Quantitative Gait Analysis: Techniques and their Challenges

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Outline

What is Motion Analysis

Kinematics
Kinetics
Gait Analysis (Case Studies)

Instruments

Kinematics
Kinetics
Electromyography

New Frontiers

Musculoskeletal Modelling
Markerless
Inertial Sensors
What is gait analysis?
Outline

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- Markerless
- Inertial Sensors
Motion Analysis is the Definition of the Position & Orientation in any given instant of time of:

- specific points
- body segments
- the whole body
Background – What is Motion Analysis

Kinematics: Definition of the Position & Orientation in any given instant of time during the execution of a task
Kinematics: Definition of the Position & Orientation in any given instant of time
Of a body segment during the execution of a task
We need to substitute a complex morphology with a simple one

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**Kinematics:** Not only position but also orientation of the local, relative to the global, frame and is referred to as the orientation matrix

\[
\theta_{cd}^p = \theta_{cd}^p n_{cd} = \begin{bmatrix}
\theta_{cdx}^p & \theta_{cdy}^p & \theta_{cdz}^p
\end{bmatrix}
\]

\[
\theta_{cd}^p = \begin{bmatrix}
\cos\theta_{x_p} & \cos\theta_{y_p} & \cos\theta_{z_p} \\
\cos\theta_{y_p} & \cos\theta_{z_p} & \cos\theta_{x_p} \\
\cos\theta_{z_p} & \cos\theta_{x_p} & \cos\theta_{y_p}
\end{bmatrix}
\]
**Kinematics:** Not only position but also orientation of the local frame relative to the global frame and it is referred to as the orientation matrix.
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Background – Stereophotogrammetry & Kinematics

Stereophotogrammetry: can provide this information
Background – Stereophotogrammetry & Kinematics

Stereophotogrammetry: can provide this information

System Parameters

2D Single Camera Coordinates \( x, y \)

Mathematical Mode (pin hole & triangulation)

3D Coordinates \( X, Y, Z \)
2 Approaches

**Background – Stereophotogrammetry & Kinematics**

Stereophotogrammetry

| simple morphology | markerset |

2 Approaches

| Technical protocol | Anatomical protocol |

Gait & Posture 2005 21, 186-196DOI: (10.1016/j.gaitpost.2004.01.010)
CAST

Technical
Anatomical

CAST (Cappozzo et al 1995)
Background – Stereophotogrammetry & Kinematics

CAST
- Technical
- Anatomical

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Background – Stereophotogrammetry & Kinematics

CAST

Technical Anatomical

CAST (Cappozzo et al 1995)

Gait & Posture 2005 21, 186-196 DOI: (10.1016/j.gaitpost.2004.01.010)
Davis-Helen Hayes (Davis et al 1991)

Technical | Anatomical
---|---
Calf and Thigh wands | Anatomical landmarks
**Background – Stereophotogrammetry & Kinematics**

### Davis-Helen Hayes (Davis et al 1991)

<table>
<thead>
<tr>
<th>Technical</th>
<th>Anatomical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calf and Thigh wands</td>
<td>Anatomical landmarks</td>
</tr>
</tbody>
</table>
Background – Stereophotogrammetry & Kinematics

Ior-Gait (Leardini and Sawacha et al 2007)

<table>
<thead>
<tr>
<th>Technical</th>
<th>Anatomical</th>
</tr>
</thead>
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<tr>
<td>Anatomical Calibration</td>
<td>Anatomical landmarks</td>
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</tbody>
</table>
Background – Stereophotogrammetry & Kinematics
Background – Stereophotogrammetry & Kinematics

Joint Kinematics

<table>
<thead>
<tr>
<th>Technical</th>
<th>Anatomical</th>
</tr>
</thead>
</table>

Joint Reference System

Technical Reference System | Anatomical reference System

Gait & Posture 2005 21, 186-196 DOI: (10.1016/j.gaitpost.2004.01.010)
Background – Joint Kinematics (ISB)

Calibration

Marker & Technical Reference Frame

Local Reference Frame

Reconstruction

Anatomical Landmarks

Local Reference Frame in Global Reference Frame

Background – Stereophotogrammetry & Kinematics

Joint Kinematics

Joint angles

Cardano

\[ \gamma: \text{about distal axis } z \]
\[ \alpha: \text{about distal axis } x \text{ (after the } 1^\circ \text{ rotation)} \]
\[ \beta: \text{about distal axis } y \text{ (after the } 2^\circ \text{ rotation)} \]

With Courtesy of Prof Cappozzo

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**Cardano angles**

Has a functional representation

- flexion-extension (1)
- Abduction-adduction (2)
- Internal-external rotation (3)

