Kinematic Analysis of the Human Movement: Gait Cycle and Mountain Climber

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ABSTRACT — *In the realm of kinematic analysis, the scrutiny of motion mechanics holds paramount importance across diverse fields, spanning from sports science to physical therapy. This study delves into a comprehensive kinematic analysis focused on two different movements; gait movement and the Mountain Climber exercise. The experimental data was meticulously collected within the Biomechanics of Motion Lab at Instituto Superior Técnico and meticulously processed using a 2D Multibody Model crafted through MATLAB. While the gait cycle aligns with existing literature on various aspects, discrepancies in knee joint angles are attributed to marker placement and individual anatomical variations. The analysis of the Mountain Climber exercise highlights its dynamic nature, revealing significant knee joint angle variations. The results gleaned from this analysis have offered valuable insights into the biomechanics of the Mountain Climber. They provide a comprehensive understanding of how the knee and hip joints operate during this exercise, shedding light on the nuances of muscle engagement, joint angles, and the coordination required for optimal performance. These findings not only contribute to our understanding of the exercise but also serve as a foundational resource for fitness professionals, physiologists, and enthusiasts seeking to maximize the benefits of the Mountain Climber in their fitness routines.*

1 Introduction

Kinematics is a specific branch of mechanics that describes the motion of objects/body parts, such as acceleration, velocity and position, without reference to the forces causing the motion. In a more specialized context, multibody kinematics analysis entails the dissection of these dynamic attributes for each distinct body within a system [1]. By providing a non-invasive means of collecting data of a body movement, kinematics has great use in different fields such as robotics and medical devices. Biomechanical models and kinematic analyses help differentiate healthy movements from abnormal ones, aiding in the diagnosis and treatment of movement disorders and injuries. They play a pivotal role in identifying hazardous movement patterns, thereby shaping injury prevention strategies. This is particularly valuable in sports and physical therapy, enabling the customization of rehabilitation programs to suit individual requirements and expediting the recovery process following injuries or surgeries.

For the current report, with use of kinematics we will be analyzing two different motions: the gait cycle and the mountain climber exercise.

1.1 Motion description: Gait cycle

Human gait is the most common of all human movements, yet it is also among the most challenging tasks to learn. During the gait cycle, a multitude of muscles, tendons and joints work in harmony and opposition to create the coordinated and rhythmic motion of our limbs, which is not merely a repetitive sequence of steps but a dynamic, multifaceted phenomenon that has intrigued the attention of many professionals. [2]

Individuals have distinctive and relatively consistent walking patterns, making it possible to recognize them by their gait from a distance. Although there is some variability in gait between individuals, efforts to normalize measurements, such as dividing by body mass or using cadence groups, aim to reduce this variability and create more universal gait profiles, although more effective normalization methods may be developed in the future. [2]

Gait analysis research varies in its focus, with clinical investigators examining visual measures like stride length and joint angles, neurological researchers using EMG measures, and biomechanical researchers analyzing kinematics, reaction forces, and more. While different measures provide specific insights into aspects of human gait, it's crucial to distinguish between variables that reveal the cause of gait patterns and those that describe the resulting effects, with measures like EMG, moments of force, and power offering insights into the underlying causes. [2]

In our upcoming report, we will explore kinematics within the context of gait analysis, shedding light on aspects such as joint angles, displacements, velocities, and accelerations. This analysis helps us gain insights into the mechanics of human locomotion without delving into the underlying forces that drive these movements.

1.2 Motion description: Mountain Climber

The Mountain Climber exercise is a dynamic movement that mimics the motion of climbing a mountain. During this exercise, the individual starts in a plank position with the body in a straight line and alternately moves their legs forward towards the chest and then extends them back to the starting plank position. The core of the exercise lies in the Alternation of Sides, as both knee pull and knee extension phases are executed alternately for each leg. This back-and-forth leg movement simulates the act of climbing while keeping the upper body stable in the plank position. Mountain Climbers are often used as a cardiovascular and full-body strengthening exercise.[5] Analyzing these movements can provide insights into muscle activation patterns and strength development, which can be relevant for designing rehabilitation exercises and assessing fitness levels. Additionally, it enhances understanding of joint biomechanics across different motion planes, benefiting balance disorder diagnosis. It plays a vital role in the sport of rock climbing. It significantly enhances safety measures, aids in skill development, and informs equipment design. By identifying movements that may lead to injuries, biomechanical analysis contributes to fostering skill enhancement. Furthermore, it refines training programs to enhance climbing abilities and encourages adaptive climbing, making the sport more accessible to individuals with disabilities.

In the kinematic analysis of the Mountain Climber exercise, we examine the motion of various anatomical points such as the head, shoulders, elbows, wrists, hips, knees, ankles and toes.

