2.1 Kinematic and Dynamic Analysis of Motion

To be able to use joint moments as design parameters in the development of new lower limbs, effective methodologies for their recording and analysis have to be in place. Before the implementation of computerized motion analysis systems like Peak, Vicon, and others (Hirsch 2000), the computation of joint moments required tremendous efforts and was extremely time-consuming. The current terms motion analysis and gait analysis relate to specialized hardware and software for collecting, processing, and analyzing kinematic and dynamic parameters of locomotion. Let us consider the structure of this methodology, its capability, and limitations.

The French astronomer Pierre Janssen may have suggested the use of cinematography in investigating locomotion; but it was first used scientifically by Etienne Marey (1830–1904), who first correlated ground reaction forces with movement and pioneered modern motion analysis (Fischer 1895). Marey used a camera with a device that recorded movements on one photographic plate. His pictures primarily concerned his studies of the human body in motion, where the subjects wore black suits with metal strips or white lines, and they passed in front of black backdrops (Fig. 2.1).

In Germany, Wilhelm Braune and Otto Fischer (Braune and Fischer 1987) significantly improved the technique using recent advances in engineering mechanics (Kobrinskiy et al. 1958). In the 1930s in Russia, Nikolas Bernstein in his scientific polemic against Braune and Fischer stressed the need for detailed investigation of the multiple contributions to locomotion from different levels of motor control. He did not filter the kinematic and dynamic characteristics of human motion; rather, he interpreted the deviations from smooth graphs not as noise, but as part of the message from the complex system of organization of motion. He built the first model of hierarchy in motor control, which led eventually to the creation of the first prosthetic arm with biofeedback at the Central Institute of Prosthetics in Moscow (Bernstein 1967).

The works by Bernstein and his school provided worldwide inspiration in the field of prosthetic studies and attracted renowned specialists in engineering, mathematics, electronics, and cybernetics (Bernstein 1948, 1961). However, with regard to the motion analysis data as a gate to the inner chambers of motor control, Bernstein’s ideas are still waiting for implementation. Nowadays, diagrams with a multitude of spikes
Fig. 2.1 Marey’s “Motion Capture” suit
2.1 Kinematic and Dynamic Analysis of Motion

Fig. 2.2 Vertical (above) and horizontal (below) components of the total force applied to the body center of mass during gait (Bernstein 1967)

(Fig. 2.2), which had a great deal of meaning to Bernstein, are made smooth again. The manufacturers of the motion analysis systems incorporate different filtering models to their software as default parameters, as there is no demand for the raw data that Bernstein would admire.

Advancements in prosthetics would be more notable if some of Bernstein’s ideas could be implemented. The most promising, as we believe, would be his probabilistic approach to the organization of goal-directed motion. Our theory of spectral optimization in locomotion (Chap. 6) was inspired by Bernstein’s works.

Kinematic data from cinematography and ground reactions serve as an input for the mathematical model of a polylinker, which simulates a human body. The output of the model includes forces and moments applied to the segments of this polylinker. The mathematical model consists of a system of differential equations of the inverse problem of mechanics. The system depends on the number of the links, and on the conventions regarding their connection with each other. In addition, several assumptions have to be made about the geometry of mass. In most algorithms, free-body diagrams are built and calculation of forces and moments begins from the bottom up for every segment, starting with the foot (Meglan and Todd 1994). The resultant force \( \vec{F}_r \) applied to the joint can be determined from the equation

\[
\vec{F}_r = m \ddot{a} - mg - \sum_{i=1}^{n_j} \vec{F}_{ij} - \sum_{i=1}^{n_e} \vec{F}_{ei}
\]

where \( m \) is the mass of the segment, \( \bar{g} \) the acceleration due to gravity, \( \ddot{a} \) the acceleration of translation of the segment, \( \vec{F}_{ij} \) the forces acting on the segment from \( n_j \) joints connected to this joint, and \( \vec{F}_{ei} \) are the external forces applied to the segment. The resultant moment \( \vec{M}_r \) acting on the segment is determined from (2.2):

\[
\vec{M}_r = \vec{J} - \sum_{j=1}^{n_j} \vec{M}_{ji} - \sum_{i=1}^{n_j} \vec{P}_{ij} \times \vec{F}_{ij} - \sum_{j=1}^{n_e} \vec{M}_{ej} - \sum_{j=1}^{n_e} \vec{P}_{ei} \times \vec{F}_{ei} - \vec{P}_r \times \vec{F}_r
\]