**Background – Stereophotogrammetry & Kinematics**

Rotation about the axis $z_{sp}$, femur or pelvis medio-lateral axis

1.  
   \[
   \begin{align*}
   &y_p \\
   &y_{d1} \\
   &y_{d2} \\
   &\gamma
   \end{align*}
   \]

2.  
   Rotation about the axis $x_{sp}$, femur antero-posterior axis

3.  
   Rotation about the axis $x_{sp}$, femur longitudinal axis

*With Courtesy of Prof Cappozzo*

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Cardano angles
Has a functional representation

Grood and Suntay

Background – Stereophotogrammetry & Kinematics

ABDUCTION (+)
FLEXION (+)
ADDUCTION (-)
EXTENSION (-)

EXT. ROTATION (-)
INT. ROTATION (+)

(Grood and Suntay, ASME J.Blonech. 1983)
Background – Errors in Stereophotogrammetry

Instrumental Errors
- Spot-checks proposed in the literature for assessing performance based on inter-marker distance measurements

Anatomical landmark misplacement
- Anatomical Calibration Techniques
- Functional Joints centers locations
- Open Challenge
- *Gait & Posture* 2007 26, 179-185 DOI: (10.1016/j.gaitpost.2007.04.009)

Soft Tissue Artifact
- Multiple Calibration Techniques
- Fluoroscopic Gold Standard
- Compensation algorithms
- Open Challenge
Background – Errors in Stereophotogrammetry

Still an Open Challenge: Dual Fluoroscopy is the actual gold standard

With Courtesy of Prof Cappozzo and Prof Cappello
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Inertial Sensors
**Background – Kinetics**

**Human Kinetics**

- Ground Reaction Forces
- Joint contact Forces

**Internal Forces**

- Ligaments
- Tendon
- Muscle

*With Courtesy of Prof Cappozzo*
Background – Kinetics

Human Kinetics

| Complex Model | Simple Model | Rigid Body |

Internal Forces

| Ligaments | Tendon | Muscle |

With Courtesy of Prof Cappozzo

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Background – Kinetics

WithCourtesy of Prof Cappozzo
Background – Kinetics

\[ \begin{align*}
R + W + \bar{F}_h + \bar{F}_g + \bar{F}_p + \bar{F}_b &= m\bar{a}_{CM} \\
M^K_R + M^K_W + M^K_{F_h} + M^K_{F_g} + M^K_{F_p} + C_b + C_R &= I_K \alpha \\
\end{align*} \]

\[ \begin{align*}
\bar{F}_{is} &= \bar{F}_h + \bar{F}_g + \bar{F}_p + \bar{F}_b \\
C_{is} &= M^K_{F_h} + M^K_{F_g} + M^K_{F_p} + M^K_{F_b} + C_b
\end{align*} \]

\[ \begin{align*}
\bar{R} + \bar{W} + \bar{F}_{is} &= m\bar{a}_{CM} \\
M^K_R + M^K_W + M^K_{F_{is}} + C_{is} + C_R &= I_K \alpha
\end{align*} \]

With Courtesy of Prof Cappozzo
Force Plates:
- Piezoelectric Sensors
- Strain Gage
- Platforms

Variables: 3D Forces, Torque, Center of Pressure

Plantar Pressure Sensors:
- Capacitive
- Resisitive
- Platforms & Insoles

Variables: Pressure, Force, Contact Surface, Center of Pressure

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Background – Electromyography

Muscle tissue conducts electrical potentials

Muscle action potential.

Surface EMG

recording the information present in these muscle action potentials.

Backyard Brains

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Background – Surface Electromyography

Backyard Brains electrodes Ag-AgCl
Background – Surface Electromyography

Motor Unit Action Potential (MUAP)
Background – Surface Electromyography

Motor Unit Action Potential (MUAP)
Background – Surface Electromyography

Surface Emg Probes
Background – Surface Electromyography

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Background – Surface Electromyography
Background – Surface Electromyography

EMG intensity

- **Raw signal**
  - Filters: mechanical artifacts <30 Hz

- **Rectified signal**

- **Envelope**

- **RMS**

Amplitude: 0.10 di mV - 2 mV
Armonic Frequency: 10 Hz - 400 Hz
Background – Surface Electromyography

Artifacts

Raw signal

Interference

EEG artifacts

ECG removal procedures: high-pass filtering (HPF), Butterworth filters with a cut-off frequency of about 30 Hz (Redfern et al., 1993, Drake and Callaghan, 2006).
Prolonged exercise