2 Methods used in the analysis

In this analysis, we employed a multidisciplinary approach, combining biomechanical modeling, data acquisition with sophisticated motion capture technology, and data processing techniques. Our methods encompassed the development of a 2D multibody system, projection into the sagittal plane, data filtering, and the evaluation of body positions and drivers, ultimately facilitating comprehensive kinematic analysis of human movements.

2.1 Biomechanical model for the human movement

In this section of our report, the biomechanical model utilized for the analysis of both exercises is presented. The model consists of a 2D multibody system, as depicted in Figure 1a. It comprises 14 rigid bodies, each of which is connected by at least one of the 13 distinct revolute joints. A marker has been placed in the location of each joint for tracking purposes.

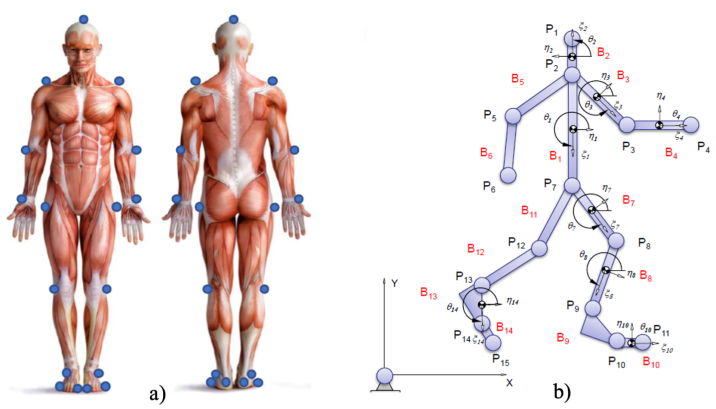


Fig. 1: a)Illustration of the anatomical landmarks for the placement of retroreflective markers;[3]

b)Schematic representation of 2D biomechanical model. [4]

To accommodate the analysis within a 2D plane, the data collected was projected into the sagittal plane. This entailed considering only one of the two markers located in the shoulders and hips, with these markers representing the points in the middle of each pair. The chosen coordinate system for this analysis is Cartesian, with the position of each body being defined within a global reference frame. The configuration of each body is represented by a vector that consists of the translation coordinates of its center of mass (x and z) and the angle of rotation of the given segment concerning a specific axis:

$$q_i = [x_i \ \ z_i \ \ \Theta_i \ ]$$

The model encompasses a total of 42 coordinates, as each body is defined by three coordinates. However, since each pair of bodies is connected by a revolute joint, and each joint imposes two kinematic constraints, the number of degrees of freedom is determined by:

$$n_{dof} = n_{coordinates} - n_{constraints} = 42 - 13 \times 2 = 16$$

It is worth noting that the chosen biomechanical model cannot assess depth, and thus any movements of the rigid bodies occurring outside the sagittal plane are associated with errors.

For this report, the file *model.txt* defines the model. This dataset specifies the relationships between rigid bodies, joints, and constraints. The function *ReadDraftInput* reads this dataset, and stores the pertinent information in data structures.

2.2 Data acquisition methods at the Lisbon Biomechanics Laboratory

The data acquisition for the analysis consists in acquiring the data from the gait and the mountain climber movements, through measuring values from the physical world with sensors and then transforming them into digital data.

To facilitate this data acquisition, our laboratory is equipped with a sophisticated motion capture system (MOCAP), consisting of 14 high-precision IR Cameras (Qualisys ProReflex 500/1000), which play a vital role in ensuring the accuracy of our motion data. The MOCAP system operates at varying acquisition frequencies to cater to different aspects of the motion capture process. The cameras are set to record at a frequency of 100Hz, which provides detailed and dynamic tracking of the markers. In the first part of the project the data collected by the EMG and the force platforms will not be analyzed but it will be of use for the dynamic analysis. The subject whose data was acquired was a 22 year-old woman, weighing 49 kg and of height 1.64m.

Regarding the number of trials conducted, we typically aim for a variable number of trials, with a focus on ensuring that at least 5 good trials are collected. This approach helps minimize the impact of outliers and ensures that the recorded data accurately represents the subject's typical motion patterns. Precisely measuring the lengths of different body segments is made possible through the analysis of a static position in which the subject assumes the anatomical reference posture.

The approach taken is to compute the midpoints, which results in the creation of point P2 for the shoulders and point P7 for the hips, as illustrated in Figure 1b. Notably, the points corresponding to the left and right heels are not considered in this projection, reducing the total number of points from 19 to 15. Each body in the biomechanical model is now characterized by two points, resulting in the identification of 14 distinct bodies.

different steps of the pre-processing methodologies.