where the components of the vector
J = \begin{bmatrix}
I_{xx}\alpha_x + (I_{zz} - I_{yy})\omega_y\omega_z \\
I_{yy}\alpha_y + (I_{xx} - I_{zz})\omega_z\omega_x \\
I_{zz}\alpha_z + (I_{xx} - I_{yy})\omega_x\omega_y
\end{bmatrix}

are formed by the segment’s angular velocities, angular accelerations, and the components of the main moment of inertia \((I_{xx}, I_{yy}, I_{zz})\); \(\bar{M}_{ji}\) is the moment applied to the joints connected to this segment; \(\bar{M}_{ei}\) the moment acting on the segment from the outside; the vector products \(\bar{P}_{ji} \times \vec{F}_{ji}\) are the moments applied to the joints; and the vectors \(\bar{P}_{ji}\) describe the position of the joints in a coordinate system attached to the segment.

### 2.2 Modeling the Human Body for Motion Analysis

Computerized motion analysis systems include a software package for customizing the model of the moving object under investigation. The moving object can either be a body part or a “man–device” system. A “device” can be a shoe, clothes, athletic equipment, prosthesis, and other pieces of the environment. Every such model requires a specific placement of the markers on the subject’s body and on the “device.” There are also standardized schematics for the markers’ placement, which decrease the needed time of the trial, and also allow for more realizable comparison of the results from different trials and different laboratories.

A systematic following of the Marey method of representing the human body with a stick figure has led to a series of conventions about the number of the markers and their positioning on a subject. The most popular is a schematic developed at the Helen Hayes Hospital, West Haverstraw, New York (Kadaba et al. 1989, 1990) shown in (Fig. 2.3).

To customize the model for a specific subject, his/her anthropomorphic parameters (body mass, height, length of arms, legs, etc.) have to be added to the list of the averaged statistical data (Elftman 1938).

### 2.3 Equipment for Motion Analysis

Equipment of the biomechanical laboratory may include among other components:

1. Video-based motion analysis system(s)
2. Force plate(s)
3. Pressure measurement system(s)
4. Instrumentation for EMG

Video cameras are attached to the walls or a ceiling, and the force plates are mounted within the walkway. Video cameras capture images with a frequency in the range of 50–500 Hz; the computerized procedure allows the 3-D coordinates of the reflective
markers to be calculated on a time scale. Using a body model selected by the researcher, the motion analysis system calculates joint angles, velocities, accelerations, temporal data, and other kinematic characteristics.

The force plate design is similar to piezoelectric or tensometric scales. Their prototype is the force plate introduced by Elftman (Antonsson and Mann 1985; Gillespie and Dickey 2003). The signal from the force plates is synchronized with the video camera images and completes (2.1)–(2.2).

In force measurement, Kistler\(^1\) sensors use the piezoelectric effect directly. The quartz sensor element generates a measurement signal proportional to the force applied. In a slightly modified form, torque or strain can also be measured directly (Rossi et al. 1995).

If a spatial force of unknown direction is applied, only a three-component sensor is capable of detecting the total force simultaneously. This is done in the form of the three

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\(^1\)Sensor manufacturer.
orthogonal components $F_x$, $F_y$, and $F_z$. For this type of measurement, the piezoelectric sensor is preferable. Special sensors, similar in form to load washers, are used for measuring torque. The sensor measures the moment vector parallel to its own axis. The value of the torque measured always relates to the origin of the coordinate system.

The ability to measure the components of the ground reaction vector and its moment relative to all three coordinate axes makes force plates a necessary part of the equipment of a gait laboratory (Kerrigan et al. 1998).

Portable Force Plates with built-in amps 9286AA can be mounted within a walkway, which is installed on a regular floor. Kistler Force plates can be integrated with almost all motion analysis systems used in a biomechanics laboratory. If used independently, Kistler Force Plates should be operated with the *BioWare* data acquisition and analysis software package for research.

