ramp descending, loading phase rate of change in COM acceleration/vibration.
- A-Vertical-$'a_{COM}$: Ramp ascending, vertical direction in sagittal plane rate of change in COM acceleration.

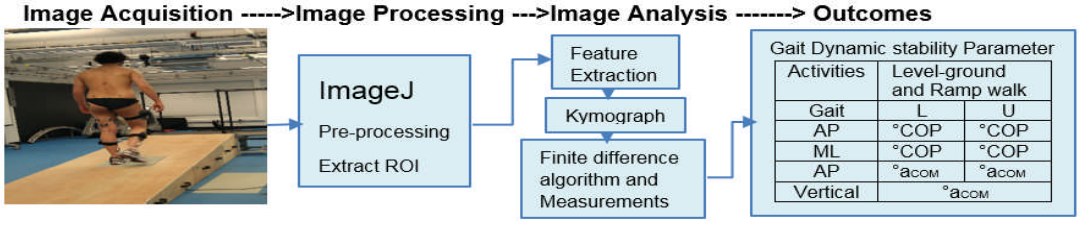


Figure 1 Experimental protocol for gait dynamic stability analysis in anterior-posterior (AP), medial-lateral (ML) and vertical directions.

III. RESULTS

The posturographic test was performed over 16 feet to model dynamic stability. Motor I/O signals i.e. $\acute{}a_{COM}$ and COP velocity presented a non-normal distribution. The Spearman's correlation was applied using SPSS (IBM SPSS Statistics 22) for 16 trials in each case. The inter-trial average correlation was found between 0.9-1. The dynamic models were estimated using MATLAB curve fitting tool. The non-linear least square regression (least absolute residual) method was applied to estimate motor output response and sum of sinusoids used to model vibrations input signal. The gait transient responses were modelled maximizing the coefficient of determinant (R^2) and 95% of confidence bounds. The sample plots are shown in Figures 3-6 for AP (L/U) and vertical directions.

Our modelling approach achieved better accuracy than previously adopted parameter estimation based inverted pendulum or negative exponential models [5]. The gait cycle was categorized in loading and unloading phases, both in AP and ML directions for COP signal, and, AP and vertical directions for a_{COM} signal.

A. Modelling equations for motor output response ˊCOP

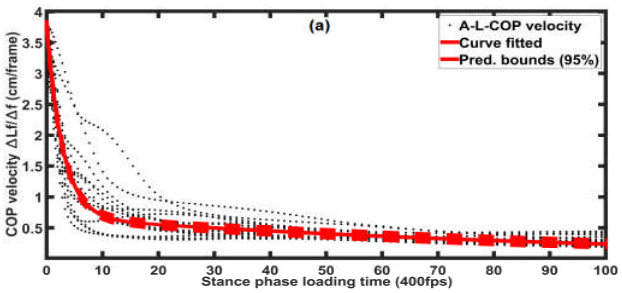
Motor output impulsive signals were modelled as two phase exponential functions using best fit coefficient of determinant (R^2). The loading phase was observed to be decaying with significantly greater *ˊCOP* initial magnitudes, while unloading showed a growing response (see Fig. 3 and 4). Eq. (1) represents motor input signal as transient and steady state components. The average R^2 lies in 99% for loading and 84±2% for unloading phases including AP and ML for the 16 trials.

$$\acute{}COP = a\, e^{bt} + c\, e^{dt} \tag{1}$$

where a and c are gains ($K_{net} = a+c$). Parameters b, d (±) are reciprocal of time constants ($\tau_{net} = bd \,/\, b+d$). The time constants were positive for growing and negative for decaying exponential models. The time domain stability index (I), previously defined in [5, 10], has been extended in this work as shown in Eq. (2), by correlating loading (L) and unloading (U) during double limb stance support.

$$I = \frac{\tau_L \times K_L}{\tau_U \times K_U} \tag{2}$$

where τ_L, τ_U are loading, unloading phase time constants respectively and K_L and K_U are respective gains.