2.3 Data acquired and pre-processing

For the first part of the PreProcessing() function, we prepare the biomechanical model by reading input data, including both model details and static data.

The *"model.txt"* is provided to the *ReadDraftInput()* function, which is responsible for reading and compiles necessary information for the interface such as the number of bodies, revolute joints, ground elements, and driver joints, as well as specific details about each body, revolute joint and driver joint of the system.

After the "*model.txt*" is read, we need to read and process the static.xlsx through the *ReadProcessData()* function, which will contain information such as the number of frames, sampling frequency, and coordinates for various parts of the body, it revolves around transforming the 3D data into a 2D sagittal plane, excluding the y-coordinate data and focusing solely on x and z coordinates. After the data is processed, we use it in the *ComputeAverageLengths()* function, which will calculate the average lengths of different body segments using motion data.

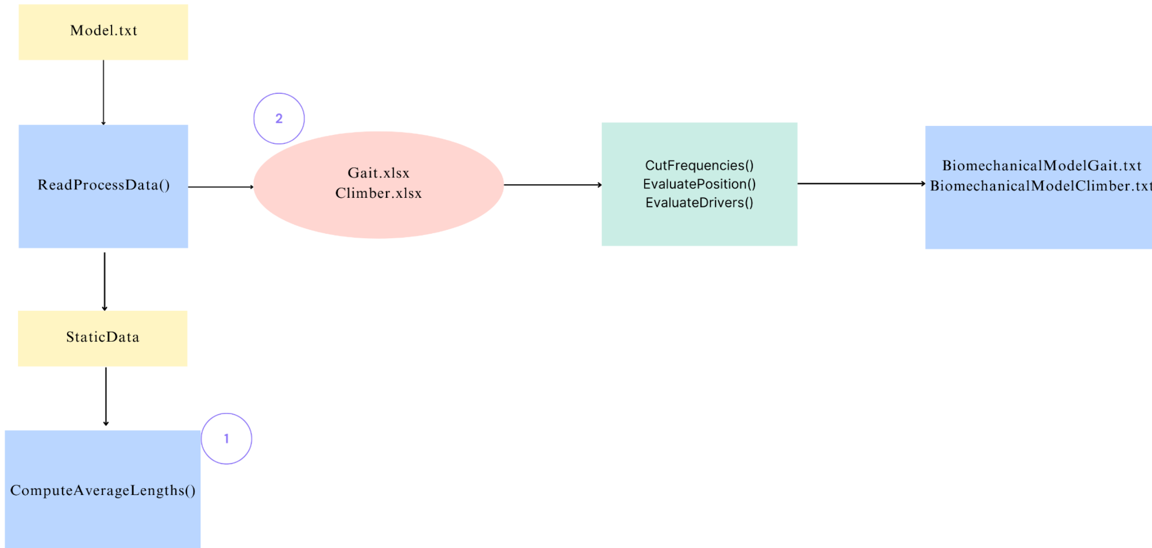


Fig. 2: Flowchart that represents the pre-processing interface for the kinematics analysis.

The second part involves choosing the motion we want to analyze, by opening the gait.xlsx or climber.xlsx and reading through the ReadProcessData() and *CutFrequencies()* functions. The *CutFrequencies()* precesses motion data and calculates the cut-off frequencies for filtering the x and y coordinates through the function *FilteredCoordinates().* The *FilteredCoordinates()* function refines movement data, utilizing a 2nd order Butterworth low-pass filter with zero-phase lag to filter the data iteratively at multiple cut-off frequencies, enhancing the 'x' and 'y' coordinates independently and effectively assessing the data at various filtering strengths.

After the data have been processed, the information goes to the *EvaluateDrivers()* and EvaluatePositions() so the information can be defined as the position and orientation of the bodies and the variations of the degrees of freedom of the biomechanic system over time. The degrees of freedom are driven by drivers I and III, and are inputted in the *EvaluateDrivers() f*unction. The type I describe the absolute coordinates of the multi-body system and refers to the body 1 (trunk), the type III is defined as the difference of the orientation of two bodies, with angles defined with respect to the horizontal axis and measured counterclockwise. The constraint of each driver is shown in Table 1.

Table 1: Types of driving constraint

	Function	**Equation of the constraints**
Type I (3 implemented)	Positions the whole system in space, according to the coordinates x, y and Φ	$\Phi(t) = z_i - z_i(t) = 0$ $\Phi(t) = x_i - x_i(t) = 0$ $\Phi(t) = \Theta_i - \Theta_i(t) = 0$
Type III (13 implemented)	Describe the angle between two bodies linked by a revolute joint	$\Phi(t) = \Theta_{ij} - \Theta_{ij}(t) = 0$ with $\Theta_{ij} = \Theta_j - \Theta_i$

The ultimate function within the interface, WriteModelInput(), generates and provides the essential input values for the kinematic analysis program in the form of text files. As part of the analysis, a series of .txt files is created, with each file corresponding to a specific driver within the system, in addition to this document.

