Biomechanical Modeling and Analysis of Human Motion

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Abstract:
Human motion is accomplished through muscle actuation producing torque about each joint. Inverse dynamics allows for the measurement of these forces and torques to be determined with non-invasive data collection techniques at low cost. Video was processed using MATLAB to determine position data of markers on each joint throughout a given motion. Position data was then converted into a series of rigid links to determine the angular position of these links for each frame of the given video. Internal forces and torques about each joint were then determined from the equations of motion using an inverse dynamics method. The vertical component of the ground reaction force was validated using a force plate. Simple position data cases were also developed and analyzed as validation of forces and torques determined by the inverse dynamics method. This research has verified the feasibility of a low cost, non-invasive system of analytical analysis of human motion. A direct result of this research is the possibility of a broad range of applications in the field of human kinetics, including gait analysis, prosthetic design and fitting, and locomotion in low gravity environments.
Introduction:
Modeling and analysis of the human body will provide information about the limitations and capabilities of human motion. The purpose of this research is to develop a method of determining the internal forces and torques required for this motion. It is useful for the understanding of why injuries have occurred as well as preventing future injuries. Knowledge of internal forces and torques can also allow analysis of gait efficiency. It could also provide a tool for the analysis and recommendations of low gravity locomotion. This can be done using other methods; however, this research used inverse dynamics. Inverse dynamics is a method used to compute forces and torques from the known motion of the body and its properties. This method can be applied to the human body to provide a better understanding of its actuation. The inverse dynamics method presented provides the opportunity for a low cost, non-invasive system for analysis of the internal forces and torques required for human motion.

Video Capture System:
Video capture was used for obtaining positional data of joint locations over time. The program to track the joint positions was written in MATLAB. The video data was acquired using a KODAK PLAYSPORT video camera. This camera was capable of a video resolution of 720 by 1280 pixels and a frame rate of 60 frames per second. Small green and blue balls with a one and three quarter inch diameter were connected to elastic bands and then tied to the center of each joint tracked. Video was taken of the motion while wearing these markers. The frames were then filtered based on the intensity of the colors green and blue. This introduced specific requirements for the clothing that were used to collect data. The clothing worn needed to contrast these colors as much as possible. If colors similar to green or blue were worn, the program would incorrectly recognize other objects as markers resulting in inaccurate data. Clothing colors most effective for successful processing were black, grey, and white. Also, like color markers located close together were incorrectly labeled as a specific marker during the search process. This happened because more than one marker was within the search radius of the specific marker, and the first marker found would then be chosen as that marker. For example, a marker located on the ball of the foot would interfere with the marker positioned on the ankle. To solve this problem, green and blue markers were instead alternated for each joint to provide a greater distance than the search radius between like color markers.

The MATLAB program would display the first frame and allow the user to input a known distance to calibrate pixel distance and then prompt the user to click the initial locations of each marker. All other colors in each frame was then filtered out based on the threshold value representing the intensity of the specific color. The frame was then converted to a binary image with the markers represented as collection of white pixels in a frame of black. MATLAB then calculated the location of the centroids of each of these white areas. With these centroid locations, the program would then check to verify that the calculated location was within a user specified search radius of the previous location of each specific marker. This method was employed twice for each frame of the video, once for the color green, and once for the color blue. Marker position validation was accomplished by displaying each frame on a figure and then plotting the calculated positions over that frame. The positions were then visually compared to the actual location of each marker. An example of this
validation technique is shown in figure 1. The positions are plotted using the white circles. As shown in the figure, they are located directly over the true positions of the markers.

![Figure 1: Video Validation Technique](image)

A Butterworth filter was then applied to the data to reduce any noise from the video processing method. Once filtered, the position data was converted into a series of links representing each piece of the body to obtain the angular position of each link. The frame rate of the camera was then used to determine the angular position with respect to time, or the angular velocity, of each link. This was repeated using the angular velocities to determine the change of the angular velocities with respect to time, or the angular accelerations, of each link for each frame of the video.

