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KINEMATIC ANALYSIS OF THE HUMAN KNEE JOINT TRAJECTORY DURING STAIR CLIMBING STANCE PERIOD

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ABSTRACT

In this paper an automatised method for kinematic analysis of human body segments in CAD environment has been established. 3D coordinates of marked points on lower extremities recorded by the ELITE measuring system and Kistler force plate were the input data for the computer simulation, which calculates and reconstructs the spatial orientation and trajectories of human body joints. Within this research, special attention is focused on the study of locomotion during energy-demanding movements like stair climbing, as an activity that requires large amount of metabolic energy and thus represents great difficulty in performing daily activities for people with disorders of the musculoskeletal system. Using this technique, the characteristic percentages of stance period during stair climbing have been determined, at which the knee joint makes a characteristic loop on its trajectory, in order to allow the conversion of muscle energy into potential energy when lifting the body to a higher level of the next stair.

Keywords: kinematic analysis, computer simulation, knee joint

1. INTRODUCTION

Computer modeling and simulation are used to perform three-dimensional biomechanical analysis of movement of human body, with the aim of gaining insight into the way of achieving motion under normal and pathological conditions, optimization of the specific activities of the musculoskeletal system, as well as a diagnostic tool for the identification and correction of gait disorders. Standard CAD systems have been used to help in engineering design and modeling for representation, analysis and manufacturing. Recent advances in computing technologies have contributed in the advancement of CAD in biomedical engineering in applications ranging from clinical medicine, customized medical implant design to tissue engineering [1].

Modern CAD computer technology should facilitate the integration of existing sophisticated features with classical biomechanical analysis, which is mainly carried out through specialized software and systems for motion tracking. As part of this research, special attention is focused on the development of new interactive methods of motion simulation of virtual human models within the highly developed CAD computer technology. For performing biomechanical kinematic analysis, the methodology of combining data captured by the magnetic tracking system with the current CAD/CAE computer technologies developed in research [2] has been used. The development of methodology for biomechanical 3D computer simulation that truly emulates the real motion within the CAD system based on data of recorded magnetic and optical monitoring systems provides a possibility of performing detailed biomechanical analysis of kinematics and dynamics in various aspects of human locomotion.

The focus of this study is locomotion of human knee joint when climbing stairs, as an activity that requires large amount of metabolic energy, and thus represents difficulty in performing daily activities for people with lower limb problems. Therefore, a better understanding of the kinematics while performing this activity is important.

2. METHODS

In biomechanical tests, due to extreme complexity of the structure of human body, structural diagram of the human skeleton is usually displayed as a mechanism comprised of members, which are connected in a series of kinematic chains. The kinematic model of lower extremities used in this research consists of 15 members (5 joints and 10 links) [2]. The mobility of the system is achieved through three rotational degrees of freedom between joints and links (spherical joints), and by one translational and one rotational degree of freedom between all proximal and distal links in the direction of their longitudinal axis (cylindrical joints).

The gait analysis equipment used for this experimental measurement consisted of Elite system with two CCD cameras and stairs that consisted of two steps with the standard slope of 17 cm in height and 29 cm in depth. Measuring took place in a pre-calibrated working volume of 2.2 m length, 1.8 m height and 1.5 m wide, with a recording frequency of 50 Hz. The first step was mounted with the Kistler force platform for measuring of three component ground reaction forces.

Ten subjects ranging in age from 20 to 40, with no apparent abnormalities of the locomotor system, were studied. The climbing was performed with the speed that the subjects considered as their normal speed of climbing. Special attention was given to naturalness in walking and a constant walking velocity. The kinematic analysis has been performed using the automatised method for determination of spatial orientation of lower limb segments [2]. 3D coordinates of the marked points recorded by the ELITE measuring system and Kistler force plate were the input data for the computer simulation, which calculates and reconstructs the trajectories of joints and spatial orientation of lower limb segments.

In order to be able to compare the characteristics of climbing, the parametric analysis of determined parameters has been done. Parametric analysis includes statistical analysis which determines the average values and standard deviation of analysed motion parameters. For comparing and determining the variability of the data for each of the examined subjects and for all measurements conducted, there are three defined patterns: individual, typical and general pattern. An individual pattern represents each functional dependence of the measured parameter on time or on the normalised percentage of stance period for each of the subjects. From individual patterns of motion characteristics, a typical pattern for every subject has been established. A general pattern for a particular motion has been determined from typical patterns of all subjects for the same manner of climbing. Determination of the mean value of the curves representing the dependency of selected parameters on the percentage of stance period has been made by the method of normalization, that is, dividing one cycle of each curve in equally spaced data points, after which the mean value is determined for all points of the curve. Since the number of data identified by measuring is different depending on the speed of walking, spline interpolation was used to determine 100 equally spaced data points. Typical and general patterns of the studied features are shown with the belt to +/- one standard deviation. Data captured by the measuring system ELITE have been transfered to the software package MATLAB via software commands written in Excel Link interface. To prevent the generation of stochastic errors of broad frequency spectrum and to remove "noise" of measurements, the filtering of the measured data is performed in MATLAB by Moving Average filter [3]. A moving average filter smooths data by replacing each data point with the average of the neighboring data points defined within the span. This process is equivalent to lowpass filtering with the response of the smoothing given by the difference equation:

