Kinetics and Kinetic Measurement Techniques

Kinetics Theory
Force Measurement
Pressure Measurement

Kinetics

Physics
Mechanics
Statics
Dynamics
Kinematics
Kinetics

Other areas of physics

Kinetics: branch of dynamics which deals with the forces and moments (torques) that cause motion

Role of Kinetic Analysis in Biomechanics

• Kinetic data by themselves may provide useful information about a human movement
  – A particular pathology may produce characteristic changes in force production profiles
  – Ground reaction forces are related to motion of the whole body center of mass

• Some kinetic quantities can be measured directly, but others must be derived by combining multiple data sources
  – Inverse dynamics (kinematic & kinetic data)

Kinetic Measurement

Force Transducer

• A device for converting a force measure into an electrical signal (voltage) that is proportional to the applied force
• Typically based on very small deformations of object to which force is applied

Two major technologies:
  – Strain gauges
  – Piezoelectric crystals

Kinetics

All kinetic analyses of human movement are based upon the linear and angular forms of Newton’s second law:

\[ \Sigma F = m \ a \]
\[ \Sigma M = I \ a \]
**Kinetic Measurement**

- Strain gauges form the basis for many commercial force transducers
  - AMTI and Bertec force platforms
  - S-shaped load cells (hydrostatic weighing)
  - Load arm in some isokinetic dynamometers
- Can be applied almost anywhere for custom force measurement applications
  - Force sensing bicycle pedals
  - Instrumented starting blocks
  - Instrumented canes or other assistive devices

**Piezoelectric transducers**

- Based on piezoelectric effect discovered by Curie brothers (1880’s)
- Certain crystals (e.g. quartz) develop electrical charge on surface when loaded (caused by minute deformation in the atomic structure)
- Magnitude of electrical charge is proportional to applied load

**Kistler (Switzerland) is the major commercial source for piezoelectric-based force transducers (force platforms and other load measuring devices)**

- These plates most commonly tell us 3D forces and center of pressure location

**Center of Pressure (COP)**

- The force under the foot doesn’t actually act at a single point, but is distributed
- The COP is the point about which the distributed forces balance, or the point about which \( \sum F_y d_i = 0 \)

**Force Platforms**

- A simplified view of COP calculation:

  \[
  \begin{align*}
  M_X &= -(F_Y \times P_Z) \\
  M_Z &= F_Y \times P_X
  \\
  so \quad P_X &= \frac{M_Z}{F_Y} \\
  P_Z &= -\frac{M_X}{F_Y}
  \end{align*}
  \]

  Note: \( P_y \) is the fixed distance from plate surface to the origin

**Force Platform Uses**

- Investigating functional asymmetry: Gait is typically asymmetrical, but why? Causes may include morphology, footedness, environment, and/or other neuromuscular factors

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**Images:****

- Image of a shoe with force sensors.
- Diagram showing the center of pressure (COP).
- Graphs illustrating vertical, anterior/posterior, and medial/lateral ground reaction forces.
### Force Platform Uses

**Investigating functional asymmetry:**
Gait is typically asymmetrical, but why? Causes may include morphology, footedness, environment, and/or other neuromuscular factors.

#### Walking Speed

<table>
<thead>
<tr>
<th>Walking Speed</th>
<th>Impulse due to APGRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow</td>
<td></td>
</tr>
<tr>
<td>Preferred</td>
<td></td>
</tr>
<tr>
<td>Fast</td>
<td></td>
</tr>
</tbody>
</table>

#### Data

- Non-dominant
- Dominant

*The barefoot professor*

### Force Platform Uses

**During walking, COP begins near the heel and then progresses anteriorly throughout stance:** we have used this to better understand chronic ankle instability.

### Force Platform Limitations

- Force platforms are powerful measurement tools in human movement analysis with many applications in several fields of study.
  - **Limitations:**
    - Gives net result on COM only (possible to accelerate one arm up and the other arm down, with change in ground reaction force)
    - Doesn’t measure pressure distribution - only resultant force as if concentrated at one point
    - Proper size is hard to define (too big vs too small)
    - More than one plate typically needed ($$)
    - Difficult to do field research

### Kinetic Data Processing

**It is often informative to calculate the time derivative of a kinetic quantity like ground reaction force; load rate (LR) is measured in N/s.**

This is done by dividing the change in force by the change in time:

\[ LR = \frac{\Delta VGRF}{\Delta t} \]
Kinetic Data Processing

• At other times, it is more helpful to integrate a force profile with respect to time
• Implementation:
  – Integration of a force with respect to time can be done using the “trapezoidal method”

Numerical Integration

The integral
\[ A = \int F \, dt \]
of force (F) with respect to time (t) gives the area under the force-time curve, and represents the impulse of that force.

Numerical Integration

During “constant-speed” running, the area \( A_1 \) must be equal to area \( A_2 \)
In other words, the propulsive impulse must be equal and opposite to the braking impulse
The integral must therefore be zero over the gait cycle

Numerical Integration

For the trapezoid at left, \( a \) equals the sampled value at \( t_1 \), \( b \) equals the sampled value at \( t_2 \), and \( h \) equals the interval between samples \((h = 1/\text{SR})\)

For a periodic function, errors will cancel out

Numerical Integration

Given the following force values (sampled at 100 Hz) calculate the impulse over the first 0.05 seconds:

