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SOFTWARE TOOL FOR SIGNIFICANT ANALYSIS OF COMPLEMENTARY DOMAINS ON HUMAN GAIT

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Abstract: *Over time many important contributions have been made at the methodological and technological level to the study of human movement with possible impact and applications at ergonomics, diagnosis of neuro-musculoskeletal diseases, treatment, rehabilitation and improvement of human movement performance. State of the art on human movement study increasingly points to the need of subject specific models and extraction of significant information for the intended objective. Recent developments on imageology and modeling have greatly contributed to detection of human kinematic patterns with the underlying causes of registered movement and translational research an open issue. Proposed tool presents as an upper layer software application taking subject specific entire series of internal and external kinematic, kinetic and electromyographic data from human movement acquisition software and musculoskeletal modeling and simulation tools, extracting and exhibiting in a user friendly graphic environment hidden features and relations of biomechanical signal at complementary time, frequency and phase domains. Developed software application is presented using modified and normal gait case study of subject specific model, grouping head, arms and trunk as the passenger of the locomotion system composed by the lower limbs interconnected through the pelvis. Presented features* *include 2D and 3D visualization, continuous and step by step animation of lower limb stick-figures according to joint cartesian coordinates, ground reaction and resultant force vectors during feet contact, hip, knee and ankle joint sagittal angular displacement, angular velocity and acceleration, flexion / extension joint force moments presentation with dynamic time line during normal gait, stiff knee and slow running tests. Time series analysis include boxplot, histogram, time profile, descriptive local and dispersion measurements of signals during selected time period, linear and cross-correlation, maximum correlation, time delay and animation, Fourier transform analysis, phase and amplitude, signal reconstruction and root mean square deviation, cross-spectral analysis, phase plane analysis, Rayleigh test, histogram and rose diagram, selected muscle action representation and analysis with magnitude, phase and combined measures. Presented tool aims to contribute for increase of translational research of human movement analysis into clinical gait diagnosis and rehabilitation, overcoming big data management complexity and unveiling hidden data relations on time, frequency and phase domains.*

1 INTRODUCTION

Software tools for human movement study can be classified on three distinct dimensions. The first dimension corresponds to the modeling and simulation tools where we can find mainly two different approaches usually designated by the inverse and the forward approach, along with the possibility of iterative combination for the inverse-forward approach [1]. Basically, the inverse approach takes input information from contact forces and force moments such as the force platforms from ground contact, and kinematics of marks or markless anatomical points and estimates joint internal loads according to general or specific subject modeling, with the possibility of muscle or muscle group forces estimation based on optimization criteria or muscle grouping, solving indeterminacy of our muscle system redundancy and comparing with direct measures of muscle or muscle groups activity from electromyography. The second approach, forward dynamic, takes information on activation and stimulation of muscles and muscle groups, along to general or specific subject model, integrating activation for estimation of muscle actions, joint muscle actions, and joint actions along with mass, dimension and inertia of body segments to estimate whole body movement at specific conditions, comparing it with registered kinematics. The inverse and forward approaches can be combined at an iterative process of inverse kinematics and dynamics estimating joint and muscle actions comparing it for adjustment with EMG and proceeding with forward dynamic and kinematic determining body segment movement for comparison with direct body segment kinematic measurements, adjusting the forward process and iterating inverse and forward processes until error from estimated direct and inverse measurement are considered as acceptable or iteration limit is achieved. The second dimension corresponds to the software tools provided with the required equipment for acquisition of data from human movement necessary for analysis, modeling and simulation [2]. These equipment's are generally grouped on four main categories corresponding to (*i*) kinetics of forces, force pressures and force moments acquisition from contact namely with the ground, (*ii*) kinematics of body segments either inertial, magnetic or image, visible or infra-red, (*iii*) electrical for myographic or cerebral acquisition and processing of signal control responsible for human movement, and (*iv*) internal images from ultra-sound, nuclear magnetic resonance and computed axial tomography scanning for subject specific modeling, PET, SPEC and molecular imaging, namely fluoroscopy. These equipment's are usually supplied with software tools ensuring data acquisition and some level of data processing, typically filtering, amplitude and dispersion calculation with main focus on discrete measures. The third dimension corresponds to the commercial or author nature of the software namely on what concerns with modeling and simulation tools [3], with main advantage on commercial and open source tools on existence of developed libraries and comparison of attained results with tool community and advantage on author tools on control of the entire development process with major drawback at the need for developing from scratch entire tool, from analysis to implementation and test, to which it adds the difficulty of absence of a community to compare attained results or the need to share author developed tool. Under this scenario of the available software tools and the interrelated, time dependent and highly correlated nature of data for human gait study there is a strong need for development of software tools considering entire signal series provided by human movement data acquisition systems and modeling and simulation systems enabling complementary analysis and domains assessment, extracting hidden and main features explaining observed behavior and pointing for correction of subject specific diagnosed gait problem

