An Instrumented Step Beyond Gait Speed

Carolynn Patten, Ph.D., PT
Ilse Jonkers, Ph.D., PT
Marilynn Wyatt, M.A., PT
Steven A. Kautz, Ph.D.

Stroke Intervention Studies
gait speed as primary outcome

• Westlake et al 2009
• Hidler et al 2009
• Buurke et al 2008
• Yen et al 2008
• Hornby et al 2008
• Dias et al 2007
• Sullivan et al 2007
• Plummer et al 2007
• Duncan et al 2007
• Tong et al 2006
• Peurala et al 2005
• Ech et al 2004
• Ada et al 2003
• Barbeau et al 2003
• Sullivan et al 2002
• Werner et al 2002
• Koski et al 2000
• Pohl et al 2002
• Da Cunha Filho et al 2002
• Lauffer Y et al 2001
• Nilsson et al 2001
• Dean CM et al 2000
• Liston R et al 2000
• Visentin et al 1998
• Hesse et al 1995
• Richards et al 1993
• Malouin et al 1991

Life’s Burning Questions

• How important is gait speed?
• Does walking better necessarily mean walking faster?

Order of Events

• Introductions & Overview
• What is instrumented gait analysis?
• Translation from observational gait analysis to instrumented measures
  — Kinematics
  — Kinetics
  — EMG
• Case Studies – pathological gait
• Stroke outcomes post-intervention I
• Stroke outcomes post-intervention II
• Discussion & Questions
GENERAL ASPECTS OF GAIT: TERMINOLOGY

Gait Cycle
Walking involves repetitive patterns of movement resulting in each foot periodically moving from one position of support to the next. These movements are cyclical in nature. Therefore, we can describe gait based on one unit of this cycle. Therefore, when describing human gait it is conventional to do so in terms of the gait cycle. As the moment of floor contact is the most readily defined event in the sequence of movements that is walking, this action is conventionally chosen to mark the beginning of the gait cycle. Any event in the cycle could be chosen. A complete gait cycle or stride begins when one foot strikes the ground and ends when the same foot strikes the ground again.

The gait cycle is divided into two major phases, STANCE PHASE and SWING PHASE (Fig 1).
- **STANCE PHASE** is defined as the period of time when the foot is in contact with the ground. It begins with initial contact, which in normal gait is with the heel and ends at toe off when swing phase begins.
- **SWING PHASE** is defined as the period of time when the foot is not in contact with the ground. It occurs from toe off until the foot hits the ground again.

If we define the period of time for a complete gait cycle as 100% (normalisation), then, each of these events in the gait cycle is defined sequentially as occurring in specific percentages of the cycle. **Initial contact** is defined as occurring at 0% and 100% of the gait cycle. During normal walking, **toe off** occurs at approximately 60% of the cycle. Therefore, **stance phase** represents approximately 60% and **swing phase** 40% of the cycle.

During walking there are two periods of double support when both feet are on the ground. Each of these periods constitutes about 10% of the cycle.

The **first period of double support** is referred to as **LOADING RESPONSE** and is a period of deceleration when the shock of impact is absorbed and body weight is transferred from one lower limb to the other.

This is followed by a period of **single stance, SINGLE SUPPORT**, occupying about 40% of the cycle, during which the opposite limb is going through a swing phase. In walking, **single support** on the stance side must be equal to the period of swing of the opposite limb. The period of **single stance** can be sub-divided into mid stance and terminal stance:
- **MID STANCE** occurs from 10% to 30% of the gait cycle and is a period of body progression over a stable foot. Stability of the lower limb is an
important feature of this phase. In normal gait it ends when the body weight is aligned over the forefoot.

- **TERMINAL STANCE** occurs from 30% to 50% of the gait cycle, beginning with **heel rise** and ending with **initial contact** of the contralateral limb. During this phase the body weight is progressed beyond the supporting foot.

