1. Cover

In this presentation I am going to discuss some of the common technology used in gait and motion analysis which is used in orthopedic research as a tool to help diagnosis, to plan mechanical aspects of treatment, to evaluate the mechanical outcomes of therapy, to design, apply and adjust prosthetic and orthodic orthopedic devices and the like.

1. Outline

In this speech I will discuss the subsystems of a typical gait analysis system.

1. Overview

There are many devices used in medicine to help doctors utilizing cutting edge technology and engineering principles like many modalities of medical imaging, rehabilitation devices, surgery robots, etc. Gait and motion analysis systems are a similar device.

Most of the system hardware utilizes electronics engineering.

Mechanics is used to reconstruct motion of the subject on computer, evaluation of joint angles, computation of joint reaction forces and moments about the anatomical axes. Just mechanically it is not possible to calculate individual muscle forces from the calculated joint moments. Joint moment is the resultant of moments of individual muscle forces. Long story short, you add two or more unknown numbers and you know the sum only. The numbers can be anything. However there are techniques utilizing methods beyond pure mechanics to estimate individual muscle forces which are clinically significant. Similarly there is ongoing research on estimating how the gait may change based on certain changes in muscle forces or in point of application of muscle forces.

There is a great deal of software some visible like the user interface or some in background like the running codes that do the biomechanical computations, storing, retrieving, classifying subject data. There is ongoing research in machine learning, less operator intervention and automated analysis, assisting in diagnosis, data mining and the like.

1. Major Subsystems

The subsystems of a gait analysis system may be classified in many ways. One example is based on the discipline like the one in previous slide, electronics, mechanics and software. However here I am going to use a different classification:

The kinematic subsystem, sometimes termed as motion capture is one major part that detects the motion of the subject.

The kinetic subsystem measures ground reaction forces through which the joint reaction forces and moments and even mechanical power generated by each individual joint is producing can be calculated.

There is a biomechanical model of the subject, based on this model the kinematic and kinetic quantities are evaluated. Here I would like to discuss so called “mathematical modelling” which is used extensively in engineering to predict the behavior by utilizing mathematical formula. In addition to nature being not so simple, some systems that are modelled do not have deterministic behavior. In gait analysis we are lucky that in kinematics, body obeys simple geometric equations and in kinetics it obeys Newton-Euler equations which are exact under everyday conditions. However human body in gait is not a simple structure to model by mathematical equations. Therefore certain simplifications and idealizations are necessary to obtain tractable equations. Some very common simplifications are, body segments like thigh or shank are rigid (i.e. does not change shape under the forces), hip joint is a spherical joint etc. If these simplifications reflect the real system accurately then the predictions of the mathematical model is expected to reflect the behavior accurately. However if over-simplifications exist then the predictions of the mathematical model will be different than the physical system.

Finally there are auxiliary systems like the computer which controls the hardware, collects data, does computations and present result that are clinically meaningful and stores the data. There may be devices for calibration, joint center estimation etc.

1. Kinematic Systems

The kinematic or sometimes called motion capture systems are traditionally multi-camera based (sometimes called opto-electronic) systems with markers. However markerless systems are getting more widespread with the advancing technology which removes the burden for instrumenting the subject.

With the development of micro electro-mechanical systems (MEMS), the inertial measurement units (IMU) became an alternative to multi-camera systems.

Actually any device that can detect the position of a point in three dimensional space or position of a point on a rigid body and orientation of the body in three dimensional space can serve for a kinematic system. There are such few devices in market.

1. Multi-camera Systems

All multi-camera systems rely on two-eye sight. The traditional systems have infrared light sources around camera lenses that light retro-reflective passive markers. The markers reflect this infrared light back to the lens. The filter in front of the lens permits only infrared light therefore two dimensional camera images of the markers are obtained.

Although two cameras are sufficient to obtain three dimensional position of a point most systems have more than two cameras because of two reasons:

* At any instant each marker has to be seen by at least two cameras but the subject may occlude some markers
* If a marker is seen by more than two cameras then the accuracy of the estimated position of the marker is improved. This is very valuable because the accuracy of kinematic data is not very good. The inaccuracy in kinematic data affects kinetic computations as well.
1. Multi-camera Systems

Estimation of three dimensional position of a point by two non-parallel cameras is simple in principle. The object should be on a line normal to image plane of the camera. If you have such two (or more) normals, ideally these normals should intersect at the location of the marker which can be calculated easily if the cameras are pre-calibrated. However in real life it is not that simple, the normals mostly do not intersect due to imperfections. The midpoint of the shortest line segment between two normals may be a good candidate for the location of the marker.