2 MATERIAL AND METHODS

Presented software tool has been developed under the author classification as an upper layer application for internal and external kinematic, kinetic and electromyographic data analysis from human movement acquisition software and musculoskeletal modeling and simulation tools, extracting and exhibiting in a user friendly graphic environment hidden features and relations of biomechanical signal at complementary time, frequency and phase domains. Software application is presented using modified and normal gait case study of subject specific model, grouping head, arms and trunk (HAT) as the passenger of the locomotion system composed by the lower limbs interconnected through the pelvis. Attention was focused on case study of one adult healthy male subject 70 kg mass and 1.86 m height during normal gait (NG), stiff knee gait (SKG) and slow running (SR) at motion capture laboratory. Experiment was performed in accordance with ethical guidelines of the North Denmark Region Committee on Health Research Ethics (N-20130014) and the participant provided full written informed consent prior to experiment. Adhesive reflective markers were plugged in to subject palpable skin surface including right and left anterior and posterior superior iliac spines, thigh superior, knee medial and lateral, shank superior, ankle medial, lateral and toes following Plug-in-Gait Marker Placement Protocol. 3D cartesian coordinates of reflective markers were obtained from direct linear transform (DLT) of captured images with eight camera Qualisys system at 100 Hz during NG, SKG and SR. Simultaneous acquisition of ground reaction forces and force moments during ground feet contact on NG, SKG and SR were acquired with two AMTI force platforms sampling at 2000 Hz and surface electromyography (sEMG) of lower limb selected muscles, soleus medialis (SM) and tibialis anterior (TA) of the subject's right leg were acquired with Noraxon wireless system at 2000 Hz. Musculoskeletal analysis was performed using AnyGait v.0.92 set up for the experimental setup, starting with generation of stick-figure model based on a static trial, over-determinate kinematic analysis over the dynamic trial and joint angles, morphing Twente Lower Extremity Model (TLEM) to match the size and joint morphology of the stick-figure model followed by inverse dynamic analysis based on joint angles and kinetic boundary conditions. AnyGait was set up to produce output using polynomial muscle recruitment criterion of power 3 and recorded sEMG was band-pass filtered at 10 Hz and 400 Hz, rectified and low-pass filtered at 6 Hz and normalized to dynamic maximum voluntary contraction (MVC) with counter movement jump for SM and leg swing for TA.

3 PRESENTATION OF GAIT SOFTWARE TOOL

According to the interest on coordination analysis of the pelvis and lower limb joints on modified gait presented modeling tool is based on stick-figure representation of lower limb segments and pelvis. Considerable movement of the pelvis on transversal plane during gait in addition to lower limb dominant flexion-extension movement at sagittal plane, point for the importance of visualization and analysis of lower limb and pelvis movement on 3D in complement of the 2D visualization of the movement at the sagittal plane, with the possibility of stick figure rotation choosing intended perspective for desired analysis, Figure 1.

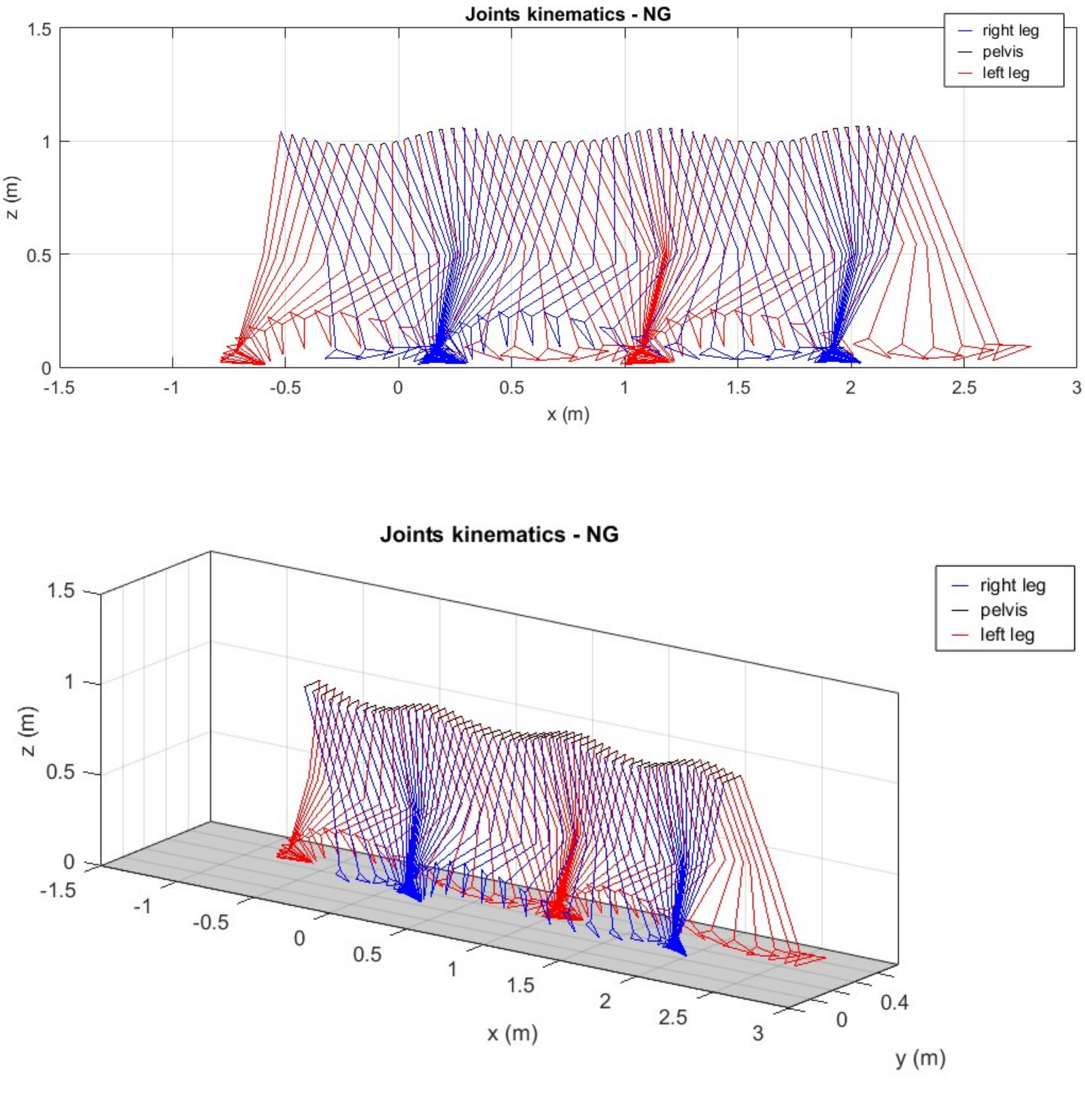


Figure 1: Sagittal 2D and 3D perspectives of lower limb stick figure stroboscopic NG representation.