Decrease of oxygen

Production of lactic acid

Increase of ions H^+

Unbalance of ATP

Accumulation of Ca^+ in myoplasm

Alteration of Ca^+ / Na^+ / K^+ concentration

Decrease of pH

Accumulation of inorganic phosphate

Alteration of transport in SR

Decrease of release from terminal cistern

Change the affinity with troponin

Muscles contraction and release become slower than normal

Mean Frequency of the Power Spectral Density function
Frequency. Electrical Manifestation of Muscle Fatigue: The median frequency of the power spectrum
**Frequency. Electrical Manifestation of Muscle Fatigue:** The median frequency of the power spectrum

- Low Pass Filter (10 e 450 Hz)
- Rectified Signal
- RMS
- Fourier Transform

- Mean frequency (MNF)

- Dimitrov Index

- Instantaneous Mean Frequency (IMNF)

\[
x_{\text{RMS}} = \sqrt{\frac{1}{T} \int_0^T x^2(t) \, dt}
\]

\[
MNF = \frac{\int_{F_1}^{F_2} f \cdot PS(f) \cdot df}{\int_{F_1}^{F_2} PS(f) \cdot df}
\]

\[
F_{I_{\text{nsm}5}} = \frac{\int_{F_1}^{F_2} f^{-1} \cdot PS(f) \cdot df}{\int_{F_1}^{F_2} f^5 PS(f) \cdot df}
\]

\[
IMNF = \frac{\int_{F_1}^{F_2} f \cdot PS_{cw}(t,f) \cdot df}{\int_{F_1}^{F_2} PS_{cw}(t,f) \cdot df}
\]
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Background – Gait Analysis

Why Gait Analysis?
To Fill The Gap between Observation and Quantitative Evaluation
Background – Gait Analysis

![Diagram of gait analysis stages]

- HS (Heel Strike)
- TO (Toe Off)
- MidStance
- MidSwing

Time (% of gait cycle)

Left:
- Double Support
- Single Support

Right:
- Stance (R)
- Swing (R)
- HS

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Background – Gait Analysis

Which Pathologies?

- Diplegia
- Hemiplegia
- Mielomenigocele
- Other
- Norms
- Elderly
- Parkinson
- ACL
- Pregnancy
- Down
Background – Gait Analysis

How?


Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Review

SIAMOC position paper on gait analysis in clinical practice: General requirements, methods and appropriateness. Results of an Italian consensus conference


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Gait Analysis

How@DEI?

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Background – Musculoskeletal Modelling

Musculoskeletal models:
computational models of human body that can be scaled using patient specific data

• Can provide information that cannot be experimentally measured like muscle forces

• Can help in understanding the complexity of the human motion
Background – Musculoskeletal Modelling

Experimental Dataset → Scaling → Inverse Kinematics

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Background – Musculoskeletal Modelling

Inverse Dynamics

Static Optimisation

Muscles Forces
The motion of the model is completely defined by the generalized positions, velocities, and accelerations.

The Static Optimization Tool uses the known motion of the model to solve the equations of motion for the unknown generalized forces.

It minimizes the following objective function:

\[
J = \sum_{m=1}^{nm} (a_m)^p
\]

where \( n \) is the number of muscles in the model;
\( a_m \) is the activation level of muscle \( m \) at a discrete time step;
\( p \) is a user defined constant
Diabetes mellitus is a chronic disease affecting 6.6% of the world population[1]. 15-25% develops an ulcers [1]. Global diabetic foot ulcer prevalence is 6.3% [2].

Diabetic foot leads to ulcerations and amputations. The social and economic burden of diabetic foot calls for Early Preventive Interventions.

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Aim: improve diabetic foot prevention by improving the prediction of diabetic patients @ high risk for plantar ulcers and plantar ulcers location by combining Opensim (static optimization) derived muscle forces estimation - internal stresses - plantar pressure distribution in diabetic subjects
Over **12,000** articles relevant to diabetes and gait, with the annual publication rate rising steadily over the past 2 decades from 165 in 1998 to 924 new publications in 2015 [4-6].

**Recent Evidence** Gait analysis improves Diabetic foot management

---

**Diagram**

- **Presurgical Biomechanical Assessment**
  1. Joint Range of Motion
  3. Gait Analysis (Static & Dynamic)

- **Limb Salvage Procedure**

- **Post-surgical Biomechanical Assessment**
  1. Joint Range of Motion
  3. Gait Analysis (Static & Dynamic)

- **Elective Balancing Procedures**
  1. Tendon Lengthening/Transfers
  2. Bony Reconstruction/Fusion

- **Devices**
  1. Prosthetics
  2. Custom Accommodative and/or Functional Orthotics
  3. Bracing
  4. Custom Molded Shoes

---

Figure 1. General pathway of where the biomechanical examination fits in the environment of limb salvage.