2.4 Kinematic analysis of the human movements

To successfully perform the kinematics analysis, we first need to understand our system. It consists of 14 rigid bodies and 13 revolute joints. The function ReadInput() will start calculating our degrees of freedom for the 14 rigid bodies, since each body has 3 degrees of freedom, the program initially with 32 degrees of freedom ($14\,x\,3 = 32$). For the 13 revolutes joints, the function JointRevolute() is responsible for handling the constraints of the 13 joints, each of which contributes to 2 constraints (position and orientation). Therefore there are 26 constraints in the system($13\,x\,2 = 26$). The remaining 16 degrees of freedom ($32 - 26 = 16$), are used to describe the motion of the 16 driving constraints in the function Driver().

Finally running the KinematicsAnalysis(), which will perform position, velocity and acceleration analysis using PositionAnalysis(), VelocityAnalysis() and AccelerationAnalysis() functions. Reporting the results using the ReportResults() function. It also generates two output files. One of these files contains comprehensive data, including positions, velocities, and accelerations for each body at every time step of the analysis. The other file records the time history of positions, velocities, and accelerations for specific points of interest. This function essentially helps us visualize and document the results of the biomechanical analysis.

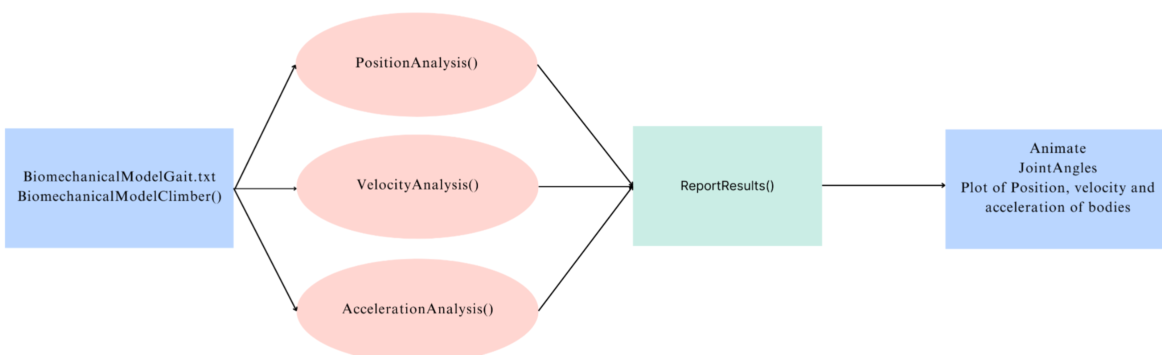


Fig. 3: Flowchart that represents the kinematics analysis

The PositionAnalysis() function employs the Newton-Raphson method to solve a nonlinear system of equations,$\Phi(q, t) = 0$, allowing us to determine the positions of the bodies at a specific point in time. It begins by having an initial guess, ideally as close as possible to the true solution, q_i, and interates using $q_{i+1} = q_i - ((\Phi(q_i, t)/\Phi_{qi}(q_i, t))$, it keeps iterating until a certain tolerance **ε** is met, and with each iteration, the approximation gets closer to the true solution.

After knowing the position given from the PositionAnalysis(), we can compute the velocity by differentiating the position equating it with the respect to time. Doing the same process for the acceleration, but differentiating the velocity by the time in order to compute the acceleration in the AccelerationAnalysis() function, as shown in Table 2.

$$\Phi(q, t) = 0 \Rightarrow \partial\Phi(q, t) = 0, \Rightarrow \Phi(q, \partial\partial t) = 0$$

Table 2: Velocity and acceleration constraint equations.

Velocity constraints equation	Acceleration constraint equation
$\partial\Phi(q,t) = \Phi_q \partial q = v$ $v = -(\partial\Phi/\partial t)$	$\partial\partial\Phi(q,\partial q,t) = \Phi_q \partial\partial q = \alpha$ $\alpha = -(\partial^2\Phi/\partial t^2) - (\Phi_q \partial q)_q \partial q$

3 Case Studies

The subject whose data was acquired was a 22 year-old woman, weighing 49 kg and of height 1.64m. In the context of our biomechanical model, we used the ComputeAverageLengths function to determine the length of each rigid body. This method was applied to our static file. Below, you'll find a table presenting the computed lengths of these rigid bodies.