3.1 Gait Analysis

Continuous and step by step animation of lower limb stick-figures are made available according to joint cartesian coordinates, along with ground reaction and resultant force vectors during feet contact, hip, knee and ankle joint sagittal angular displacement, angular velocity and acceleration, flexion / extension joint force moments presented with dynamic time line during normal gait, stiff knee and slow running tests. Presented module, Figure 2, allows the selection of the gait mode, namely NG, SKG and SR as well as the presentation of the joint angular displacements, velocities and accelerations, synchronizing time line with stick figure, both controlled by time scroll bar and presentation of the curve values at time line. The synchronization of stick figure with angular kinematic, ground reaction forces and force moments assumes particular importance on detection by inspection of these quantities' values contributing for association of gait modification with changes at stick figures and time signal profiles.

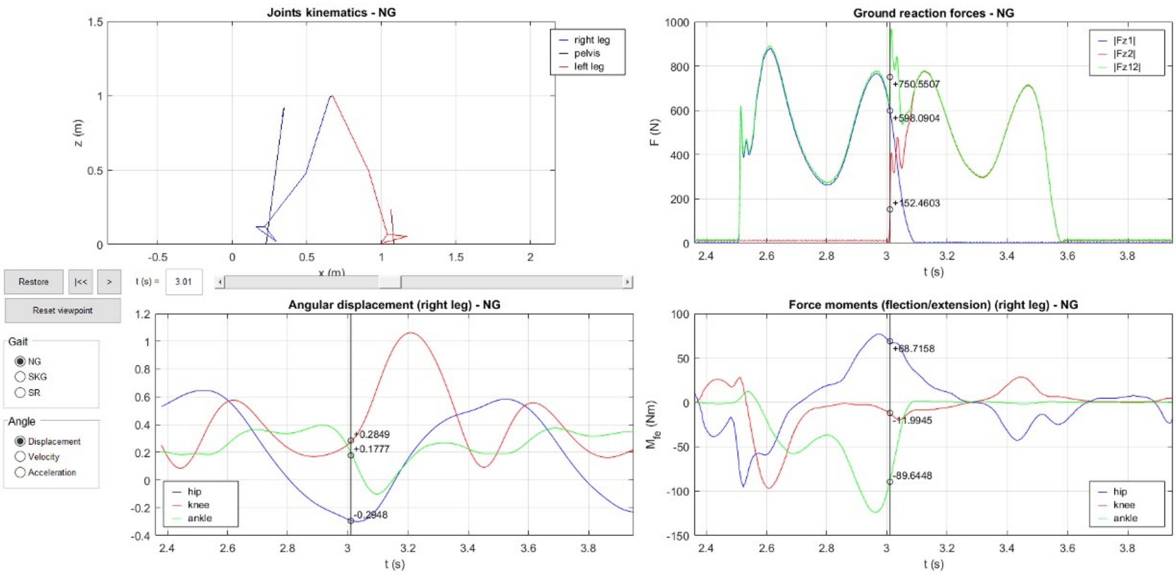


Figure 2: Gait analysis with stick-figure joint kinematics, angular displacement, ground reaction forces and force moments at NG.

3.2 Time series analysis

According to interconnection of human body segments the modification of the movement at one joint such as stiff knee can affect the movement at the other joints, namely of the hip and ankle at the same limb. For this reason, joint movement was compared on entire time period of one complete stride at normal gait, stiff knee and slow running in order to detect differences at location of dispersion measurements. For this purpose, a module entitle time series analysis was developed, enabling selection of interest time period at available signal, namely, ground contact forces and force moments, joint angular displacement, velocity and acceleration, internal joint forces and force moments, presenting time signal profile, box plot diagrams and histograms as well several statistical measurement such as the mean, median, standard deviation, minimum, maximum, first and third quartile and interquartile amplitude assessment of selected signal and time period, Figure 3.

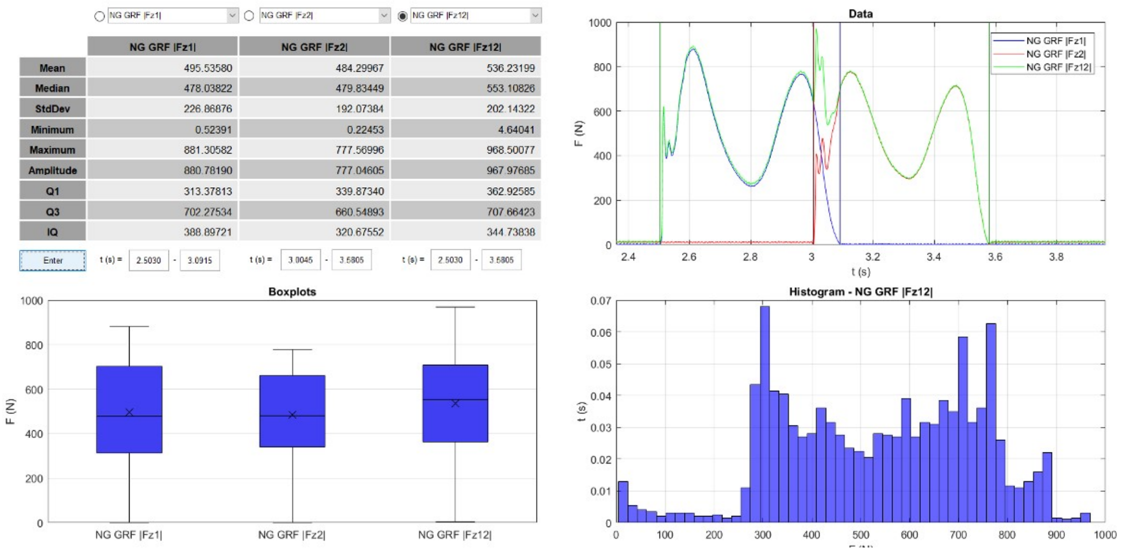


Figure 3: Time series analysis with signal presentation at selected interest time period, box plots, histograms, location and dispersion measurements of the signal at selected time period.