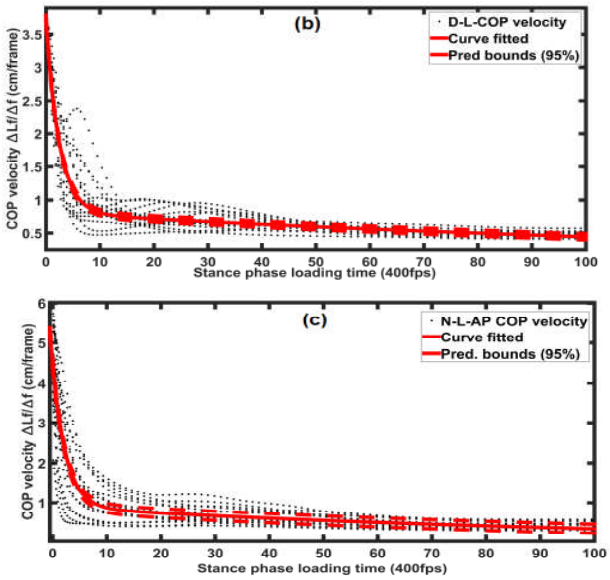


Figure 3 AP COP velocity at loading phase (a) Ramp ascend, (b) Ramp descend, (c) Level-ground walk at normal speed, where ΔLf – change in foot length, Δf – change in time in terms of frame rate, AP-anterior-posterior.

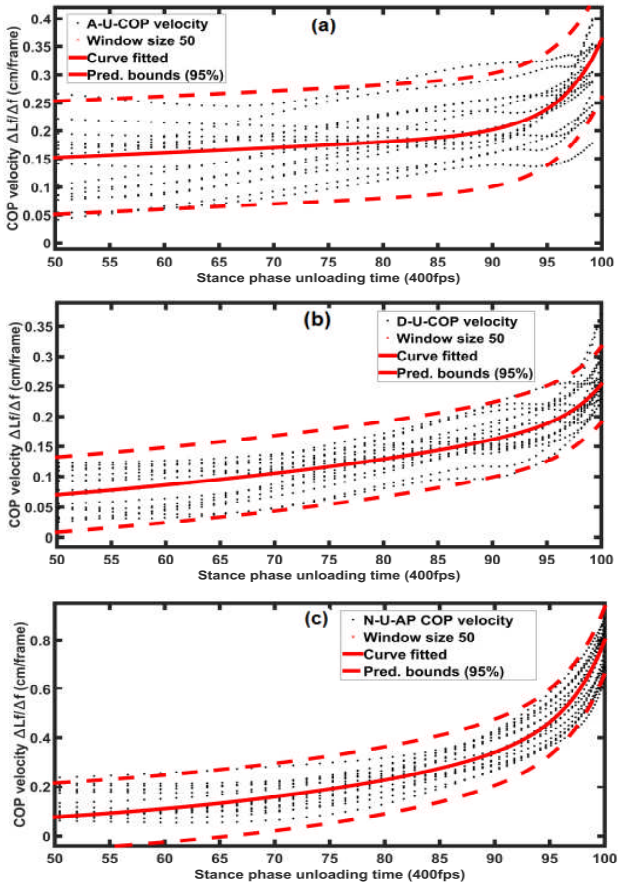


Figure 4 AP COP velocity at unloading phase (a) Ramp ascend, (b) Ramp descend, (c) Level-ground walk at normal speed, where ΔLf – change in foot length, Δf – change in time in terms of frame rate, A-ascend, D-descend, N-normal, U-unloading, AP-anterior-posterior.

