Power spectrum analysis of contact forces and force moments during normal and modified gait

Carlos Rodrigues[1], Miguel Correia[2] João Abrantes[3], Jurandir Nadal[4] and Marco Benedetti[5]

[1] *Centre for Biomedical Engineering Research, INESC TEC, cmbr@inesctec.pt*
[2] *Department of Electrical and Computer Engineering, FEUP, mcorreia@fe.up.pt*
[3] *MovLab - Laboratório de Tecnologias e Interfaces, ULHT, joao.mcs.abrantes@ulusofona.pt*
[4] *PEB - Programa de Engenharia Biomédica, COPPE/UFRJ, jn@peb.ufrj.br*
[5] *PPGEE - Programa de Pós-Graduação em Engenharia Elétrica, benedetti@ufpe.br*

Introduction: According to difficulty on direct measurement of internal joint forces and force moments under natural gait, multibody system dynamics (MBD) presents as a valuable tool for modelling and simulation estimating internal joint actions for registered movement, with the need of assessment of these joint actions [1]. Classical analysis of human gait has typically been performed on time domain using discrete measures of local or global extreme, maximum and minimum values and their corresponding time instants of occurrence. Discrete time analysis can be useful when there are clear differences between selected parameters but it does not take into account continuum pattern of the signals, with possible test conditions or subjects presenting similar discrete values but different continuum patterns [2]. On intra-subject variability assessment at different gait modes namely stiff knee gait (SKG) and slow running (SR) in relation to normal gait (NG) variation of internal estimated actions are frequently subtle with the need to consider continuum pattern variation of the signals. The purpose of this study is thus to assess power spectrum of subject specific joint contact estimated forces and force moments in relation with ground reaction forces, during SKG and SR for comparing its variation with NG at frequency domain.

Methods: Due to the interest on subject specific analysis and difficulty on average sample to represent specific subject, attention was focused on case study of an adult healthy male subject 70 kg mass and 1.86 m height during NG, SKG and SR trial at motion capture laboratory. During trial tests ground reaction forces were acquired with two AMTI force plates sampling at 2000 Hz and cartesian coordinates of adhesive reflective markers at right/left anterior/posterior superior iliac spines, thigh superior, knee medial/lateral, shank superior, ankle medial/lateral and toes were acquired during gait trials with 8 camera Qualisys system at 100 Hz. Stick-figure model was generated based on static trial and over-determinate kinematic analysis was performed over dynamic trial obtaining hip, knee and ankle joint angles, morphing Twente Lower Extremity Model (TLEM) to match the size and joint morphology of the stick-figure model for inverse dynamic analysis based on joint angles and kinetic boundary conditions. Vertical ground reaction forces (*GRFz*) as well as hip, knee and ankle joint vertical forces (*JFz*) and flexion-extension force moments (*Mfe*) were decomposed on Fourier domain with frequency of the maximum FFT coefficient amplitude assessed along with frequency of the 90th percentile of FFT relative accumulated frequency. The frequencies of the fundamental harmonics for the FFT decomposition of *GRFz*, 1.7 Hz at NG, 1.5 Hz at SKG and 3.6 Hz at SR were defined according to the time period of the right foot contact with the ground and the frequencies of the fundamental harmonics for the FFT decomposition of *JFz* and *MFe*, 0.75 Hz at NG, 0.67 Hz at SKG and 1.03 Hz at SR were defined according to the time period of the vertical joint reaction forces and the flexion-extension joint force moments for each of the considered tests.

Results: Higher amplitude coefficients from FFT *GRFz* decomposition were found, apart from *dc* constant component, at 3.4 Hz for NG, 3.0 Hz and 4.5 Hz for SKG and 3.6 Hz for SR. 90th percentile contribution of the frequencies to the overall power spectrum component were registered at lower frequency 3.6 Hz for SR and higher frequencies 66.2 Hz for NG and 63.4 Hz for SKG. The amplitude of the maximum FFT coefficient from *GRFz* decomposition was higher at SR than NG and higher at NG than SKG.