Table 3: Length of the anatomical segments of the biomechanical system

Body	Length (m)
1	0.5388
2	0.3084
3	0.3117
4	0.2276
5	0.3080
6	0.2167
7	0.3835
8	0.3414
9	0.1134
10	0.0660
11	0.3854
12	0.3482
13	0.1161
14	0.0636

This section showcases the outcomes achieved through the implementation of kinematic analysis using MATLAB for both movements under study. The results included here have been selected for their significance in the analysis of these motions. Furthermore, this section undertakes a thorough comparison and discussion, aligning the obtained results with values found in relevant literature.

3.1.1 Movement case 1: Gait

In our gait analysis, particular attention will be given to the movements of the lower limbs, as they are of special interest for this motion. With this objective in mind, the cycle analysis is initiated by examining the vertical displacement, as well as the vertical and horizontal velocities of the feet, specifically the metatarsal and toe, and comparing the results with existing literature. For the comparison of the joint angles , the hip angle is a valuable tool for grasping the orientation of the thigh in space, while the knee angle aids in deducing the leg's spatial orientation and the relative ankle angle offers a reliable estimate of the foot's orientation in space.

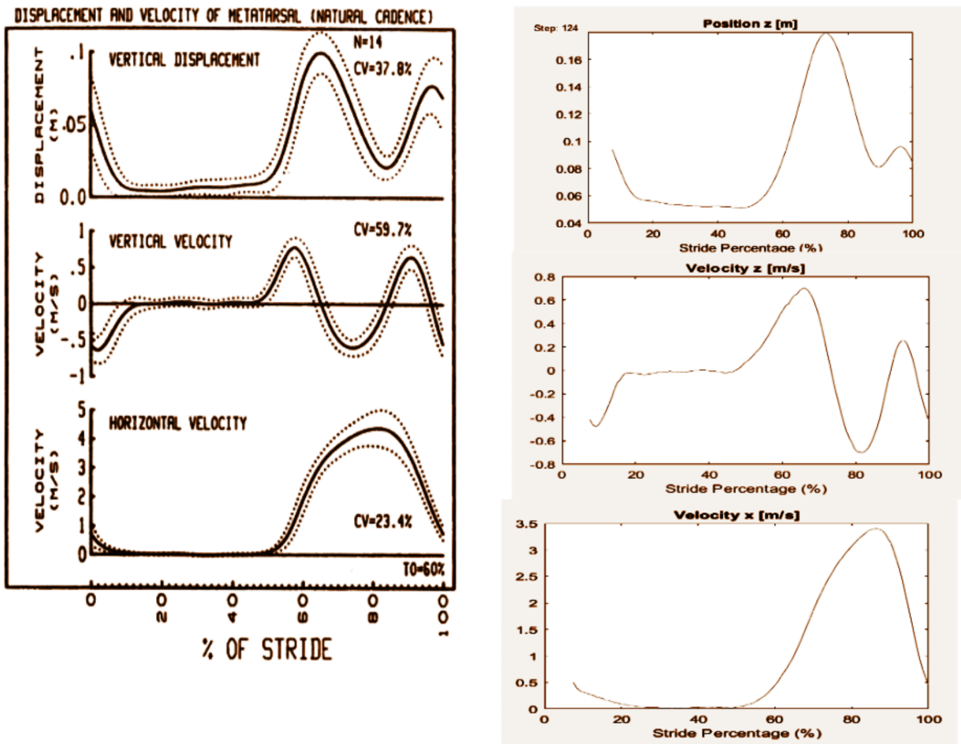


Figure 5: Vertical displacement (in meters), vertical velocity (in m/s) and horizontal velocity (in m/s) of the right metatarsal. Left: retrieved from Winter(1987).13 Right: obtained from lab data from the body 14-right toe, after processing.

Only the results for the right toes' displacement and velocities are displayed. Upon analysis, it becomes evident that the profiles for both graphs exhibit remarkable similarity, reaffirming the accuracy of the model in replicating the gait movement. Consequently, the graphic profile obtained closely resembles that found in Figure 5 (left), which pertains to the metatarsal—a bone located between the tarsal bones of the hind- and mid-foot and the phalanges of the toes, specifically in the median part of the foot.

While our analysis has successfully corrected the ankle and leg (corresponding to the hip) angles, we acknowledge that the knee joint angles exhibit notable discrepancies from the expected idealized graphic. Figure 6. These differences may be attributed to several factors, such as marker placement during the experiment and individual anatomical characteristics might introduce inaccuracies. Additionally, the subject's adaptation to the experimental setup and conditions may alter their joint angles from a typical walking pattern. With that, the knee angles have proven to be more challenging to adjust accurately.