3.3 Fourier transform analysis

Developed Fourier transform analysis module allows the selection of the signal and time period analysis for decomposition at Fourier domain with multiple frequencies of the fundamental harmonic, presenting the amplitude and phase of each component, as well as the convergence of the Fourier series, the root mean square deviation (RMSD) of the series in relation to the original signal, allowing real time reconstruction of the original signal and presenting the frequency of maximum FFT coefficient amplitude and 90th percentile of the Fourier series, Figure 4.

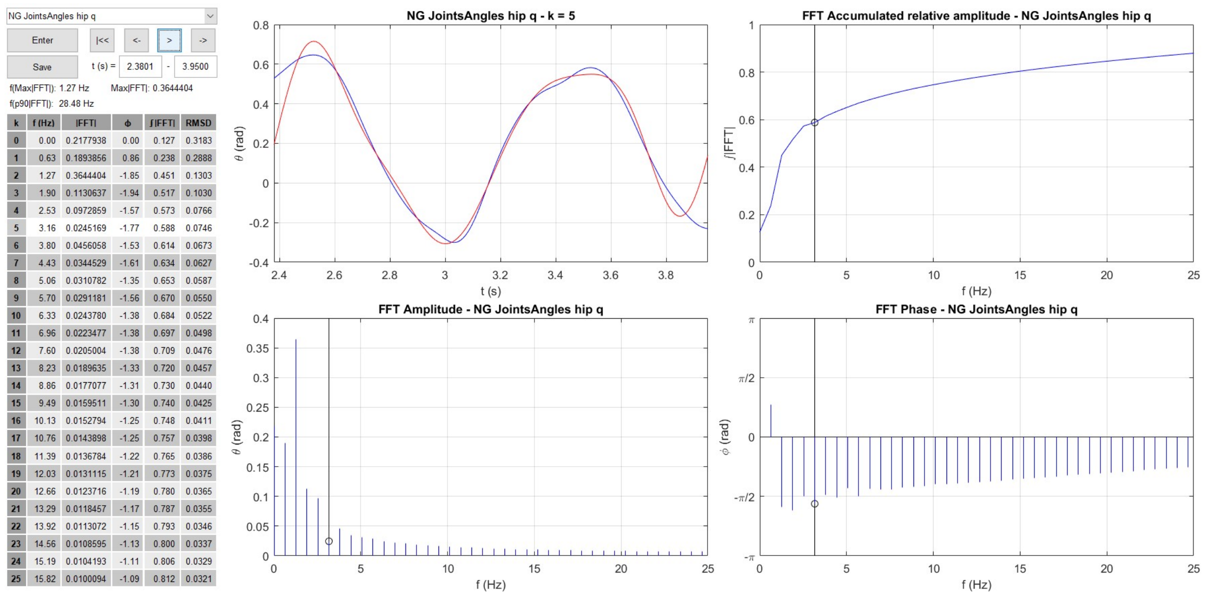


Figure 4: Fourier transform analysis with signal presentation at selected interest time period, amplitudes and phases at each harmonic frequency, convergence of the Fourier series and RMSD.

3.4 Linear and cross-correlation

Linear and cross-correlation was implemented for detection of synchronized correlation, maximum correlation and time delay of maximum correlation, with selection of the time period to correlate. Linear correlation module, Figure 5, allows the selection of signals to correlate and the selection of time period to correlate presenting calculated coefficient of determination (R^2) and Pearson correlation coefficient (R).

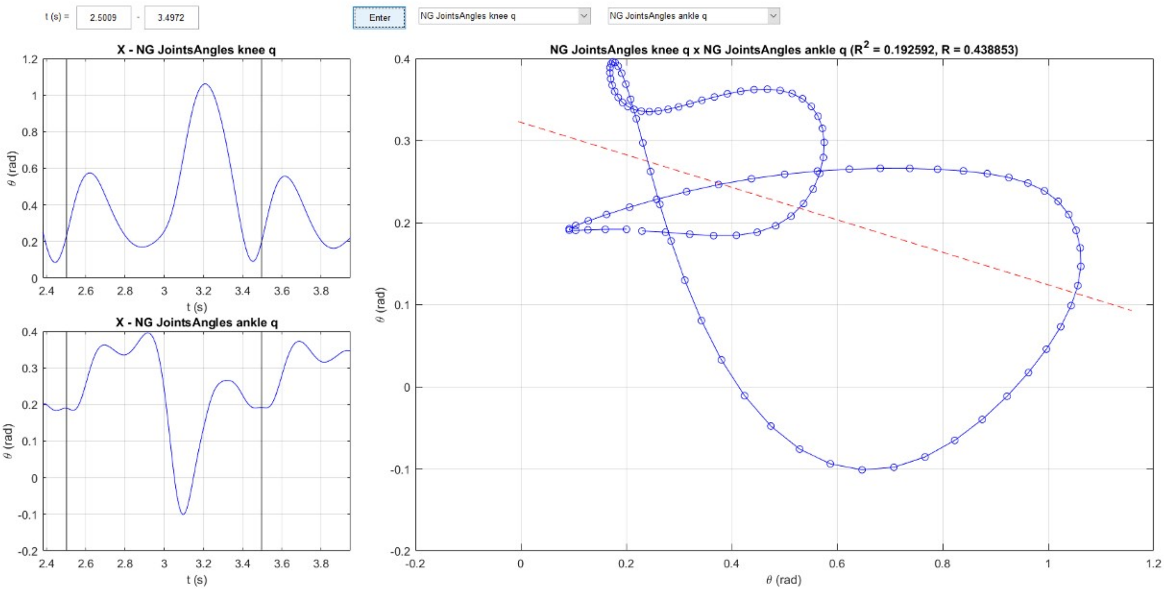


Figure 5: Linear correlation of NG hip and knee joint angles selected time period.