Separately the right (r) and left (l) sides present lower frequency of maximum FFT joint vertical forces JFz for the hip (H), knee (K) and ankle (A) than conjunct FFT decomposition of JFz at both sides with exception of JFz_A presenting at NG similar values of lower frequency FFT decomposition separately and conjunctly, Tab. 1.

f_{max}(Hz)	JFz_{Hr}	JFz_{Hl}	JFz_H	JFz_{Kr}	JFz_{Kl}	JFz_K	JFz_{Ar}	JFz_{Al}	JFz_A
NG	0.75	0.75	2.24	0.75	0.75	2.24	0.75	0.75	0.75
SKG	0.66	0.66	1.99	0.66	0.66	1.99	0.66	0.66	1.33
SR	1.02	1.02	2.04	1.02	1.02	2.04	1.02	1.02	2.04

Tab. 1: Frequency of the maximum amplitude from FFT decomposition of JFz at the right (r), left (l) and both sides of H, K and A

90% convergence of the FFT amplitude from joint vertical forces JFz decomposition, Tab. 2, occurred at low frequencies on NG and SR than SKG for the hip and the knee with the exception of JFz_{Hl} and at SKG for the ankle with the exception of JFz_{Ar}.

f_{p90}(Hz)	JFz_{Hr}	JFz_{Hl}	JFz_H	JFz_{Kr}	JFz_{Kl}	JFz_K	JFz_{Ar}	JFz_{Al}	JFz_A
NG	7.47	7.47	7.47	5.98	5.98	5.98	5.23	5.98	5.23
SKG	13.27	11.94	11.94	6.64	6.64	7.30	5.31	4.64	5.31
SR	7.14	12.24	11.22	5.10	5.10	5.10	5.10	4.08	5.10

Tab. 2: Frequency of the 90th percentile relative accumulated frequencies Σ|FFT| amplitude from FFT decomposition of JFz

NG presented for the hip, knee and ankle lower frequency of the maximum amplitude values of Mfe FFT than SR, Tab. 3. SKG presented higher frequency of the maximum amplitude values of Mfe_K FFT and lower values for Mfe_H and Mfe_A in relation to NG and SR. 90% convergence of the FFT amplitude from Mfe decomposition, Tab. 3, occurred at similar lower frequencies on NG, SKG and SR for Mfe_A with higher values at the knee for SKG and the hip for SKG and SR.

f_{max}(Hz)	Mfe_H	Mfe_K	Mfe_A
NG	0.75	0.75	0.75
SKG	0.67	3.33	0.67
SR	1.03	1.03	1.03

f_{p90}(Hz)	Mfe_H	Mfe_K	Mfe_A
NG	17.28	10.52	5.26
SKG	85.24	88.57	5.99
SR	103.23	10.32	5.16

Tab. 3: Frequency of the maximum amplitude from FFT and the 90th percentile relative accumulated frequencies Σ|FFT| amplitude from FFT decomposition of Mfe at the hip (A), knee (K) and ankle (A)

Discussion and conclusion: Larger number of harmonics with considerable amplitude and the slower convergence of $GRFz$ Fourier series for NG and SKG compared to SR can be associated to different curve shapes with two relative maximum at NG, SKG and only one relative maximum at SR, with higher frequency at NG and SKG due to oscillation of $GRFz$ at the beginning of the stance phase. Similar frequencies of individual right/left joint maximum |FFT| JFz, lower than correspondent frequencies of conjunct actions point for similar power spectrum at individual right/left joint and differences to conjunct action. Higher frequencies of the 90th percentile of JFz FFT decomposition at the hip and knee on SKG than NG and SR point for the ability of power spectrum to detect subtle differences on joint actions at different gait. Lower frequency of maximum Mfe FFT at NG than SR for the hip, knee and ankle and higher frequency at SKG for the knee, point for the ability of Mfe FFT to discriminate joint Mfe among gait modes and joints, with 90th percentile higher frequency of Mfe FFT at the hip on SKG and SR as well at the knee on SKG pointing for clear differences on Mfe power spectrum. According to detected differences on power spectrum of contact forces and force moments that could be undetected on time domain, frequency analysis presents as a quantitative metric for continuum pattern assessment of subject specific internal and external lower limb contact actions at normal and modified gaits.

References

[1] A. Erdemir, S. McLean, W. Herzog and A.J. van den Bogert, “Model-based estimation of muscle forces exerted during movements” *Clinical Biomechanics*, vol. 22, pp. 131–154, 2007.

[2] N. Stergiou, *Innovative Analyses of Human Movement*. Champaign, IL: Human Kinetics, 2004.F