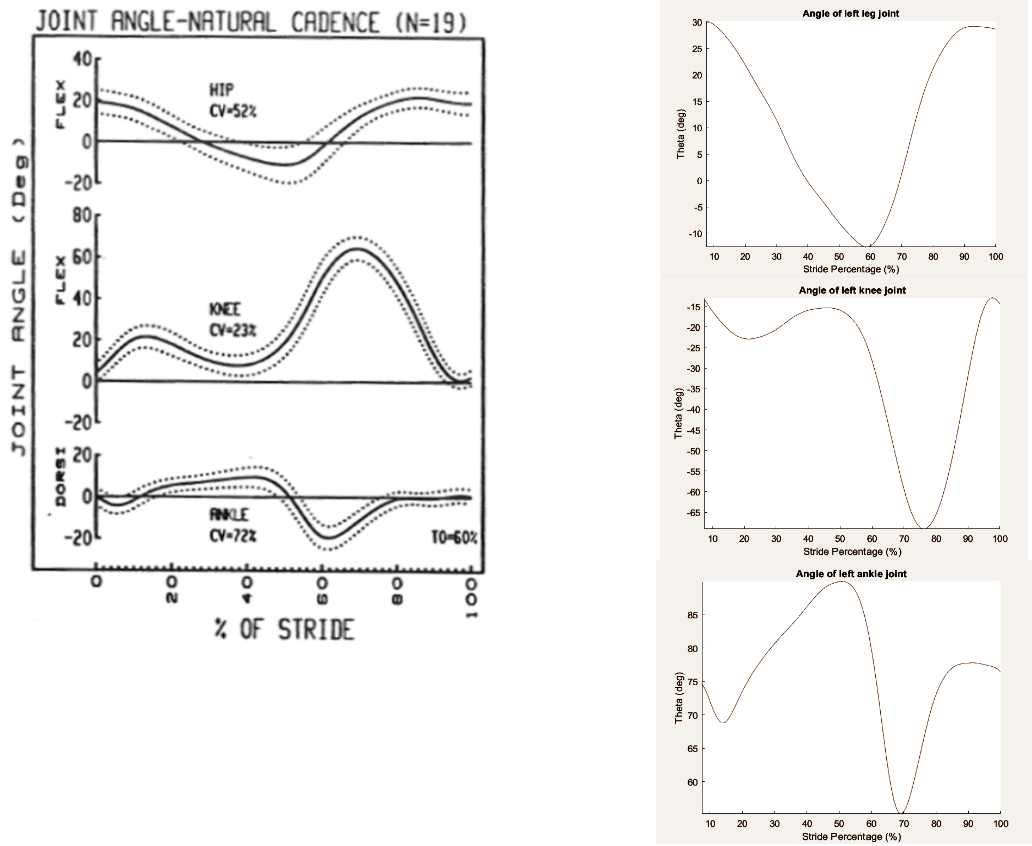


Figure 6: Joint angle (in degrees) of hip (top), knee (center) and ankle (bottom. Left: retrieved from Winter(1987).[2]
Right: obtained from lab data using KinematicAnalysis.m.

3.1.2 Movement case 1: Mountain Climber

In order to study the mountain climber movement, it was necessary to reduce the dataset to focus on a single cycle of the motion, referred to as the "*climbercycle.xlsx*," and thereby differentiate between various phases based on the percentage stride of the movement. The dataset was evaluated, and an effort was made to select a cycle that was discernible, as can be seen in Figure 7, where several cycles were performed during the experimental activity.

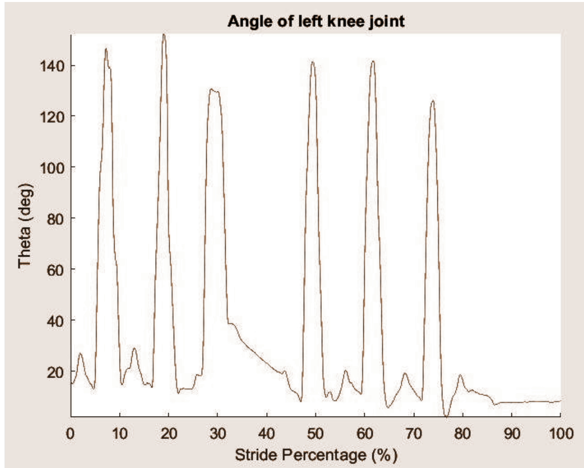


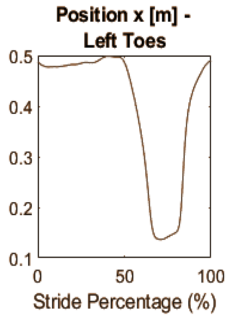
Figure 7: The graph of knee angles for the entire Mountain Climber dataset (it is also in stride percentage, but there are more than one movement cycle present).