B. Modelling equations for motor input disturbance signal $\dot{a}_{COM}$

The input sensory disturbances were modelled as three phase sinusoid functions in Eq. (3). The $\dot{a}_{COM}$ was assumed as undamped input to the motor as shown in Fig.5 and Fig.6. Finding the least instability in ML, the stability analysis was neglected in that direction. The R^2 values lies 56±6%, 32±6%, and 65% for AP loading, unloading, and vertical directions.

$$\dot{a}_{COM} = a_1 \sin(b_1 t + c_1) + a_2 \sin(b_2 t + c_2) + a_3 \sin(b_3 t + c_3) \quad (3)$$

where *a's* are amplitudes, *b's* are frequency of oscillation and *c's* are phase shifts.

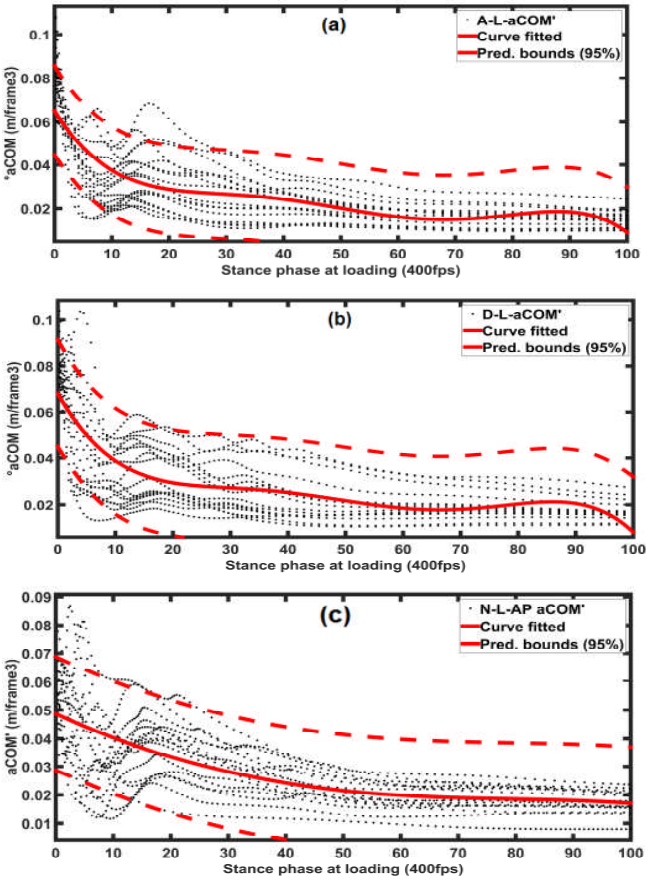
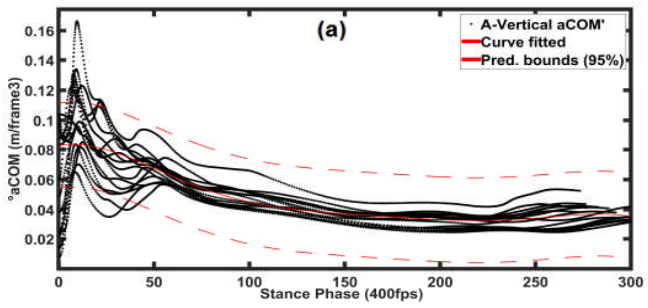


Figure 5 (a) Rate of change in $\dot{a}_{COM}$ in AP direction at loading phase during (a) Ramp ascend, (b) Ramp descend, (c) Normal speed level-ground walk.