**Mechanical Modeling**

To determine the unknowns, it was necessary to model the human body as a series of links. Figure 2 shows how the body was modeled as a system of links. The torso, head, and arms were all assumed to be one rigid link. The upper leg, or thigh, was assumed a single rigid link. The lower leg, or shank, was also assumed as a single rigid link. Nomenclature representing the values in figure 2 is located in the appendix.
Figure 2: System of Links Model

It was then possible to calculate the ground reaction forces using the point mass model. The three-link model, a simple case of a multi-link inverse dynamics method, was used to calculate internal forces and torques as well as the ground reaction forces. The equations of motion (EOMs) of this model were then developed. These are as follows:

**Link 1:**
\[
\text{GRFx} - \text{Fkx} = -(m_1)(r_1)(\dot{\theta}_1)\sin(\theta_1) - (m_1)(r_1)(\dot{\theta}_1^2)\cos(\theta_1) \\
\text{GRFy} - \text{Fky} = (m_1)(r_1)(\dot{\theta}_1)\cos(\theta_1) - (m_1)(r_1)(\dot{\theta}_1^2)\sin(\theta_1) + (m_1)g \\
\text{GRFx}(r_1 \sin(\theta_1)) - \text{GRFy}(r_1 \cos(\theta_1)) + Ta + Fkx[(l_1 - r_1)\sin(\theta_1)] - Fky[(l_1 - r_1)\cos(\theta_1)] - Tk = (l_1)(\ddot{\theta}_1)
\]

**Link 2:**
\[
Fkx + Fhx = -(m_2)(l_1)(\ddot{\theta}_1)\sin(\theta_1) - (m_2)(l_1)(\dot{\theta}_1^2)\cos(\theta_1) - (m_2)(r_2)(\ddot{\theta}_2)\sin(\theta_2) - (m_2)(r_2)(\dot{\theta}_2^2)\cos(\theta_2) \\
Fky - Fhy = (m_2)(l_1)(\ddot{\theta}_1)\cos(\theta_1) - (m_2)(l_1)(\dot{\theta}_1^2)\sin(\theta_1) + (m_2)(r_2)(\ddot{\theta}_2)\cos(\theta_2) - (m_2)(r_2)(\dot{\theta}_2^2)\sin(\theta_2) + (m_2)g \\
Fkx(r_2 \sin(\theta_2)) + Fky(r_2 \cos(\theta_2)) + Tk - Fhx[(l_2 - r_2)\sin(\theta_2)] + Fhy[(l_2 - r_2)\cos(\theta_2)] - Th = (l_2)(\ddot{\theta}_2)
\]

**Link 3:**
\[
-Fhx = -(m_3)(l_1)(\ddot{\theta}_1)\sin(\theta_1) - (m_3)(l_1)(\dot{\theta}_1^2)\cos(\theta_1) - (m_3)(l_2)(\ddot{\theta}_2)\sin(\theta_2) - (m_3)(l_2)(\dot{\theta}_2^2)\cos(\theta_2) - (m_3)(r_3)(\ddot{\theta}_3)\sin(\theta_3) - (m_3)(r_3)(\dot{\theta}_3^2)\cos(\theta_3)
\]
\[
F_{hy} = (m_3)(l_1)(\ddot{\theta}_1)\cos(\theta_1) - (m_3)(l_1)(\dot{\theta}_1^2)\sin(\theta_1) + (m_3)(l_2)(\ddot{\theta}_2)\cos(\theta_2) - (m_3)(l_2)(\dot{\theta}_2^2)\sin(\theta_2) + (m_3)(r_3)(\ddot{\theta}_3)\cos(\theta_3) - (m_3)(r_3)(\dot{\theta}_3^2)\sin(\theta_3) + (m_3)g \quad [8]
\]

\[-F_{hx}(r_3\sin(\theta_3)) - F_{hy}(r_3\cos(\theta_3)) + Th = (l_3)(\ddot{\theta}_3) \quad [9]\]

**Point Mass Model**

The point mass model represented the series of links as a single point mass. This allowed for the ground reaction forces acting on the system’s point of contact with the ground to be determined. The horizontal and vertical components of the ground reaction force were found through the application of Newton’s Second Law on the subject’s center of mass. The positional data was used as an input to then calculate the acceleration of the center of mass of the system. This acceleration was then used to attain the ground reaction forces. The point mass model did not allow for the calculation of internal forces and torques; however, it provided a simple case to verify ground reaction force calculations using the inverse dynamic analysis.