In Figure 12 of the appendix, you can see the body positions in one phase of the movement, with the blue balls representing our joints.

Observing the elbow angle graph (Figure 13) , it becomes apparent that the angle was close to 0 degrees in the Plank position, but during the exercise, this posture was not sustained due to the inherent movements leading to minimal elbow flexion. The graphs of shoulder angles also exhibit variation, with the right shoulder having higher angles in the first half of the movement, and the left shoulder in the second half. This indicates that, when pulling different legs towards the chest, the shoulders dynamically balance the body's forces and consequently shift.[6] Notably, the knee angle graphs reveal distinct peaks corresponding to the 'Knee Pull to Chest' phase observed between 0% and 45%, with a brief Plank Stabilization Phase observed between 40% and 45%.

The trunk experienced minimal movement on the order of centimeters, while the feet moved approximately one meter, as evident in the graphs obtained in the KinematicsAnalysis function. The joint that exhibits the most significant variation in angle during the movement, particularly in the 'Knee Pull to Chest' phase, is the knee, which reaches an angle of up to 140 degrees and it was expected due to the entire flexion and extension of it. During the exercise, individuals typically flex their ankles and toes as they pull their knees toward their chest and switch between legs in a dynamic and repetitive motion, as it is possible to see in the graphics of KinematicAnalysis. During the 'Leg Alternation' phase, specifically when the left leg is pulled towards the chest, it is noticeable in the graphs that the sensors detected a slight break or resistance in completing the movement, for example in the Graph at. This resulted in imperfect peaks in the graphs for the left leg, knees, and feet.

There is a discrepancy between our data and the ideal movement due to the fact that our analysis was limited to the sagittal plane, and regrettably, mitigating rotation was not feasible.



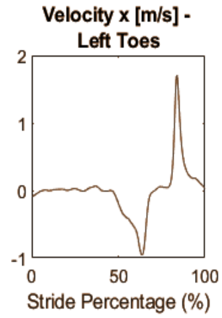


Figure 8(on the left) and Figure 9 (in the middle): Graph of horizontal position and velocity of left toes during the Mountain Climber movement,

Figure 10 (on the right): Graph of the Left knee angle during the Mountain Climber movement.

4. Conclusions

In closing, this comprehensive kinematic analysis focused on two distinct human movements: the gait cycle and the Mountain Climber exercise. Our study entailed meticulous data collection within the Biomechanics of Motion Lab at IST and rigorous processing through a 2D Multibody Model implemented in MATLAB. Our comprehensive kinematic analysis of the gait cycle and the Mountain Climber exercise has provided valuable insights into the mechanics of these distinct human movements. The data analysis revealed an alignment with existing literature for various aspects of gait, such as vertical displacement, velocities, and joint angles. However, the knee joint angles presented notable discrepancies, highlighting the influence of factors like marker placement and individual anatomical characteristics.

For the Mountain Climber exercise, our analysis showcased the dynamic nature of this movement, with significant variations in joint angles, particularly at the knee joint. While our analysis was limited to the sagittal plane, it illuminated the complexity of this exercise, shedding light on the interaction between different body segments.

Ultimately, the insights gained from this kinematic analysis contribute to the broader knowledge base in biomechanics, providing a valuable resource for researchers, fitness professionals, physiologists, and enthusiasts seeking to optimize human movement and performance.

References

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5. Appendix

Cut-Off Frequencies

In our biomechanical analysis, one of the pivotal considerations lies in the selection of optimal cutoff frequencies for low-pass filters. These frequencies dictate the range at which the filter attenuates the input signal, making them an essential parameter in striking a balance between noise reduction and data preservation. By optimizing cutoff frequencies, our aim is to deftly reduce the influence of noise. The result is that we obtain movement profiles that are not only smoother but also more interpretable, adept at capturing the essential features of human locomotion.

To arrive at the most suitable cutoff frequencies for the low-pass filter, we embrace a systematic approach inspired by the work of *Winter* (2009) and the utilization of the 'FilteredCoordinates()' function. Our methodology entails conducting residual analyses across a spectrum of frequencies, ranging from 0.1 Hz to 10 Hz, with intervals of 0.1 Hz, systematically applying Butterworth filters to x and y coordinates. The root mean square of noise for each frequency was quantified. To select optimal cutoff frequencies, we employed linear regression analysis, setting a minimum correlation threshold of 0.9. Using the cutoff frequencies obtained, we filtered the coordinates.