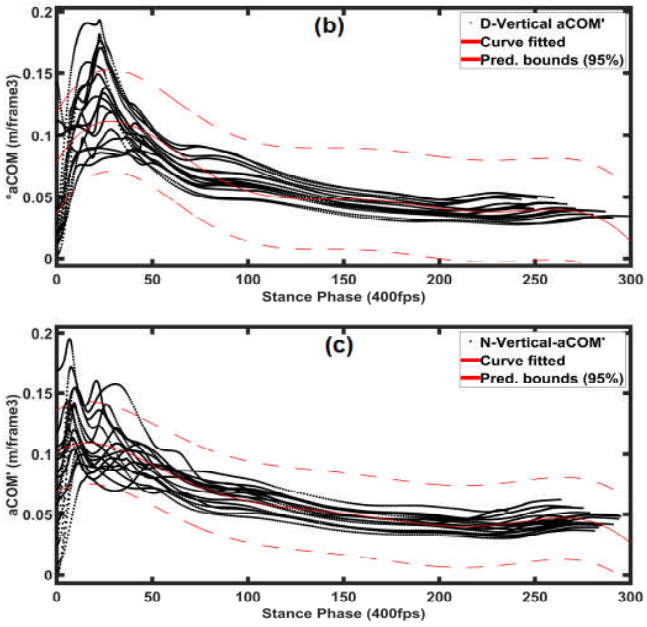


Figure 6 (a) Rate of change in $\dot{a}_{COM}$ in vertical direction during stance phase for (a) Ramp ascend, (b) Ramp descend, (c) Normal speed level-ground walk.

For all 16 trials in each case, I/O time domain signals were modeled in Eq. (1) and Eq. (3). Laplace transform was implemented assuming single-input single-output linear time invariant (LTI) open loop systems. Frequency domain stability were characterized as phase and gain margins by obtaining Bode plot for individual model as shown in Fig. 7(b, c). The vibration signal was used as the motor input, while loading and unloading were motor output. The stability thresholds for output and input signals in both time and frequency domains are shown in Table 2(a) and Table 2(b) respectively.

TABLE 2(a). The stability thresholds for motor output signals ($\dot{COP}$) modelled as multi-phase exponentially decaying functions in loading phase and growing functions in unloading phase.

Ramp/ level ground- phase- direction	Time Domain		Frequency Domain		R^2
	τ (frames)	Net Gain K	Gain Margin GM (dB)	Phase Margin PM (deg)	
A-L-AP	2.802±0.02	3.78±0.016	∞	94.362	0.99
D-L-AP	2.43±0.016	3.722±0.01	∞	94.92	0.99
N-L-AP	2.427±0.02	4.470±0.02	∞	94.163	0.99
A-L-ML	4.7±0.05	3.336±0.02	∞	92.808	0.99
D-L-ML	3.35±0.04	3.01±0.02	∞	94.366	0.99
N-L-ML	6.402±.056	2.989±0.01	∞	92.363	0.99
A-U-AP	4.0±1.32	0.115±0.02	-26.3	87.23	0.45
D-U-AP	3.588±1.76	0.025±0.00	-0.811	24.373	0.76
N-U-AP	7.554±0.69	0.087±0.00	-20.5	84.58	0.90
A-U-ML	4.07±0.135	0.015±0.00	-7.25	64.289	0.99
D-U-ML	3.13±1.38	0.004±0.00	15.6	∞	0.99
N-U-ML	3.510±0.04	0.003±0.00	18.1	∞	0.99

TABLE 2(b). The instability threshold for motor input disturbance signals ($'a_{COM}$) modelled as sum of sinusoids functions.

Ramp/ level ground-phase-direction	Frequency Domain		R^2
	Gain Margin GM (dB)	Phase Margin PM (deg)	
A-L-AP	-35.7	13.039	0.63
D-L-AP	-39.0	9.114	0.57
N-L-AP	-36.1	90.322	0.50
A-U-AP	33.435	-44.356	0.056*
D-U-AP	42.6	-23.6184	0.57
N-U-AP	-29.3	-89.560	0.32
A-Vertical	-110.0	89.1475	0.65
D-Vertical	-113	73.837	0.68
N-Vertical	-152	89.915	0.63

*least predictive model for stability analysis.