**Three-Link Model**

The subject is modeled as a three-link system, where the links are the shank, thigh, and torso. Figure 2 depicts the three-link human model with the forces and torques acting on the subject. Equations of motion (EOMs) were developed for the three bar linkage model by summing the forces acting on the system and setting them equal to the product of the mass and the acceleration of each link's center of mass. This resulted in the horizontal and vertical components of the forces in each joint. The sum of the moments of each link were then set equal to the derivative of the angular momentum of each link providing three more equations. This totaled nine equations overall, three for each link. Angular position, velocity, and acceleration data was then used as the inputs to these EOMs. MATLAB was then implemented to calculate the unknown forces and torques of the subject at each frame.

**Results and Validation:**

**Point Mass Model**

The output of the point mass model MATLAB code was the horizontal and vertical components of the ground reaction forces. Figure 3 displays the horizontal and vertical components of the ground reaction force for a squat.
The blue line in figure 3 depicts the calculated horizontal component of the ground reaction force. The force plate data does not validate the horizontal ground reaction force components; however, it was expected that the horizontal component is to be minimal because the squat being performed had a much greater vertical motion than horizontal motion. The green line in figure 3 represents the calculated vertical component of the ground reaction force acting on the subject’s center of mass. The red line in the figure shows the experimental data from the force plate for the squat. As shown, the force plate data closely overlaps the point mass model calculation. This verified that the point mass model produced an accurate representation of the ground reaction forces for the squat. The increase in the calculated data from zero to 0.2 seconds resulted from the filtering of the video capture data. The squat was not performed until after this section of data, therefore this data was neglected, as it served no purpose to the research.

**Three-Link Model**

The outputs of the multi-link model were internal forces and torques. Figure 4 displays the ground reaction forces that were calculated using the three-link model. As in figure 3, the blue and green lines represent the horizontal and vertical components of the ground reaction force, respectively. The red line shows the experimental data acquired from the force plate.

![Figure 3: Point Mass Calculated Ground Reaction Forces versus Force Plate Data](image)

The blue line in figure 3 depicts the calculated horizontal component of the ground reaction force. The force plate data does not validate the horizontal ground reaction force components; however, it was expected that the horizontal component is to be minimal because the squat being performed had a much greater vertical motion than horizontal motion. The green line in figure 3 represents the calculated vertical component of the ground reaction force acting on the subject’s center of mass. The red line in the figure shows the experimental data from the force plate for the squat. As shown, the force plate data closely overlaps the point mass model calculation. This verified that the point mass model produced an accurate representation of the ground reaction forces for the squat. The increase in the calculated data from zero to 0.2 seconds resulted from the filtering of the video capture data. The squat was not performed until after this section of data, therefore this data was neglected, as it served no purpose to the research.

**Three-Link Model**

The outputs of the multi-link model were internal forces and torques. Figure 4 displays the ground reaction forces that were calculated using the three-link model. As in figure 3, the blue and green lines represent the horizontal and vertical components of the ground reaction force, respectively. The red line shows the experimental data acquired from the force plate.
As shown in figure 4, the calculated vertical component of the ground reaction force was a less accurate representation of the force plate data than in the point mass model. The horizontal ground reaction force also increases to a larger magnitude, which is different than the calculated values from the point mass model.

To calculate the torques resulting from muscle actuation, the internal forces at each joint were also calculated. Figure 5 depicts the calculated internal forces that acted on the knee and hip. Most of these internal forces remained within realistic values. However, some appear larger than what may realistically occur.
Figure 5: Three-Link Calculated Internal Forces

Figure 6 shows the torques at the ankle, knee, and hip. These torques were the result of the subject’s muscle actuation. The torques at each joint were the main output from the three-link model. They provided insight to the motion of the subject.

Figure 6: Three-Link Calculated Internal Torques
Conclusions and Recommendations:

The point mass model provided a measurement tool for the accuracy of the video capture and inverse dynamic methods. Motion was captured on a force plate and then compared to the vertical component of the ground reaction force found using the point mass model. This model was determined to be accurate but had limitations with the amount of information that could be derived from it. The point mass model does not determine the internal forces and torques at each joint. The three-link model was determined to be less accurate based on the ground reaction force data. Also, internal torques reaching up to 5,000 Nm was intuitively unrealistic. However, this model has room for refinement and improvement.