In combination with data from force plates, the motion analysis system calculates ground reactions, forces, and moments in anatomical and prosthetic joints. The multi-component ground reaction forces and moment recordings cannot be obtained with pressure measurement systems like Tekscan, where only normal forces are generated. However, pressure measurement system records pressures and forces between stump and socket and between foot and ground, and therefore plays an important role in prosthetics research.

### 2.4 Architecture of Computerized Gait Analysis

The Motion Capture industry has made extensive advancements over the years since the early days of digitizing video data. Today, 3-D data is available in real time and can be used in a wide range of applications\(^2\) (Isakov et al. 2000).

The subject comes into a laboratory and has some basic physical measurements taken before the markers are placed on the person in the appropriate locations to conform to protocol of testing for that day. A static trial is captured and some additional information is recorded by the software. The person then goes through the dynamic trials that were decided by the managing group or physician, and the kinematic and kinetic data are collected. The 3-D data and analog data can all be seen on the screen instantaneously as the subject moves in the capture volume using Vicon Software. The data are also collected on the computer and processed further in seconds. A report with all the results of the test can be available in a few minutes after the data are collected. These data include a complete text window with the subject’s physical exam information, temporal parameters, notes, and hyperlinks. A color video of the subject can also be shown alongside the 3-D workspace with a rendered skeleton or other mesh. The complete set of kinematic and kinetic variables are also available on graphs. Other information can be added to the report like digital photos, X-rays, links to html, and data from other devices like Oxygen Consumption

\(^1\)Kistler Instrument Corp, Amherst, NY.
\(^2\)Information about Vicon Motion Analysis System is a courtesy of Vicon, Inc., www.vicon.com
2.4 Architecture of Computerized Gait Analysis

Systems, Pressure Pads or plates, etc. This complete multimedia report can be exported to as a viewer report and can be then displayed on any computer. The comments and interpretation can be added later to complete the report.

The basic steps for 3-D gait analysis as summarized in a chart (Fig. 2.4) are:

1. Correct marker placement (see Fig. 2.3)
2. Capture of camera data
3. Conversion of 2-D data into labeled 3-D marker coordinates
4. Application of a biomechanically appropriate model to convert marker data to segment data
5. Restructuring this data to the body’s own internal reference frame
6. Normalization of data
7. Selection of relevant outputs, angles, forces, moments, etc.
8. Authoring of a report with the data presented in an easily accessible format

**Fig. 2.4** Schematic of computerized gait analysis. Input – video signal and ground reactions. Output – kinematic and dynamic parameters of gait
The steps, from capture through biomechanical modeling and normalizing to time and the body’s own reference frame, are all done automatically by the workstation. The data may be displayed graphically with suitable annotation or it may be shown in the rendered workspace. This report can be saved or a template made for instant import of subsequent patient data. This can then be distributed as a self-contained document. Example screen grabs from a Vicon Polygon report are shown in (Fig. 2.5).

Markers used with the Vicon 3-D System are small, lightweight, and do not require any wires that could get twisted up during data collection. The Vicon Software automatically identifies the markers on the subject or objects and outputs the data in real time and can be collected offline. The Vicon System can also be synchronized with force plates, EMG, or other analog components (Zajac et al. 2003; Simon 2004). This allows for kinematics and kinetics to be calculated by the software. A digital video camera can also be synchronized with the Vicon data to have a visual reference of the data collected.

2.5 Interpretation of Gait Analysis Results

Interpretation of the results of computerized gait analysis requires clinical experience, and clear understanding of the method’s limitations (Pitkin 2009). An important limitation

![Golf Swing Analysis](image)

**Fig. 2.5** An example screen grabs from a Vicon Polygon report on sports performance (courtesy of Vicon, Inc.)
derives from the inaccuracy of a stick-figure modeling the subjects’ body and building this stick-figure from the markers’ coordinates. While the video cameras allow for 0.1 mm of precision in determining the markers’ position within the 2D frame, a manifold error is apparent in placing markers on the subject. That is why, to increase the reliability of the conclusions, it is better to rely on data obtained in the same laboratory. Reliability is greatest if a study is designed in a way that it uses data from the same subject with unchanged position of the markers for all trials within the session: for example, if one compares gait with and without an orthopedic device.

Standardized report templates that are part of a system software package usually contain extra information not linked to the specifics of a particular study. At the same time, the templates may not display data, which are important for the study. Therefore, the format of the report has to be discussed along with the study design and before the study begins.

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