The use of similar cut-off frequencies for both walking and the 'Mountain Climber' is appropriate as both movements involve weight transitions, joint flexion/extension, and body rotations, enabling kinetic analysis to understand the forces and moments involved. This approach considers common movement frequency patterns and facilitates result comparability between different studies, establishing reference guidelines.

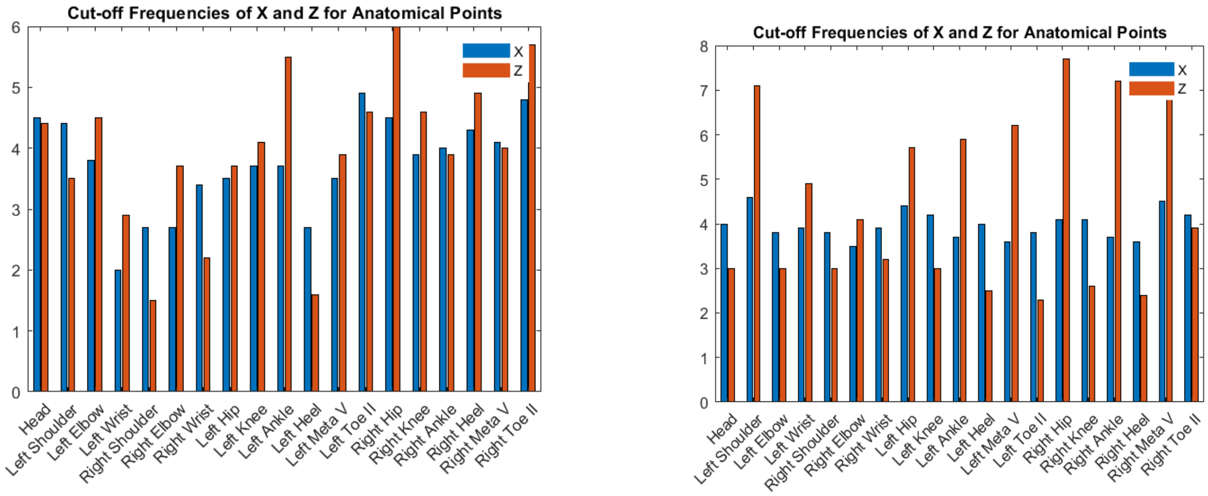
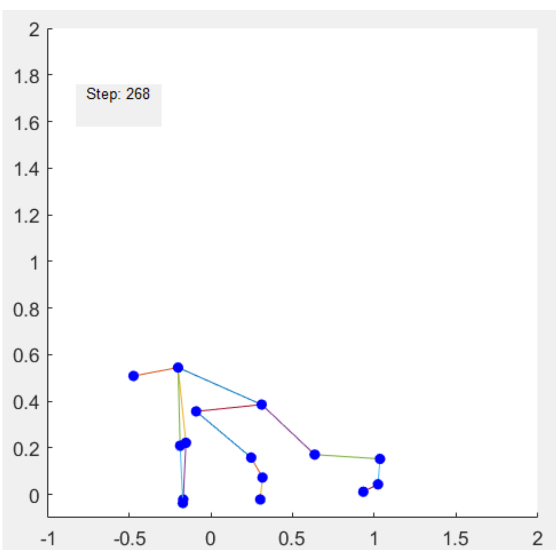


Figure 11: Cut-Off Frequencies utilized in the filtering procedure for each marker for gait (left) and mountain climber (right). Graphs were obtained using CutFrequencies function

Mountain Climber Movement



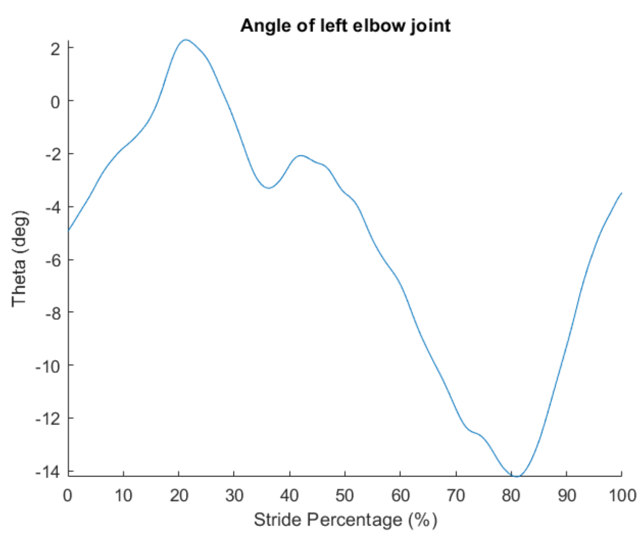


Figure 12: Animation Body of Mountain Climber Movement

Figure 13: Graph of the Left Elbow Joint of in Mountain Climber