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>125</td>
</tr>
<tr>
<td>0.01</td>
<td>234</td>
</tr>
<tr>
<td>0.02</td>
<td>345</td>
</tr>
<tr>
<td>0.03</td>
<td>107</td>
</tr>
<tr>
<td>0.04</td>
<td>-203</td>
</tr>
<tr>
<td>0.05</td>
<td>314</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
A_{t_1-t_2} &= \frac{1}{2} (125 + 234) \times 0.01 = 1.80 \\
A_{t_2-t_3} &= \frac{1}{2} (234 + 345) \times 0.01 = 2.90 \\
A_{t_3-t_4} &= \frac{1}{2} (345 + 107) \times 0.01 = 2.26 \\
A_{t_4-t_5} &= \frac{1}{2} (107 - 203) \times 0.01 = -0.48 \\
A_{t_5-t_6} &= \frac{1}{2} (-203 + 314) \times 0.01 = 0.56
\end{align*}
\]
Numerical Integration

Given the following force values (sampled at 100 Hz) calculate the impulse over the first 0.05 seconds:

<table>
<thead>
<tr>
<th>Time</th>
<th>Force</th>
<th>Interval</th>
<th>Area</th>
<th>Impulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$</td>
<td>125 N</td>
<td>–</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$t_2$</td>
<td>234 N</td>
<td>1.80</td>
<td>1.80</td>
<td>1.80</td>
</tr>
<tr>
<td>$t_3$</td>
<td>345 N</td>
<td>2.90</td>
<td>4.70</td>
<td>4.70</td>
</tr>
<tr>
<td>$t_4$</td>
<td>107 N</td>
<td>2.26</td>
<td>6.96</td>
<td>6.96</td>
</tr>
<tr>
<td>$t_5$</td>
<td>-203 N</td>
<td>-0.48</td>
<td>6.48</td>
<td>6.48</td>
</tr>
<tr>
<td>$t_6$</td>
<td>314 N</td>
<td>0.56</td>
<td>7.04</td>
<td>7.04</td>
</tr>
</tbody>
</table>

After 0.05 seconds, the impulse generated by the force was 7.04 N·s

Numerical Integration

What does an impulse that equals 7.04 N·s produce:

Remembering the impulse momentum relationship, $F \Delta t = m \Delta v$

An impulse of 7.04 N·s, could result in a change of velocity of 0.10 m/s for a 70-kg individual.

Numerical Integration

Other applications

- Can be used to calculate mechanical work
  
  $W = \int F \cdot dr$

- Can be used with angular kinetic quantities
  
  - Integrate joint moment with respect to time or joint angular displacement

- Can be used with kinematic quantities
  
  - Integrate acceleration to get velocity or integrate velocity to get displacement
  
  $v = \int a \, dt \quad d = \int v \, dt$

Pressure

Pressure is force divided by the area of force application

$$P = \frac{F}{A} \quad \text{units are Pascal (1 Pa = 1 N/m}^2)$$

If pressure is chronically too high, injury may result

- Patella-femoral pain
- Diabetic ulcers

Pressures Measurement

Generally involves creating a matrix of force sensors with high spatial resolution

Many possible technologies can be used, but a couple are most common:

- Capacitance sensors
- Pressure-sensitive films

Pressure Measurement

Capacitance Sensors

- A sandwich of conductive (e.g., copper) strips arranged perpendicular to each other in two sheets, separated by a non-conductive elastic material

- Resolution increases with number of metal strips

- However, more strips requires more cables
Pressure Measurement

Capacitance Sensors
- Each intersection serves as a capacitor and forms a single force/pressure element
- e.g., resolution for insoles is currently 4 sensors/cm²
- Application of load compresses non-conductive material, which changes local capacitance in proportion to load

Pressure Measurement

Conductor Sensors
- Very similar in construction to capacitive sensors
- As force is applied, resistance of material changes

Piezoceramic Sensors
- An array of piezoelectric transducers are fixed in a sheet or mat
- Each sensor provided an independent force/pressure reading

Pressure Measurement

Pressure Sensitive Film (Fuji foil)
- Microcapsules containing a color producing agent and a color sensitive layer, between two thin sheets
- Application of force causes capsules to rupture onto color sensitive layer
- Intensity is proportional to peak local pressure
- Very thin, can be used to make pressure measurements in tight spaces such as joints
- Only gives peak pressure, and no timing information

Pressure Measurement

In-shoe Devices
- Typically based on capacitive sensors
- Allows measurement between foot and shoe
- Some questions about reliability/validity
- Vendors:
  - Novel (EMED)
  - Tekscan (F-Scan)

Pressure Measurement

Cycling Research

Pressure - Applications

Cycling Research:
MRI Seat Loading Device

Bressel, Reeve, & Parker (2008)
Pressure - Applications
Diabetic Foot Ulcers
- Development of plantar surface ulcers believed to be related to local regions of high pressure
- Special shoes can be designed to alleviate pressure in a specific area, but pressure pattern must be know

Pressure - Applications
Wheelchair Seat Design
- Individuals with quadriplegia or paraplegia have little or no sensation below waist
- Can lead to pressure sores at interface with wheelchair seat
- Pressure mats can be used to assess distribution of pressure on seat

Pressure - Applications
Joint Loading
- Fuji pressure sensitive film can be placed in cadaver or artificial joints
- New capacitive sensors from Novel & Tekscan can be used for same purpose
- Allows measurement of dynamic pressure within a joint

Pressure - Applications
Prosthetic-Stump Interface
- New sensors from Novel & Tekscan (capacitive) can be used to measure pressure at the stump-socket interface in amputees

Pressure Measurement - Limitations
- Only provides pressure due to normal forces
  - Shear forces may actually be more important in many situations
  - Devices to measure shear forces not readily available from commercial sources
- Measurement devices can have limited flexibility (e.g. a single sized pressure mat)
- Portable (in-shoe) devices can encumber the subject with many cables

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