In stance, **the second period of double support** is called **PRE SWING**. It begins at about 50% of the gait cycle and lasts until **toe off the stance side**. **Pre swing** of the ipsilateral stance limb is equivalent to **loading response** on the contralateral (opposite) limb and is equal in time. During pre swing the limb moves from a position of general extension into flexion, and, although a stance phase, it is functionally important for limb advancement by preparing the limb for swing.

**Toe off** marks the beginning of the **SWING PHASE** of walking. **Swing** is generally divided into three phases:

- **Initial swing** occurs from 60% to 73% of the cycle and is a period of limb advancement and clearance of the foot. It begins when the foot is lifted from the floor and ends when the swinging foot is opposite the stance foot.
- **Mid-swing** occurs from 73% to 87% of the cycle and ends when the swinging limb is forward and the tibia is vertical with the main functional objectives again being foot clearance and limb advancement.
- **Terminal swing** is the final phase of the gait cycle and is a period of deceleration and preparation for next ground contact.

All of these phases and events of a single gait cycle normally occur during a period of just over one second.

Further characterisation of human walking can be done with **distance or spatial measurements** such as **step length** and **stride length** and when these are combined with temporal measures parameters such as **walking velocity** and **cadence** can be defined.

**Step length** is defined as the longitudinal distance between the two feet generally expressed in meters (m). It is the distance from a point of contact of one foot with the ground to the following occurrence of the same point of contact of the other foot with the ground. In normal walking **the right step length** is defined as the distance measured from heel strike of the left foot to heel strike of the right foot. The **left step length** is defined as the distance measured from heel strike of the right foot to heel strike of the left foot.

**Step time** is the time taken for one step and is measured as the period of time from an event of one foot to the following same event of the other foot, expressed in seconds (s).
**Stride length** is the distance covered during a complete gait cycle and represents the sum of the right and left step lengths. Stated differently, it extends from the initial contact of one foot to the following initial contact of the same foot.

**Step width** is defined as the mediolateral distance between the feet.

**Cadence** is the number of steps taken during a given amount of time, usually steps per minute.

**Walking velocity** is expressed as a distance over time relationship, such as m/sec or m/min and is the rate of change of linear displacement along the direction of progression measured over one or more strides. A child and an adult can walk at the same velocity but the child has a shorter stride and therefore a faster cadence. Walking velocity is generally constant after about age 5 or 6. However as the lower extremities grow longer, step length increases and cadence slows. This continues until growth is complete.

**Natural walking velocity** is the velocity of walking which is voluntarily assumed and is generally the most efficient in terms of energy consumption for that particular person.

**Figure 1.**
Figure 2

\[ \text{Stridlength} = \text{Right step} + \text{Left step} \]
What is Motion Analysis?

- Study of Human Movement:
  - Motion Analysis
    - Human movement science
    - Head, arm, trunk
    - Throwing
    - Spine
    - Sports – swimming, cycling, golf swing
  - Gait Analysis
    - Measurement of walking
    - Measurement of running

Elements of instrumented Gait Analysis

- Kinematics
  - Measurement of motion

- Kinetics
  - Measurement of forces and moments

- Dynamic or Kinesiological EMG
  - Measurement of muscle activity during motion

- Energetics
  - Measurement of energy expenditure or mechanical work

Gait Analysis Team

- Multidisciplinary Approach:
  - Gait Analysis Laboratory Team
    - Research Physical Therapist
    - Kinesiologist/Biomechanist
    - Bioengineer
    - Applied Physiologist
  - Physicians
    - Physical Medicine and Rehabilitation
    - Orthopedic Surgeons
    - Residents/interns
  - Physical Therapists
  - Prosthetists

Gait Analysis Applications

Provide reliable and repeatable data for:

- Clinical Decision Making
- Research
  - Clinical Outcomes
  - Basic Science
- Teaching
  - Biomechanics

NMCSD Biomechanics Laboratory

- 720 sq ft space
- 12 Camera Real-Time Motion Capture System
  - Motion Analysis Corporation
  - Four Force Platforms Embedded in Walkway
  - AMTI
- 2 Video Cameras Synchronized with Motion Capture System
  - Canon XHA1
- Telemetered EMG System
  - Motosim Lab Systems, Inc.
  - Surface & Fine-wire Capability
Kinematics

• 30 reflective markers placed over anatomical landmarks.
• 3-D coordinates of joint centers and segments calculated to produce model.