When three cameras can see the marker then there will be three normals. Ideally they should intersect at a point where the marker is. However in real applications most likely they will not. Taking two at a time and finding three candidate points as in the case of two cameras will form a triangle and its centroid is a good candidate for the location of the marker.

If four cameras see the marker then four points will form a tetrahedron (triangular pyramid) whose centroid is a good candidate for the location of the marker.

As can be deduced, for random errors in camera images, utilizing more images reduce this error and improve accuracy of estimation of marker location.

To be able to perform the procedure described in the previous slide the locations of markers in every camera should be matched in every frame shot by that camera which is called temporal matching (matching in time). The markers must be matched across all cameras as well. Since many markers are used, practical problems like more than one marker being aligned on a single camera normal, reflections from other objects, camera noise etc. makes computation of three dimensional position of markers a challenging task.

When marker positions in three dimensional space is computed, they can be reconstructed on computer. However this is not the end of the story. What is available is only the positions of the markers in three dimensional space, not the body segments.

Each body segment (like the pelvis, thigh and shank) can uniquely be defined by three non-collinear markers on that segment. It is possible that two segments may share a single common marker if the biomechanical model permits. Therefore number of markers may be reduced.

For this typical model pelvis is defined by the uppermost three markers. Thigh is defined by hip joint center virtual marker which I will discuss later, the mid marker and the knee marker which is shared by thigh and shank. For shank, the knee, mid and ankle markers define its position. From this information the gait of the subject can be reconstructed on computer and all kinematic quantities like joint angles about anatomical axes may be computed.

1. Markerless

Rather than instrumenting the subject, depending on the biomechanical model certain anatomical points may be automatically detected on camera images, can be used as markers to trace and three dimensional coordinates may be obtained the same way.

Whether marker based or markerless, utilizing high speed cameras not only gait but all sorts of high speed activities including sports, injury, vehicle crash can be analyzed kinematically.

1. IMU

Although camera based systems are wide spread, inertial measurement units (IMU) the sensors of many inertial navigations systems (INS) is getting very popular in motion capture. The major raw data measured by an inertial measurement unit is not the position of a point but its second time rate, the acceleration. Therefore an IMU measures three components of acceleration in its own coordinate system. Theoretically, by knowing the initial linear velocity vector and initial position, measured acceleration can be integrated (mostly numerically) twice to obtain the current position which is equivalent to marker position data. However inertial measurement units measure the three components of angular velocity as well from which orientation change can be obtained.

Like all measuring devices, inertial measurement units do not measure exact values. They also have a drift. When integrated twice, these cause considerable differences in estimated position and orientation of the body in time. Most inertial measurement units also measure direction of gravity (that is vertical) and with a magnetometer the magnetic north to complement data and utilizing various algorithms the position and orientation accuracy is improved. In this session a gait analysis system prototype utilizing inertial measurement units is presented so I will not go into details of it.

12 Others

One interesting motion capture system is ultrasonic. By measuring the travel time of ultrasound, distances are calculated. Utilizing many distances, the locations of markers in three dimensional space can be computed similar to opto-electronic systems.

13 Kinetic Systems

The other major part of gait analysis is determination of forces, or kinetics.

14. Kinetic

In theory if motion is known then the forces that cause the motion or the reactions due to that motion can be determined using Newton-Euler equations. What is interesting is, if motion is known, the unknown forces are algebraic unknowns in equations therefore the solution is relatively easy. The other problem of mechanics is known forces, determination of the resulting motion where the unknowns, position, velocity and acceleration are time derivatives therefore the equations are not algebraic but differential in unknowns therefore harder to solve compared to known motion problems.

So, known motion, the forces can be determined mathematically, why do we need to measure ground reaction forces?

During gait the double support phases are indeterminate. In other words although we can calculate the ground reaction forces using mathematical equations, this is the resultant of left and right feet during double support. We cannot individually get left and right foot ground reaction forces therefore the corresponding ankle, knee and hip joint forces and moments during double support. That is why ground reaction forces need to be measured.

By using ground reaction forces and instant position and acceleration of the body, Newton-Euler equations yield the joint reaction forces and moments for ankle, knee and hip. I would like to stress out that in kinetic equations kinematic values are necessary as well. Therefore any inaccuracy in kinematics would contribute to error accumulation in kinetics and it is not uncommon that people find fictitious forces on the torso!

15. Force Plates

Force plate is an enhanced bathroom scale! It not only measures the weight but the point it is applied as well.

Most typical force plates measure three components of the resultant force vector and three components of moment with respect to its local coordinate system. In some other force plates some of these six quantities may not be measured. Therefore a bathroom scale is a singe axis force plate if you like.