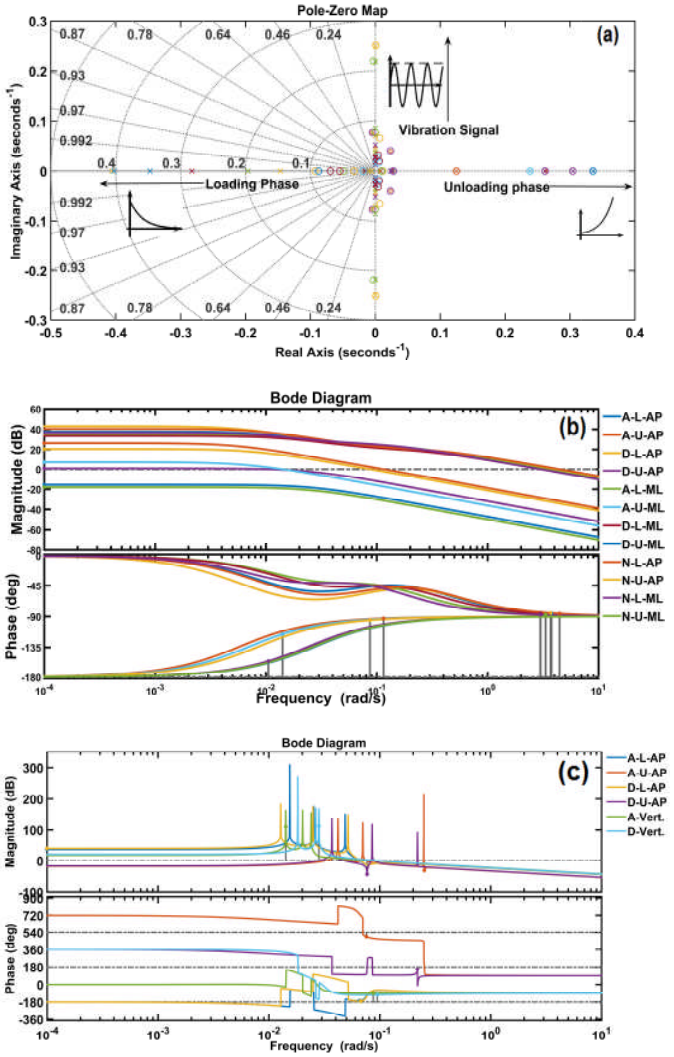


Figure 7 (a) Pole-zero plot in frequency domain, (b) Bode plot for motor output signals in gait loading and unloading phases. (c) Bode plot for motor input disturbance signal in AP-loading/unloading phase and vertical stance phases.

IV. Discussion

The gait dynamics were modelled at transition states considering $'a_{COM}$ and $'COP$ as motor I/O signals. The stability thresholds were modelled and analysed in time and frequency domains for level-ground walk, ramp ascend and ramp descend walk at normal speeds.

*A. 'COP motor **output** response – Time domain*

1). Time constant (τ) and gains (K)

The impulsive nature motor outputs presented the highest time constant at ramp ascend during loading in AP direction i.e. 14.2% more than ramp descend and normal walk which have mutual difference '$\tau < 1\%$'. That is due to ramp resistance, delayed and insufficient push-off provided by the opposite limb during loading. Given the increased range of motion in normal walk, it took more transient time during AP direction unloading i.e. 70±10% higher than ramp ascend or descend which showed the 'τ' value in-range (>90%). The gains of AP loading phase were more significant than unloading phase and found to be 16.5% more in level ground walk as compared to ramp. During unloading, the ramp descend showed less time constants both in AP and ML directions due to inertial effect and lesser shear forces provided by the ground.