Cross-correlation module, Figure 6, allows the selection of signals to correlate, selection of time period to correlate, continuous and step by step cross-correlate presenting normalized signal cross-correlation, normalized cross-correlated signal, maximum normalized cross-correlation, time delay, calculated coefficient of determination (R^2) and Pearson correlation coefficient (R).

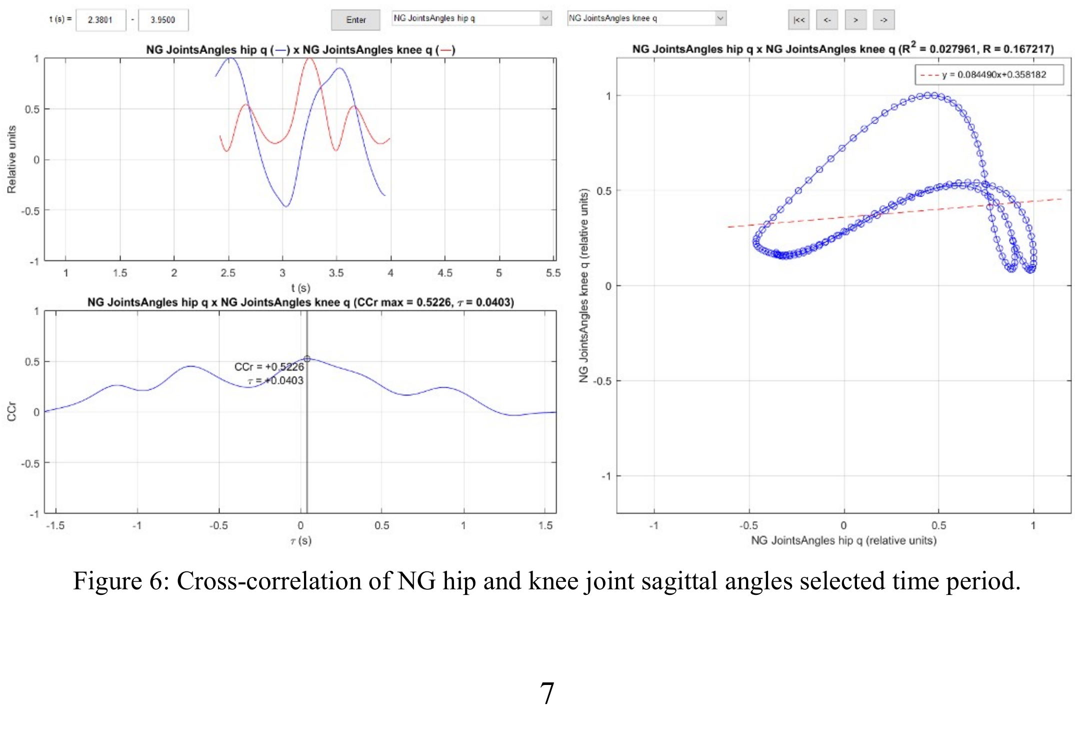


Figure 6: Cross-correlation of NG hip and knee joint sagittal angles selected time period.

3.5 Vector coding

Angle-angle diagram module was implemented along with coupling angle (γ) of the vector formed by consecutive points at the angle-angle diagram with positive direction of horizontal axis and directional concentration (ρ) obtained from the magnitude of the vector, with coefficient of correspondence (r) obtained from γ and ρ to assess lower limb joint angular coordination, Figure 7.

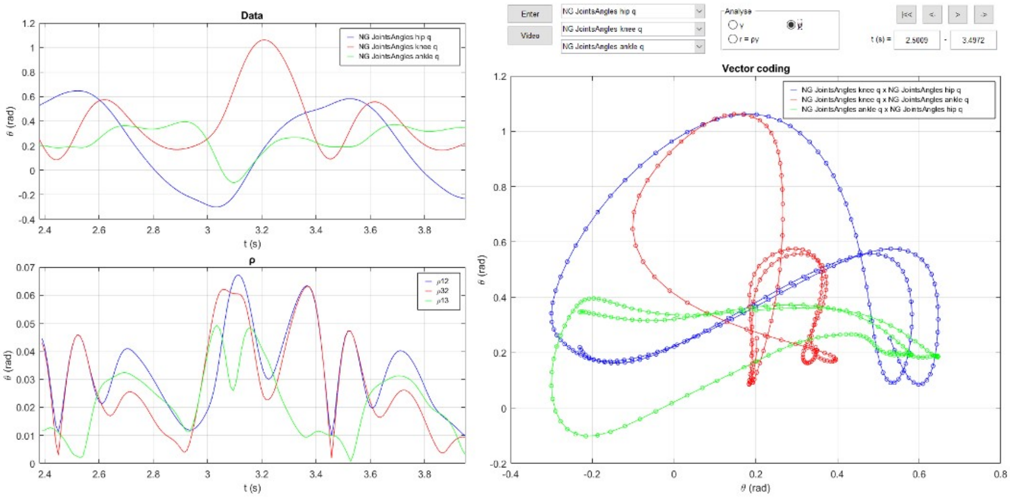


Figure 7: Spherical analysis of the pelvis transverse, coronal and sagittal angles on NG stride period.

