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REAL-TIME ANALYSIS OF HUMAN GAIT: 3D SYMMETRY AND MECHANICAL WORK OF THE BODY CENTRE OF MASS TRAJECTORY

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SUMMARY
Nowadays CPUs speed allows to continuously compute biomechanical parameters as the motor act is occurring. Here we show how 3D kinematics of body joints, obtained from motion capture systems during locomotion on a treadmill, can be processed in real-time to calculate the 3D trajectory of the body centre of mass. A mathematical regression of its 3D path is performed after each whole stride has been detected, and many biomechanical parameters (speed, gait symmetry indices, external work, duty factor, etc.) are provided. The novel methodology is supposed to open to new research topics in locomotion biomechanics, particularly when feedback protocols are involved (fatigue and comfort) as in gait pathophysiology.

INTRODUCTION
Gait analysis, and body movement analysis in general, is most often achieved by integrating data from multiple sources (optoelectronic cameras, dynamometric platforms, EMG, etc.). After sampling during the experimental session, those data are stored, for them to be analysed and interpreted in a few days time. This delay clashes with the need, particularly of clinical environments, to obtain the quantitative results as soon as possible. An extreme example is the check of orthoses adequacy, which could benefit from an 'immediate', real-time quantitative analysis of the gait. The results would close the loop and guide the orthosis setting-resetting optimization procedure.
Until a few years ago, the calculation of the biomechanical parameters involved in locomotion from kinematics or dynamometry was too computationally intensive for it to be accomplished 'while-U-walk'. Even the fastest CPU was unable to reliably manage multiple tasks as data acquisition and processing simultaneously at the required speed. Here I present a methodology to obtain complex gait analysis parameters, related to the position of the body centre of mass (BCOM), after every stride has occurred.

METHODS
The 3D position of 18 reflective markers, located on anatomical landmarks of the relevant joints, is measured by an 8-camera optoelectronic system (VICON, Oxford UK) at a sampling frequency of 100 to 300 Hz [1] while subjects locomote on a treadmill (Ergo LG; Woodway, Germany). The 54 coordinates (18 x 3) are transmitted by using TCP/IP via GigaEthernet from the Motion Analysis PC to an 3 GHz, 8-core PowerMac (Apple Computers, US) where a set of custom programs have been written to accept and process those data in real time (LabView, National Instruments, US).
The software architecture has been designed on a Producer-Consumer scheme that uses the so-called Cueing System: the Producer is a subroutine capturing the continuous data stream from the TCP/IP port. For each time frame, the position of all markers is pre-processed as to obtain the location of the whole body centre of mass. Due to the very intensive computation load of the program, a novel algorithm has been developed to reduce to a minimum the number of operations: rather than obtaining the centre of mass location of the 12 body segments first and deriving BCOM from that, a single product of two matrices (A: marker positions and B: the relative mass 'weight' of each segment extreme) is performed. The same routine detects the treadmill speed from the markers located on the feet and also calculates separate duty factors for the two contact phases.
When a complete stride has been detected, the 3D trajectory of BCOM for that stride is sent to the Consumer routine for the subsequent processing. The procedure is managed as to feed a cuing system where data will be analysed only when the previous stride has been completely processed. The Consumer calculates the mechanical external work (Wext), by obtaining BCOM potential and kinetic (on the 3 spatial axes) energies, and estimates energy recovery (RE, sagittal and lateral). Also, it implements a recent mathematical method to mathematically describe the 3D BCOM trajectory [2], which simultaneously incorporates spatial and dynamical features. For each stride, a 10 harmonics Fourier Analysis of the Lissajous contour is performed, resulting in 61 trajectory parameters ((10 harmonic coefficient + 10 phases) x 3 axes + average contour height). A number of other indices, including left/right Symmetry for the three Cartesian axes (SIx, SIy, SIz), stride frequency (SF) and double contact (DC) time are also calculated. During the same computational step, an animation of the 3D BCOM position and its re-synthesised contour (according to the regression coefficients) is displayed in a 3D graphic window together with the position of the body markers. Another set of graphic charts are updated in real-time with Wext, SIx, SIy, SIz, RE and mechanical energies time courses.

RESULTS AND DISCUSSION

Figure 1 shows the pan/tilt and zoom 3D graphic window where measured and calculated data is simultaneously displayed in real time. Particularly, the 3D trajectory of the previous stride can be inspected in detail and compared to a matching 'standard' contour.