There is a need to further validate the three-link MATLAB code. Simple position cases must be used to determine the accuracy of the three-link model. Simple cases have only begun to be implemented into the code and have not yet yielded results. An example of a simple case used to validate the code was entering position data of a model in the upright position with all angles equal to 90°. This position data was used in place of the position data outputted from the video capture system code. Simple cases allow for the ability to validate the MATLAB code because the results of the simple cases can be easily calculated and compared to the MATLAB calculation.

There were several sources of error present which are to be resolved. The markers were attached by elastic bands that made it possible for slight vibration to occur during the subject’s motion. If the movement was abrupt the markers bounced slightly as a result. Also, the video camera is a possible source of error. Increasing the sampling rate, or the frame rate of the camera, would intuitively create more accurate positional data because of diminished blurring of markers at each frame. If the subject’s motion occurs too rapidly then the camera does not attain clear images of the markers at individual frames. Rather, motion blur occurs at low enough frame rates. Motion blur may also be attributed to the camera not being perfectly fixed while motion is being captured. If the camera is not completely fixed then any external force applied to it will cause vibration of the camera during video capturing. It is unclear how much the frame rate or video resolution affected the accuracy of the position data. For future investigations, there is a need to improve the method of marking the joint locations to determine the magnitude which frame rate and resolution affect the accuracy of the data collected. Furthermore, if the camera’s frame of capture is not perfectly parallel to the subject’s plane of motion then the magnitudes of the positional data can become slightly skewed due to the method of having the user select a known, fixed distance which is used to calibrate the number of frames per this distance. Resolving the video capture system issues is a challenge which is currently being undertaken.

Future Research and Limitations:

The long-term goal of this process is to attain the ability to analyze a broad range of human motion and determine the impact of such motion through the calculation of the internal forces and torques. Some examples of the types of human motion that could be analyzed in the future are gait analysis for prosthetic patients, sports performance analysis, and low-gravity locomotion. The video capture and three-link model currently limits analysis to a two-dimensional system. This prevents the understanding of what is actually occurring within the joints during any movement. For example, while walking, there is a limited amount of side-to-side motion, as well as rotation, in a subject’s joints. The video capture system will be evolved to a three-dimensional system which will improve the capabilities and accuracy of
the model. Obtaining accurate results will allow the research to progress and develop a multi-link model capable of analyzing any number of links. This will provide the means to analyze more complicated systems as well. Furthermore, the current equations of motion limit the analysis of the model to a three link model which is fixed to the ground. The EOM’s are to be improved upon to allow analysis of motion where a subject’s feet leave the ground. This will allow the human motion being analyzed to progress from a squat to a gait or jump. The research is constantly evolving and the results attained provide promising possibilities for what is to come.
Appendix

Nomenclature:
Link 1 – Shank (Link between ankle and knee)
Link 2 – Thigh (Link between knee and hip)
Link 3 – Torso (Link between hip and shoulder)
m1 – Mass of shank
m2 – Mass of thigh
m3 – Mass of torso
l1 – Length of shank
l2 – Length of thigh
l3 – Length of torso
g – Gravitational constant
r1 – Length from ankle to center of mass of shank
r2 – Length from knee to center of mass of thigh
r3 – Length from hip to center of mass of torso
θ1 – Angular position of shank
θ2 – Angular position of thigh
θ3 – Angular position of torso
\dot{θ}1 – Angular velocity of shank
\dot{θ}2 – Angular velocity of thigh
\dot{θ}3 – Angular velocity of torso
\ddot{θ}1 – Angular acceleration of shank
\ddot{θ}2 – Angular acceleration of thigh
\ddot{θ}3 – Angular acceleration of torso
I1 – Mass moment of inertia of shank (modeled as a thin cylindrical rod)
I2 – Mass moment of inertia of thigh (modeled as a thin cylindrical rod)
I3 – Mass moment of inertia of torso (modeled as a thin cylindrical rod)
GRFx – Horizontal component of ground reaction force (force acting on ankle)
GRFy – Vertical component of ground reaction force (force acting on ankle)
Ta – Torque acting on ankle
Fkx – Horizontal component of force acting on knee
Fky – Vertical component of force acting on knee
Tk – Torque acting on knee
Fhx – Horizontal component of force acting on hip
Fhy – Vertical component of force acting on hip
Th – Torque acting on hip