Kinematics Graph

Gait Cycle

- Period of Time
- Initial contact
  - Reference side foot
- Subsequent ground contact
  - Same foot
- Total gait cycle
  - Normalized
  - 0-100%

Gait Cycle

- Phases
  - Stance
    - Foot on the ground
    - 0-60%
  - Swing
    - Foot off the ground
    - 60-100%
- Events
  - Initial Contact
  - Toe-Off
  - Initial Contact

Knee Flex/Extension

% Gait Cycle

Ext. / Flex

0 20 40 60 80 100
Time/Distance Parameters

- Velocity (cm/sec)
- Cadence (steps/minute)
- Stride Length (cm)
- Step Length (cm)
- Step Width (cm)
- Single Support Time (% of cycle)
- Double Support Time (% of cycle)
- Toe-Off Time

Gait-Rite

Kinetics

- Study of the forces that cause the observed motion of the body
- Measured with Force Platforms

Force Plates

- 4 AMTI force platforms embedded in the floor

Kinetics

- Measures 3 components of force (X,Y,Z)
  - Vertical force
  - Fore-Aft Shear
  - Medial Lateral Shear
**Kinetics**

- Normal vertical force curve
- Normalized to % body weight
- Measured during stance phase of the gait cycle

**Dynamic EMG**

- Kinesiological EMG
  - Interest in muscle firing patterns during activity
  - Surface
    - Group muscle activity
  - Fine-Wire
    - Specific muscle activity
    - Place fine wires into the muscle of interest

**EMG Electrodes**

- Technology
  - Provides reliable and repeatable measurements
- Clinical Application
  - Interpret Data
  - Clinical Judgment
  - Enhances
  - Does not replace!
Take home message...

- Instrumented gait analysis is a reliable and repeatable measure of human movement
- Gait analysis data adds a quantitative piece to the clinical picture
  - Enhances the treatment of the patient
  - Does not replace clinical judgment
- Provides a tool to support clinical research
  - Provides data that can be used to measure outcomes of treatment
    - Therapy
    - Surgery
    - Prosthetic devices or adjustments

THANK YOU!
Describing normal gait

Ilse Jonkers, PT, PhD

Describing normal gait:
Spatiotemporal parameters

Spatiotemporal parameters
Kinematics
Kinetics
EMG

Gait Cycle

Phases & Events

"A complete gait cycle or stride begins when one foot strikes the ground and ends when the same foot strikes the ground again."
Stance - "the period of time when the foot is in contact with the ground"
Swing - "the period of time when the foot is not in contact with the ground"

**Phases & Events**

**Stance**
- Initial Contact
- Single limb support 10%
  - Loading response
  - Mid Stance 10-30%
  - Terminal Stance 30-50%
  - Pre-swing
  - Initial swing 10-30%
  - Med swing 30-50%
  - Terminal swing

**Swing**
- Toe Off
- Opposite toe off 50%
  - Opposite foot contact 50%
  - Single limb support 40%
  - Double Limb 10%

**LEUVEN**

CSP, San Diego 2010
--- ONE GAIT CYCLE ---

**STANCE** 60%  **SWING** 40%

<table>
<thead>
<tr>
<th>Initial contact</th>
<th>Loading response</th>
<th>Mid Stance 10-30%</th>
<th>Terminal Stance 30-50%</th>
<th>Pre-swing 50-70%</th>
<th>Initial swing 50-70%</th>
<th>Med swing 73-87%</th>
<th>Terminal swing 30-50%</th>
</tr>
</thead>
</table>