$$y_s(i) = \frac{1}{2N+1}\Big(y(i+N) + y(i+N-1) + ... + y(i-N)\Big). \qquad ... (1)$$

where $y_s(i)$ is the smoothed value for the i^{th} data point, N is the number of neighboring data points on either side of $y_s(i)$, and $2N+1$ is the span. After the filtration of the curves was done, a set of programming commands written in MATLAB calculates the analyzed parameters (first and second derivative, i.e., speed and acceleration in the directions of the reference coordinate system axis).

3. RESULTS

Using computer simulation of motion, time dependencies of translation velocities and accelerations of the hip, knee and ankle joint during climbing have been determined. The typical pattern of joint velocities and accelerations for one of the examined subjects are shown on Figure 1 and Figure 2.

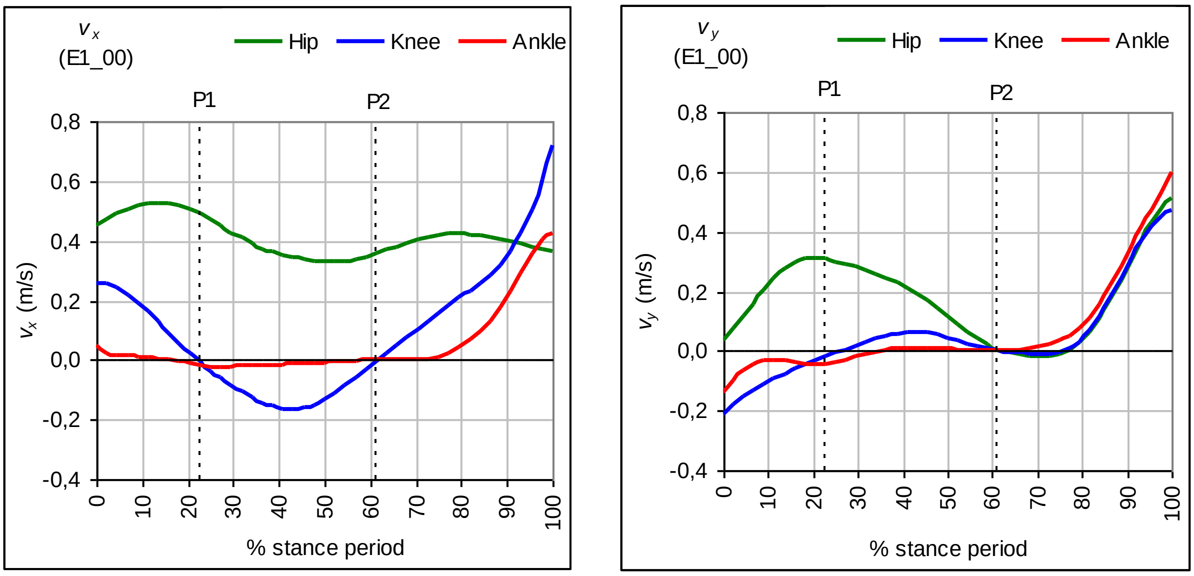


Figure 1.Typical pattern of normalised joint velocities in longitudinal (x) and vertical (y) direction