2). Stability Index (I)

For better understanding, the stability index (I) was used by correlating all time domain parameters. The loading phase with its overdamped response was observed to be most stable by location of poles on left hand side of s-plane as shown in Fig. 7(a). This suggests that the larger the stability numerator or smaller the denominator (Eq. (2)), the less instable is the system. In ML direction, both the level-ground and ramp (A/D) walk had maximum stability indices (1703±0.6, 247±7.4, 732±0.14); which imply less instability. However, in AP direction the stability index valued maximum for ramp descend i.e. 99±0.03 and normal walk had least threshold i.e. 16.5±0.14. Compared to ramp walk, the ascending was found to be relatively less stable (I = 23±0.01) than descending. During ramp descend, the GRF vector stayed closer to joint centers and reduced the load at joints, muscles energy dissipation response [15], implied more stability than ramp ascend. These thresholds described the reference for motor controlled outputs to adopt gait transitions and analysed further in frequency domain.

*B. 'COP motor **output** response – Frequency domain*

The Laplace transform was implemented over $'COP$ models and characteristics equations were obtained. The pole-zero's location showed that the loading and unloading were stable and unstable transient phases respectively for all three walking conditions. The unloading was stayed unstable stance phase where COP was behind the COM vertical projection [12]. The Bode plot showed the stability margins for ramp ascend, descend and level ground walk (see Fig. 7b). Both in AP and ML directions, the loading signals were proved to be stable with positive phase margins 94±1° and infinite gain margins.

There was no significant variation observed between level ground and ramp walk in loading w.r.t phase margin (PM) and gain margin (GM). However, during AP unloading phase, the ramp ascend was found to be the most unstable with GM (-26.3dB) and ramp descend was least instable with GM (-0.8dB) among all three walking conditions. Similarly, in ML unloading, the ramp ascending was marginally more unstable (-7.25, 64.23°) than descending and level walk. The frequency domain also showed the ramp ascending as less stable than ramp descending walk, in-consistent with time-domain analysis.

*C. ´a_{COM} motor **input** response – Frequency domain*

The undamped input vibration models were least predictive w.r.t coefficient of determinant (R^2). Applying the control theory, *´a_{COM}* stands for maximum input disturbance to which motor compensates for gaining stability. Here, the maximum disturbances and motor response were modelled and analysed. The input disturbance signal Bode plot in Fig. 7(c) showed that the ramp descending was marginally more unstable (GM = -39dB) in AP loading phase. However, during AP unloading, the level-ground walk was found to have a maximum disturbance with PM and GM (-89.5°, -29.3dB). Considering sagittal plane as the most significant, the maximum input instabilities were observed in level ground walk (GM = -152dB) than ramp walk. A study revealed the over-produced muscular energy dissipation during level ground walk [15]. During ramp ascend/descend, the input disturbances were found in close range in sagittal plane.

The current research was extended to the analysis of the gait dynamic stability in frequency domain. The study was performed for level ground and ramp walk. The input disturbance to the motor and output controlled responses were modelled at gait transients. For future work, the exact correlation between *´a_{COM}* and the *´COP* (I/O) signals and estimation of the motor controller will be investigated. This research work is part of wearable soft robotics design project and findings would be applied to characterize user needs, smart actuators design, gait impedance evaluation and control.

V. CONCLUSION AND FUTURE WORK

The aim of the current study was to investigate gait dynamic stability with varying terrain, which provides a tool for clinical assessment for orthotics. In frequency domain, the loading phase showed the most stable results for both level-ground and ramp walk. During unloading, the output '*´COP*' signal was found to be most unstable for ramp ascend both in AP and ML directions, However, the gains in ML direction were negligible. The input motor disturbances *´a_{COM}* were also found more unstable for ramp ascend than ramp descend. The motor responded continuously to both instabilities i.e. *´a_{COM}* during loading and *´COP* during unloading in lead/lag control mode. The *´COP* input signal in loading showed to be the most compensated signal generated by the motor during gait transitions. The outcome of this research work can be used for the design and evaluation of bipedal assistive or rehabilitative robotics. For future work, the research will include the estimation of motor behavioral control to adopt different terrain condition using modelled I/O signals. Furthermore, the scope of dynamic stability analysis will be extended to include subjects with gait impairments to incorporate patient's clinical needs for the design of wearable soft orthotics.