**Movie walking: sagittal plane**

---

**Stride & Step Lengths**

**Stride Length**

**Left Step** + **Right Step**

- **Right Step Length**
- **Stride Length**
- **Left Step Length**

---

**Step Width**

**Normal**

- **Step width**

---

**Cadence/Walking Velocity**

**Cadence = number of steps/time (steps/minute)**

- 8 steps
- 4 strides
- 5 ms
- 4 secs

**Cadence = 120 steps per min**

**Walking velocity = distance/time (m/sec)**

- 8 steps
- 4 strides
- 5 ms
- 4 secs

**Cadence = 120 steps per min**

**Cycle time = 1 sec**

**Stride length = 1.25 m**

**Velocity = 1.25 metres per second**
Describing normal gait
subtitle of Kinematics presentation

From motion to graph

From motion to graph

Sagittal Plane Kinematics

Ankle
Knee Flexion - Extension

Hip Flexion-Extension

Pelvis

Pelvic Tilt

Sagittal Plane Kinematics

Frontal Plane Kinematics

Pelvis - Hip
Frontal Plane Kinematics

Transverse Plane Kinematics

Transverse Plane Kinematics

Transverse Plane Kinematics

Kinetics - moments

Describing normal gait

Kinetics
**Moment = Force * Distance**

Cave! Simplification! Inertial Forces (Accelerations)

Internal Moments versus External Moments

Knee Moment

External Knee Flexing
Internal Knee Extensor

Deceleration Acceleration

Anterior-Posterior Force relates to the horizontal acceleration of the COM

Medio-Lateral Force Limited Amplitude
Power = angular velocity * moment

Dorsiflexion

Plantarflexion

(°)

Plantarflexing/Dorsiflexor Moment

Dorsiflexing/Plantarflexor Moment

Ankle Moment

Hip Moment

Knee Moment

Frontal Plane: Hip & Knee

Kinetics

Ankle Power

Knee Power

Hip Power
Describing normal gait

subtitle of EMG presentation

Tibialis Anterior
Soleus
Gastrocnemius

Ankle

Hip

Gmax
RF
BFlh

IC LR Mst Tst Psw Isw Msw Tsw

IC LR Mst Tst Psw Isw Msw Tsw
Knee

Thank you for your attention

Questions?
CASE STUDIES
PATIENTS WITH AMPUTATION

Marilynn Wyatt, MA, PT
Biomechanics Laboratory
Naval Medical Center San Diego

Clinical Case Studies

• Time/Distance Parameters
  - Sensitive measure of gait
    • Velocity
    • Cadence
    • Stride length
  - Sensitive measure of gait symmetry
    • Single stance
    • Step length

Time/Distance Parameters

• NB
• DX: Delayed trans-tibial amputation, Right
• Initial gait study 1 week after walking without assistive device

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>6 Weeks</th>
<th>6 Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (cm/s)</td>
<td>118</td>
<td>126</td>
<td>134</td>
</tr>
<tr>
<td>Cadence (steps/min)</td>
<td>103</td>
<td>108</td>
<td>107</td>
</tr>
<tr>
<td>Stride Length (cm)</td>
<td>138</td>
<td>137</td>
<td>120</td>
</tr>
<tr>
<td>Step Length (cm) Right</td>
<td>84</td>
<td>79</td>
<td>77</td>
</tr>
<tr>
<td>Step Length (cm) Left</td>
<td>73</td>
<td>74</td>
<td>73</td>
</tr>
<tr>
<td>Single Stance, Right</td>
<td>32</td>
<td>35</td>
<td>36</td>
</tr>
<tr>
<td>Single Stance, Left</td>
<td>37</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>Step Width</td>
<td>18</td>
<td>14</td>
<td>11</td>
</tr>
</tbody>
</table>

Case Study: CL

• 24 yo active-duty soldier
• Unilateral trans-tibial amputation, Right
• Delayed amputation
• Evaluated in Gait Analysis Laboratory at 9 months walking with or without an assistive device as part of his routine medical care
• Functional community level ambulator and has progressed to running
• With no complaints