There are two major technologies that are used in measuring forces. The first one is deformation of elastic materials is proportional to the force on it, Hooke’s law. This deformation is measured using electric resistance strain gauges, where the resistance change is proportional to deformation. Resistance change is converted into a potential difference by utilizing certain electric circuits like the Whetstone bridge therefore finally force can be measured by the electric potential difference that is the voltage.

16.

The other technology to measure force is piezoelectric action. Again force causes piezoelectric material to deform. Deformation of the piezoelectric material causes charge production proportional to deformation therefore force so force is measured by the amount of charge production. There are certain conditions where a strain gauge based transducer may be more suitable or piezoelectric transducer more suitable but I will omit these details.

17. Pressure Mats

There are also pressure mats. These mats are a combination of miniature bathroom scales each measure weight in a limited area. One clinically very important output, which is not available in force plates is the information of distribution of force. Therefore a pressure mat can be used as a three axis force plate to estimate center of pressure however it lacks two shear force components the antero-posterior one that produces forward motion and the medio-lateral one. Further, it does not measure the twist moment. Therefore a pressure mat does not supply necessary information for a three dimensional kinetic gait analysis.

18. Software Estimation

Force measurement needs extra equipment and sometimes laboratory environment. With markerless camera systems or inertial measurement units kinematic measurements are not laboratory bound any more however for kinetics the need for a force plate is still very restrictive. These two pioneering articles followed by others are promising for kinetic estimations without measurements. Therefore we are moving from laboratory environment to everyday environment.

19 Biomechanical Models

Biomechanical model is the mathematical representation of human body on computer. This is a graphical representation of a typical multi-camera passive marker model. The governing equations are omitted.

Before the experiment the subject is equipped with so called joint centering devices with grey markers in addition to black markers for gait and a static shot at anatomical position is taken. Using joint centering devices the knee and ankle joint centers which I will discuss in more detail later are determined. For hip joint center a regression equation is utilized that uses various antropometric measurements. Therefore the three white virtual markers inside the body, the hip, knee and ankle joint centers are determined.

Using dynamic testing and virtual markers technical coordinate systems in red are constructed. Static shot was in anatomical position and by keeping the relative orientation of anatomical coordinate system of each segment during gait constant relative to the technical coordinate system of the same segment anatomical coordinates are obtained. Kinematic and kinetic quantities in anatomical coordinate systems are clinically meaningful therefore all results are presented in anatomical coordinates.

20.

A typical joint (hip, knee and ankle) is mostly represented by three successive rotations in many systems. Therefore the intersection of the rotation axes is accepted as the joint center which I will discuss more. Each rotation of this joint in anatomical axis corresponds to say flection-extension, abduction-adduction and internal and external rotation. The joint moments are obtained around the same axes like flection moment, abduction moment, internal rotation moment.

21. Aux

Depending on the system there may be different auxiliary systems. The typical ones I will present are calibration apparatus for kinematic system and joint center estimation devices.

22. Calibration

Some opto-electronic systems may require linearization for optical distortions of the lens. Many modern cameras eliminate this need. To obtain three dimensional position of the markers in laboratory space a calibration before every experiment may be needed if cameras are not fixed. This calibration may be static like in the figure with markers of known coordinates or static and dynamic where in dynamic calibration a rod having two markers at a fixed distance or three markers at known relative positions are moved within the calibration volume. For fixed camera systems calibration may be less frequent or for other systems self calibration may be possible. The inertial measurement unit or the kinetic measurement systems mostly do not require regular calibration.

23. Joint Center Estimation

In many of the gait analysis systems the hip, knee and ankle joints are modeled by three rotations, about three fixed anatomical axes and translations are ignored. Further, some systems simplify knee as a hinge joint with just flection extension motion. Therefore estimation of the hinge axis or joint center accurately is important. Please see the motion of the rotation axis for the knee model. It is evident that there is no single joint center for knee and ankle, even the hip where the head of the femur is not a perfect sphere.

Theoretically, by measuring relative motion of the shank with respect to thigh, the instantaneous location of rotation axis as well as the joint translations can be obtained and this is often done in research. However many clinical systems do not possess this high accuracy to obtain small displacement of knee joint therefore translations are ignored. Further, some systems do not use centering devices which accelerates the experimental protocol however the computed joint center is less accurate than determined by joint centering devices.

24 Take Home

Therefore in gait and motion analysis the subject is human and people who would use the results are medical doctors. However many of the data acquisition and processing are engineering. Therefore for an efficient gait analysis medical doctors and engineers should collaborate.

25 Thank You