3.6 Spherical analysis

Spherical analysis enables the selection of the signals for 3D spherical analysis, the time period of the signals to analyze, selection of the signals for analysis, visibility of 2D planes projection and 3D space signal relation, continuous and step by step representation of plane and space signal variation, azimuth and inclination angles, radial distance and spherical radial unit with time line and signal values presentation. Presented example application, Figure 8, represents 3D cartesian and spherical relation of pelvis transverse, coronal and sagittal angles during NG stride as well as the azimuth, inclination and radial distance variation of the T,C,S measures along with time instants and measure values.

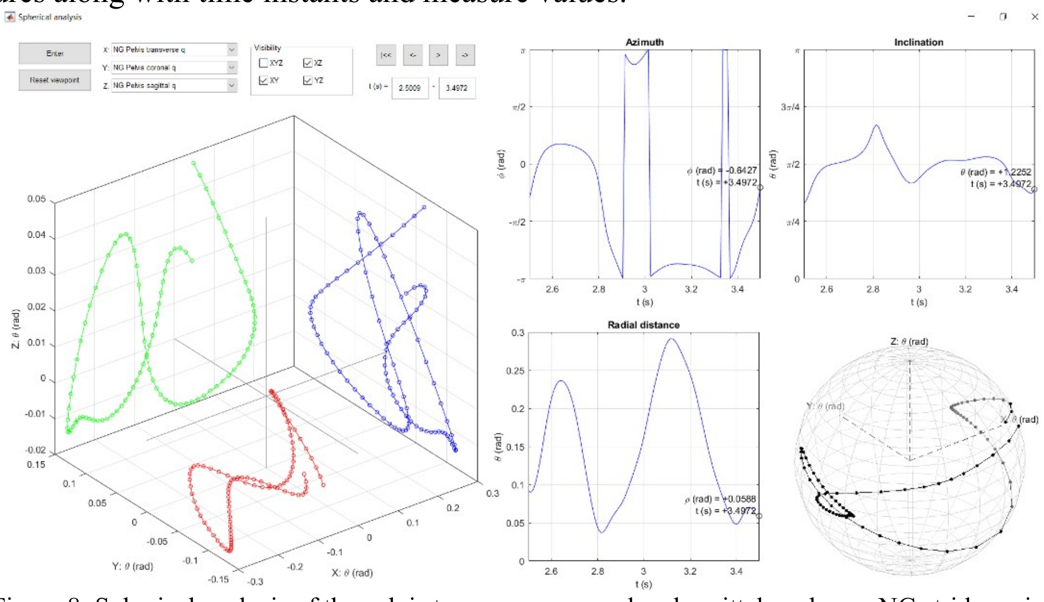


Figure 8: Spherical analysis of the pelvis transverse, coronal and sagittal angles on NG stride period.

3.7 Phase plane analysis

Phase plane analysis module, Figure 9, enables the selection of the signals for phase plane analysis, the time period of the signals to analyze, selection of the signals normalization and histogram or Rose phase representation, continuous and step by step representation of phase portrait, pointing vector, signal and phase values with dynamic time line, dynamic histogram or rose phase dynamic representation, continuous phase standard deviation (CPsd) calculus and Rayleigh test of uniformity with null hypothesis of zero phase concentration.

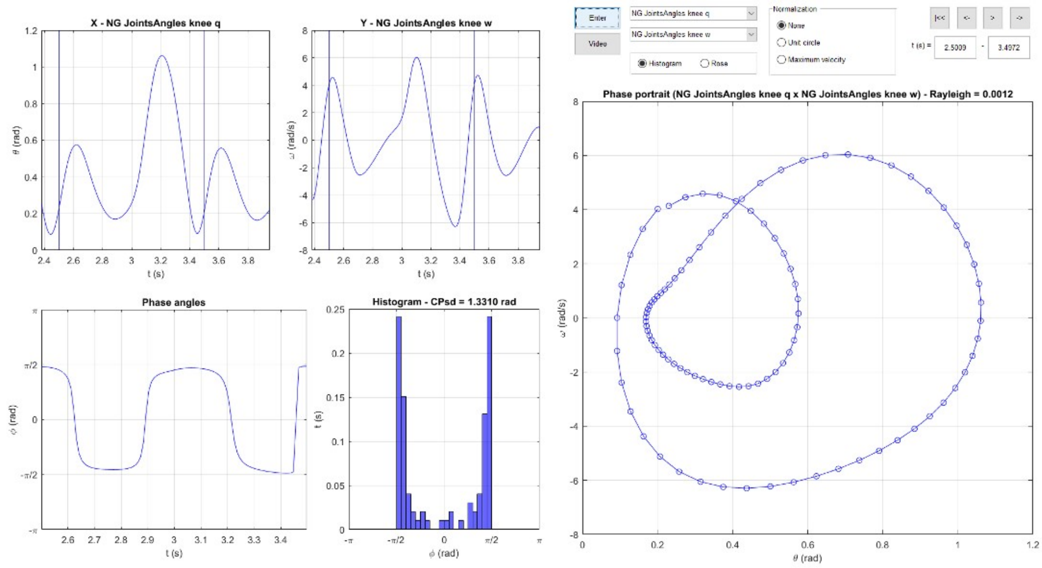


Figure 9: Phase plane analysis of knee joint sagittal angle on NG stride period.

3.8 Directional analysis

Due to circular nature of phase plane directional analysis was performed at polar plane with graphical assessment of uniformity using Rose diagram and Percentile-Percentile plot along with the mean resultant vector (r_{mean}), mean direction (ϕ_{mean}), sample circular standard deviation (s), concentration parameter (κ) and the Watson's U^2 goodness of fit test to the von Mises distribution of selected signal, gait mode and stride period, Figure 10.