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REFERENCES

[1] S. Fuchioka, A. Iwata, Y. Higuchi, M. Miyake, S. Kanda, and T. Nishiyama, "The Forward Velocity of the Center of Pressure in the Midfoot is a Major Predictor of Gait Speed in Older Adults," Int. J. Gerontol., vol. 9, no. 2, pp. 119–122, 2015.

[2] A. DiDomenico, R. W. McGorry, and J. J. Banks, "Methodological considerations of existing techniques for determining stabilization times following a multi-planar transition.," Gait Posture, vol. 38, no. 3, pp. 541–3, 2013.

[3] J. Becker, E. Pisciotta, S. James, L. R. Osternig, and L.-S. Chou, "Center of pressure trajectory differences between shod and barefoot running," Gait Posture, vol. 40, no. 4, pp. 504–509, 2014.

[4] D. Cattaneo, M. Rabuffetti, G. Bovi, E. Mevio, J. Jonsdottir, and M. Ferrarin, "Assessment of postural stabilization in three task oriented movements in people with multiple sclerosis," Disabil Rehabil, vol. 36, no. 26, pp. 2237–2243, 2014.

[5] M. Rabuffetti, G. Bovi, P. L. Quadri, D. Cattaneo, F. Benvenuti, and M. Ferrarin, "An experimental paradigm to assess postural stabilization: No more movement and not yet posture," IEEE Trans. Neural Syst. Rehabil. Eng., vol. 19, no. 4, pp. 420–426, 2011.

[6] B. Heinemann, L. House, J. Hill, and O. Ox, "British Library Cataloguing in Publication Data," Society, vol. 3, no. 3, p. 2007, 2005.

[7] D. Winter, "Human balance and posture control during standing and walking," Gait Posture, vol. 3, no. 4, pp. 193–214, 1995.

[8] V. Lugade and K. Kaufman, "Center of pressure trajectory during gait: a comparison of four-foot positions.," Gait Posture, vol. 40, no. 4, pp. 719–22, 2014.

[9] Delignières, D., Torre, K. and Bernard, P. L. "Interest of velocity variability and maximal velocity for characterizing center-of-pressure fluctuations." Science & Motricité(74): 31-37, 2011.

[10] T. Lencioni, M. Rabuffetti, G. Piscosquito, D. Pareyson, a. Aiello, E. Di Sipio, L. Padua, F. Stra, and M. Ferrarin, "Postural stabilization and balance assessment in Charcot-Marie-Tooth 1A subjects," Gait Posture, vol. 40, no. 4, pp. 481–486, 2014.

[11] Z. Mei, G. Zhao, K. Ivanov, Y. Guo, Q. Zhu, Y. Zhou, and L. Wang, "Sample entropy characteristics of movement for four foot types based on plantar centre of pressure during stance phase.," Biomed. Eng. Online, vol. 12, no. 1, p. 101, 2013.

[12] Huei-Ming Chai, (2003). "Stance and Stability," http://www.cq.com.pl/publikacje/cqstabosc_art4.pdf.

[13] ImageJ (2016). "image processing and analysis in Java." from http://imagej.nih.gov/ij/.

[14] G. D. Myer, S. C. Wordeman, D. Sugimoto, N. a Bates, B. D. Roewer, J. M. Medina McKeon, C. a DiCesare, S. L. Di Stasi, K. D. Barber Foss, S. M. Thomas, and T. E. Hewett, "Consistency of clinical biomechanical measures between three different institutions: implications for multi-center biomechanical and epidemiological research.," Int. J. Sports Phys. Ther., vol. 9, no. 3, pp. 289–301, 2014.

[15] P. DeVita, J. Helseth,"Muscles do more positive than negative work in human Locomotion,"J. Exp Biol., vol. 210, no.19, pp. 3361–3373, 2008.