CL - Kinematics

• Lack of full knee extension at initial contact
• Lack of knee extension in mid-stance
CL – Kinematic Comparison

- Prosthetic adjustment
- Improved knee extension at initial contact and mid-stance
  - 6 degree improvement at initial contact
  - 5 degree improvement at mid-stance
- Patient instantly felt his mechanics were better

CL – Time Distance Parameters

<table>
<thead>
<tr>
<th></th>
<th>Study 1</th>
<th>Study 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (cm/s)</td>
<td>149</td>
<td>157</td>
</tr>
<tr>
<td>Cadence (steps/min)</td>
<td>113</td>
<td>113</td>
</tr>
<tr>
<td>Stride Length (cm)</td>
<td>156</td>
<td>166</td>
</tr>
<tr>
<td>Step Length (cm) Right</td>
<td>79</td>
<td>86</td>
</tr>
<tr>
<td>Step Length (cm) Left</td>
<td>79</td>
<td>83</td>
</tr>
<tr>
<td>Single Stance, Right</td>
<td>39</td>
<td>37</td>
</tr>
<tr>
<td>Single Stance, Left</td>
<td>39</td>
<td>40</td>
</tr>
<tr>
<td>Step Width</td>
<td>11.7</td>
<td>10.8</td>
</tr>
</tbody>
</table>

CL- Study 2

- 22 yo active-duty marine
- s/p Blast Injury
- DX:
  - Trans-tibial amputation, Right
  - Common Peroneal Nerve Palsy, Left

CLL – Kinematics (3 Months)

- Right
  - Increased hip abduction in stance
  - Diminished peak knee flexion in swing
- Left
  - Drop Foot
  - Lack of dorsiflexion in swing
  - Lack of heel strike at initial contact
Recommendations:

- Continue Physical Therapy Program
- Continue Left AFO
- Repeat gait study

### Time Distance Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>3 Months</th>
<th>12 Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (cm/s)</td>
<td>103</td>
<td>136</td>
</tr>
<tr>
<td>Cadence (steps/min)</td>
<td>95</td>
<td>108</td>
</tr>
<tr>
<td>Single Stance, Right (cm)</td>
<td>133</td>
<td>152</td>
</tr>
<tr>
<td>Step Length (cm) Right</td>
<td>67</td>
<td>82</td>
</tr>
<tr>
<td>Step Length (cm) Left</td>
<td>63</td>
<td>70</td>
</tr>
<tr>
<td>Single Stance, Left (cm)</td>
<td>39</td>
<td>36</td>
</tr>
<tr>
<td>Step Width</td>
<td>18</td>
<td>14</td>
</tr>
</tbody>
</table>

**CLL (3 Months)**

**CLL (12 Months)**
Case Study: RP

- 23 yo active-duty soldier
- s/p Blast Injury
- DX:
  - Bilateral Trans-femoral amputations
- Prosthesis:
  - Bilateral C-Legs

Findings
- Wide based gait/increased hip abduction
- Diminished knee flexion in swing

Recommendations:
- Continue PT
- Repeat gait study in 6 months

<table>
<thead>
<tr>
<th>Time Distance Parameters</th>
<th>RP</th>
<th>Baseline</th>
<th>6 Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (cm/s)</td>
<td>65</td>
<td>94</td>
<td></td>
</tr>
<tr>
<td>Cadence (steps/min)</td>
<td>81</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>Stance Length (cm)</td>
<td>98</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>Step Length (cm) Right</td>
<td>54</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>Step Length (cm) Left</td>
<td>43</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Single Stance, Right</td>
<td>35</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Single Stance, Left</td>
<td>35</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Step Width</td>
<td>36</td>
<td>26</td>
<td></td>
</tr>
</tbody>
</table>

RP - Kinematics

Left
- Knee Flexion
- Hip Abduction

Right
- Knee Flexion
- Hip Abduction