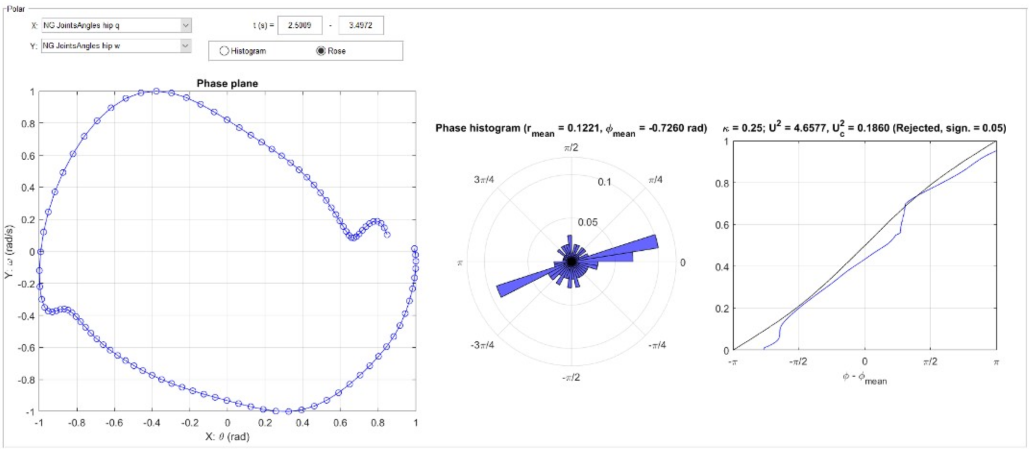


Figure 10: Phase plane with polar directional analysis of hip joint sagittal angle on NG stride period.

3.9 Phase space analysis

Phase plane analysis module, Figure 11, enables the selection of the signals, namely angular, displacements, velocities and accelerations for phase space analysis, the time period of the signals to analyze, continuous and step by step representation of phase space, azimuth and pitch phase angles, radial distance and angular phase spherical representation for synchronized detection of events, with the possibility of saving and exporting these measures for further analysis.

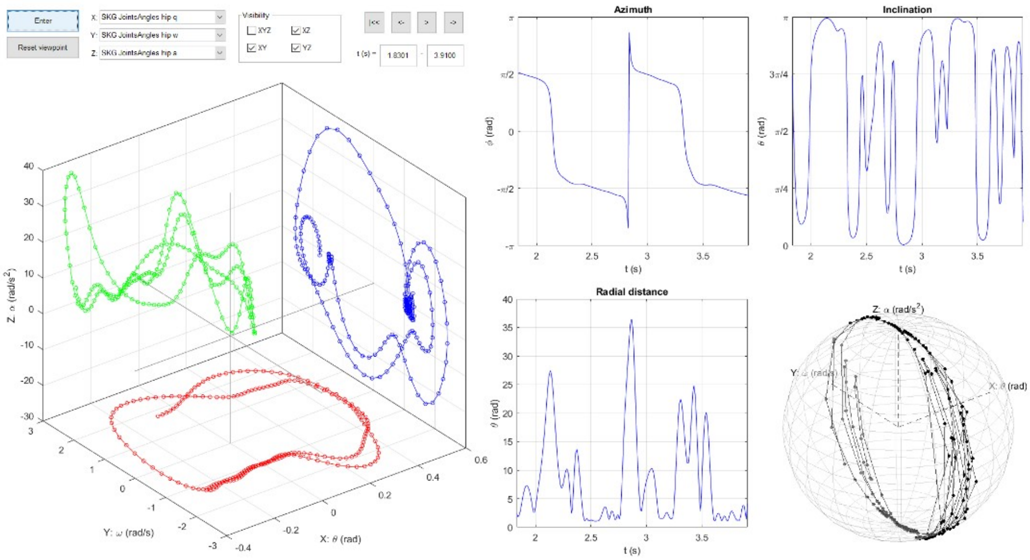


Figure 11: Phase space analysis of hip joint sagittal angle on SKG stride period.

3.10 Cross-spectral analysis

Cross-spectral analysis module, Figure 12, enables the selection of the signals and the time period for parametric and nonparametric spectral analysis, plotting Welch periodogram cross power spectral density (CPSD) estimates between selected signals, with the possibility of saving, exporting and extraction of relevant signals correlation features at the frequency domain.