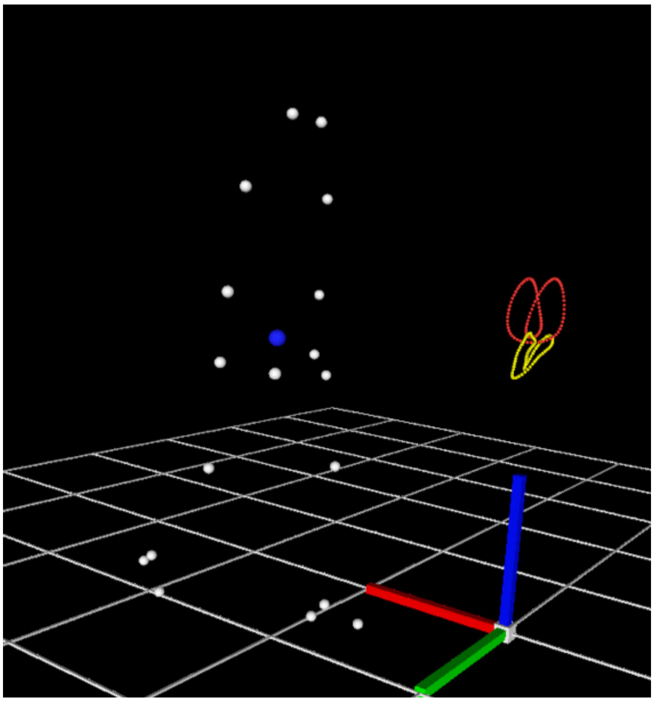

Figure 1: Real time 3D graphic animation window. White dots: reflective markers, blue dot: BCOM position, yellow contour: BCOM trajectory of the previous stride (5x amplified and offset), red contour: reference BCOM trajectory from a healthy subject database (matched for gait, speed, gradient, gender and age).

Symmetry indices of the BCoM trajectory for the 3 axes are presented in Figure 2 (they are expected to be equal to 1 in case of perfect symmetry between right and left steps). Those indices have been recently used to check normal gait restoration after knee replacement due to severe osteoarthritis [3]. The continuous monitoring of the subject during locomotion allows also to detect the effects of 'fatigue', either in terms of muscular effort or as the result of orthosis/prosthesis inadequacy.

Much care has to be paid to computational time management of each process involved, particularly when intense 3D graphics is simultaneously generated, synchronously with the moving subject. Estimated mechanical internal work, Wint [4], rather than the measured one, can be included at present, based on the calculated stride frequency, progression speed and duty factor. When CPUs will become even faster than today, stride-by-stride measured Wint and other relevant parameters (see below) could be incorporated in our software.

Based on the results from real-time analysis, the software generates, at the end of the sampling period, a summary report of the main feature of the gait, including the 'digital locomotor signature' [2] in mathematical form, for it to be compared with previous or reference contours. The transfer of the CAD version of the average BCOM trajectory obtained from those equations to a 3D printer is under development. This will generate a physical model representing a real size model report of the subject/patient's gait under investigation.

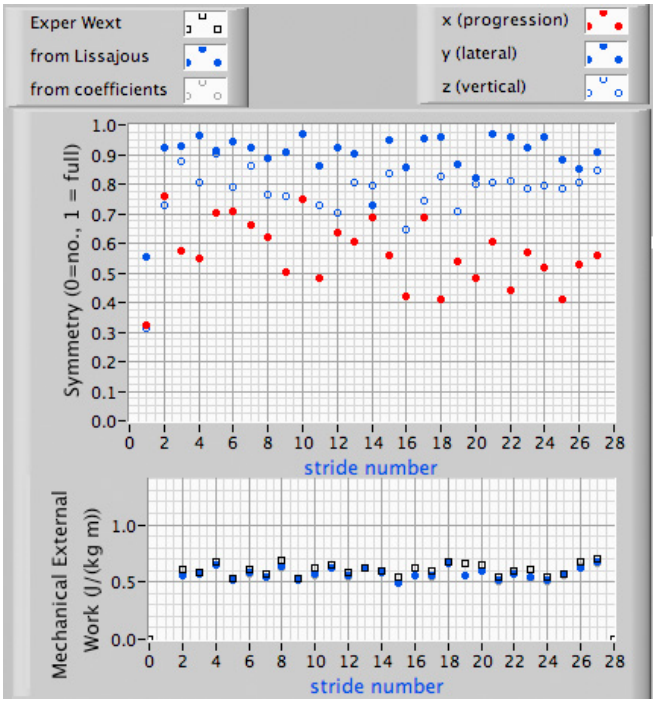

Figure 2: Example of a real-time graph of symmetry indices of the 3D BCoM trajectory in a subject walking on a treadmill at 1.05 m/s.

CONCLUSION

The present methodology represents a novel tool for biomechanics and pathophysiology of locomotion, where results are available in real time. Apart from remarkably shortening the interval between experimental tests and clinical report, such approach opens to new investigation topics taking advantage from the immediate quantitative feedback to shape the rest of the experiment or clinical test.

Depending on next CPUs speed, other applications integrating a variety of sensors could become available: real-time joint moments, centre of percussion, treadmill-on-demand protocols [5], critical joint angles (as in the squat jump), total mechanical work (Wtot = Wext + Wint), wobbling mass assessment [6], orthosis adaptation, etc.

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