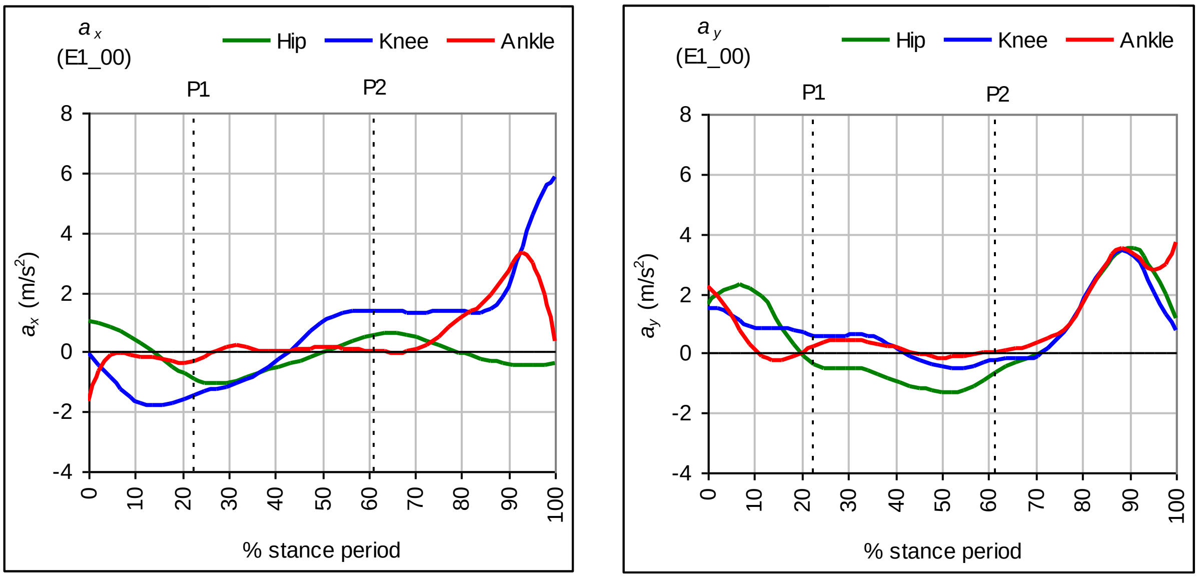
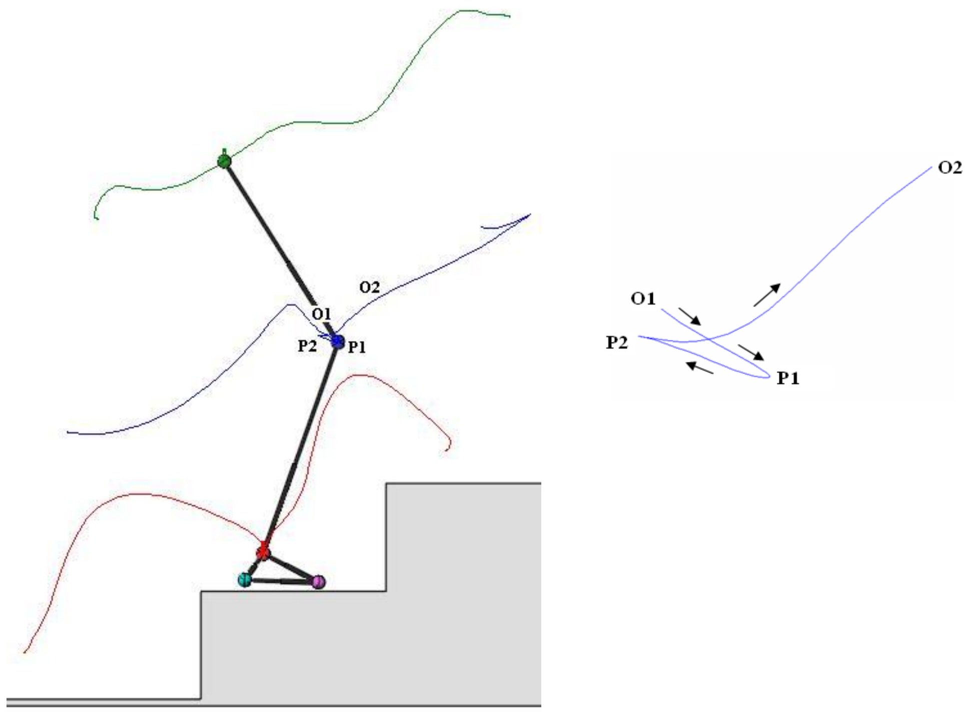


Figure 2.Typical pattern of normalised joint accelerations in longitudinal (x) and vertical (y) direction

Figure 3a) represents the kinematic model and trajectories of leg joints during stair climbing. The enlarged detail of the characteristic loop on the knee trajectory, within which a change of knee joint movement direction occurs, is represented on Figure 3b).

The position O1 marks the beginning of foot contact with the surface (force platform), the position P1 marks the maximum inclination of shank (the rightmost position in the loop of knee trajectory), the position P2 marks the leftmost position in the loop of knee trajectory and the position O2 marks the end of foot contact with the surface (force platform). Analysis of computer reconstructed trajectories of the knee joint and analysis of its velocity change in the longitudinal direction has enabled the determination of stance period percentages at which the change of knee joint movement direction occurs. It has been determined that the characteristic position P1 occurs at the 20% of stance period, and the characteristic position P2 at about 60% of stance period.



a) b)

Figure 3. a) Joint trajectories in sagital plane;bc) Enlarged view of knee joint "loop"

4. CONCLUSION

In this study the biomechanical kinematic analysis of lower limb segments during stair climbing has been analysed. An automatised method for construction of spatial orientation of body segments has been used to determine the characteristic percentages of stance period during stair climbing at which the knee joint makes a characteristic loop on its trajectory. Thereby, dependences of joint translation velocity and acceleration have been determined. The presented methodology of combining data captured by magnetic tracking system with the current CAD/CAE computer technologies used in this research can be used for better understanding of human body biomechanics as well as a diagnostic tool for identifying gait disorders and finding optimal parameters for their removal.

5. REFERENCES

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