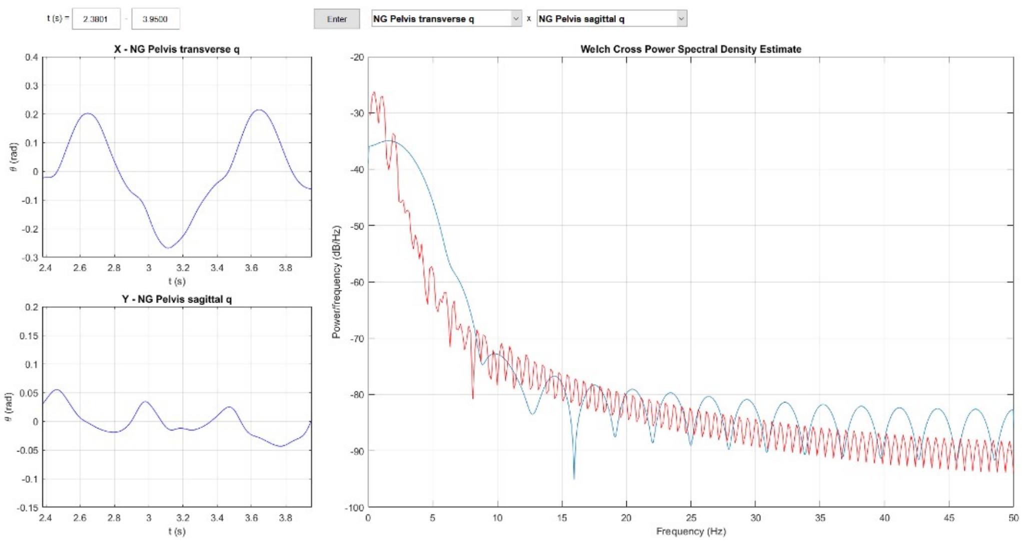
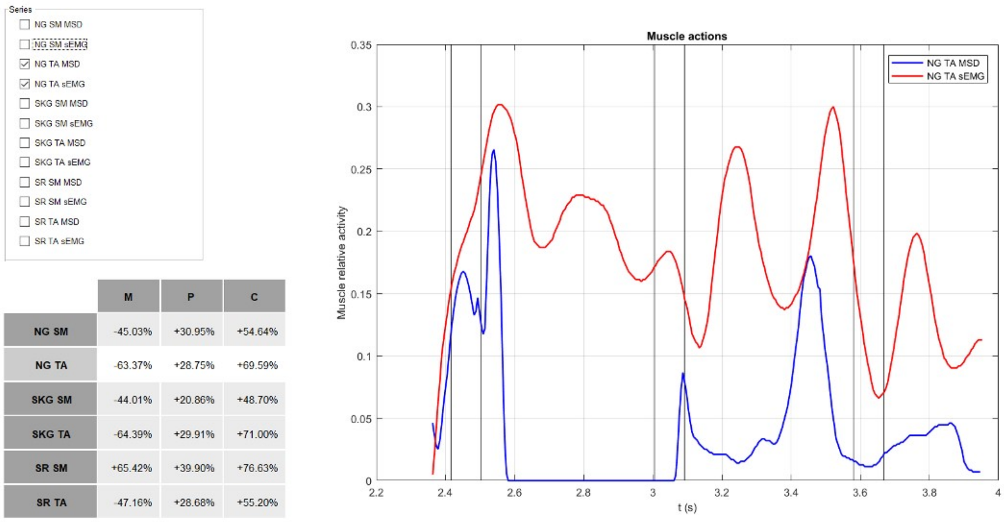


Figure 12: Cross-spectral analysis of the pelvis angular transverse and sagittal displacements SKG stride period.

3.11 Muscle actions

Muscle actions analysis module, Figure 13, enables the selection of the multibody system dynamics (MSD) muscle estimated action and processed surface electromyographic (sEMG) signals for magnitude (M), phase (P) and combined (C) metrics comparison among lower limb selected muscles, namely *soleus medialis* (SM) and *tibialis anterior* (TA) MSD and sEMG during entire stride of normal gait (NG), stiff knee gait (SKG) and slow running (SR) tacking into account different natures of MSD and sEMG, synergistic or antagonistic activity of selected muscles and differences among selected gait modes.



	M	P	C
NG SM	-45.03%	+30.95%	+54.64%
NG TA	-63.37%	+28.75%	+69.59%
SKG SM	-44.01%	+20.86%	+48.70%
SKG TA	-64.39%	+29.91%	+71.00%
SR SM	+65.42%	+39.90%	+76.63%
SR TA	-47.16%	+28.68%	+55.20%

Figure 13: MSD estimated muscle actions and registered sEMG of selected muscles at NG, SKG and SR.

4 DISCUSSION

Recognition on the complexity of human movement and difficulty of direct detailing and register based on visual inspection has been realized since the beginning of scientific research in this area. Over time many important contributions have been made at the methodological and technological level to the study of human movement with the development of new tools for measurement, analysis, modeling and simulation of human movement, with an open issue on which biomechanical variable truly captures neuromuscular control of human movement. On human gait analysis it is recognized the large number of time dependent and highly correlated signals with the need for entire time series analysis avoiding discrete and subjectively parameter selection and ignoring signal time structure. Large amount of data resulting from small time period of human movement analysis and main focus of software tools provided with required equipment on data acquisition and modeling / simulation software on providing simulation results with limited tools for significant analysis of complementary domains lead to development of presented software tool. Developed software tool emerged naturally as an author tool due to the lack of opensource software found in the research carried out with presented functionalities as a well as the need to perform significant gait analysis in an author controlled development graphical environment in an effective and efficient way.

Adopted 3D analysis allowed considering human gait movement at transverse and coronal anatomical planes with critical information of pelvis coordination of the HAT with lower limbs during gait, complementing hip, knee and ankle flexion-extension dominant movement on sagittal plane. Continuous and step by step animation of 2D and 3D pelvis and lower limb stick-figures synchronized with kinematic and internal / external kinetics enabled detection of events that could escape on direct visual inspection during registered movement. Results from time series analysis concerning maximum values of kinematic and dynamic comparing multibody subject on different gait modes were presented at [4] with main differences detected between NG, SKG, SR as well as on hip, knee and ankle joint. Fourier transform results of contact forces and force moments during normal and modified gait analysis were presented at [5] with differences at the number of harmonics with considerable amplitude and convergence of fast Fourier transform among gait modes and lower limb joints. Innovative analysis of 3D pelvis coordination on modified gait was presented at [6] with time, frequency and phase analysis of the pelvis angular oscillations at transverse, sagittal and coronal planes pointing for importance of complementary domain assessment of the pelvis coordination on different gait modes and spherical angular analysis for pelvis coordination assessment was presented at [7].

5 CONCLUSION

Presented software tool contributes for effective and efficient assessment of significant complementary domains on human subject specific gait analysis. Different and complementary metrics on time, frequency and phase domain were presented with application at translational research of human movement analysis into clinical gait diagnosis and rehabilitation, overcoming big data management complexity and unveiling hidden data relations. Additional metrics and modules proved to be useful along with extension to other forms of human movement of upper and lower limbs in addition to developed gait analysis.

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