---

Important alterations detectable through Gait analysis & Emg
(more than 150 patients database only @ our Lab 2004-2018)

Foot kinematics, kinetics and plantar pressure

Standard gait analysis (trunk and lower limb)

EMG
Important alterations detectable through Gait analysis: Kinematics
(more than 150 patients database only @ our Lab 2004-2018)

- diabetics,
- controls,
- neuropathics

Sawacha et al. JNER 2009
Integrated Kinematics-Kinetics-Plantar Pressure: Sensors Fusion

Case Study – Diabetic Foot @DEI

Joint Kinematics & Kinetics

Plantar Pressure

Integrated Methodology

• diabetics, controls, neuropathics
  Sawacha et al. Gait Posture 2012

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Integrated Kinematics-Kinetics-Plantar Pressure- Emg: Sensors Fusion

- Emg during Gait
- Emg during Stair negotiation
- Treadmill walking Emg

- diabetics, controls, neuropathics

Sawacha et al. Gait Posture 2012
## Background – Musculoskeletal Modelling

<table>
<thead>
<tr>
<th>Phase</th>
<th>DPN</th>
<th>NoDPN</th>
<th>CS</th>
<th>P</th>
<th>P*</th>
<th>P**</th>
</tr>
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<tbody>
<tr>
<td>IC 0-2% LR 0-10%</td>
<td>5.46</td>
<td>6.82</td>
<td>11.8</td>
<td>N.S.</td>
<td>0.0007</td>
<td>0.0062</td>
</tr>
<tr>
<td>Rectus Femoris</td>
<td>59.6</td>
<td>58.8</td>
<td>60.6</td>
<td>N.S.</td>
<td>N.S.</td>
<td>N.S</td>
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<tr>
<td></td>
<td>(±1.81)</td>
<td>(±1.50)</td>
<td>(±1.62)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tsw 85-100%</td>
<td>91.93</td>
<td>95.89</td>
<td>89.96</td>
<td>N.S.</td>
<td>N.S.</td>
<td>0.0230</td>
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<tr>
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<td>(±2.34)</td>
<td>(±1.43)</td>
<td>(±1.81)</td>
<td></td>
<td></td>
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<tr>
<td>IC 0-2% LR 0-10%</td>
<td>11.71</td>
<td>6.96</td>
<td>9.27</td>
<td>0.0032</td>
<td>N.S.</td>
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<tr>
<td></td>
<td>(±1.13)</td>
<td>(±1.10)</td>
<td>(±1.63)</td>
<td></td>
<td></td>
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<tr>
<td>Tibialis Anterior</td>
<td>75.04</td>
<td>72.75</td>
<td>73.6</td>
<td>N.S.</td>
<td>N.S.</td>
<td>N.S</td>
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<td>PSw 50-60% ISw 60-73%</td>
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<td>(±1.45)</td>
<td>(±2.26)</td>
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<tr>
<td>MSw 70-85% Tsw 85-100%</td>
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<tr>
<td></td>
<td></td>
<td>7.55</td>
<td>11.7</td>
<td>13.2</td>
<td>N.S.</td>
<td>N.S</td>
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<td></td>
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<td>(±2.68)</td>
<td>(±1.87)</td>
<td>(±1.89)</td>
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<td>Gluteus Medius</td>
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<td>96.1</td>
<td>91.6</td>
<td>N.S.</td>
<td>0.0410</td>
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<tr>
<td>Gastrocnemius lateralis</td>
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<td>35.9</td>
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<td>(±1.38)</td>
<td>(±2.29)</td>
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<td>Peroneus Longus</td>
<td>41.81</td>
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<td>33.4</td>
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<td>N.S.</td>
<td>N.S</td>
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<tr>
<td>MSw 10-30% Tst 30-50%</td>
<td>(±0.09)</td>
<td>(±0.11)</td>
<td>(±0.211)</td>
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<tr>
<td>Extensorum Digitorum</td>
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<td>7.72</td>
<td>7.68</td>
<td>N.S.</td>
<td>N.S.</td>
<td>N.S</td>
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<td>ISw 60-73% MSw 70-85%</td>
<td>(±1.63)</td>
<td>(±2.22)</td>
<td>(±4.63)</td>
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<td>67.2</td>
<td>0.0470</td>
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<tr>
<td></td>
<td>(±2.56)</td>
<td>(±3.45)</td>
<td>(±7.25)</td>
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</tr>
</tbody>
</table>
Stair

Posizione del picco di attivazione
Rossi neuropatici
Verdi diabetici
Giallo controlli
Posizione in % fasce ascesa e discesa scala
H=high gradino alto
L=low gradino basso
U=up salita
D down= discesa

Background – Musculoskeletal Modelling

Fig. 1 (continued)
Background – Musculoskeletal Modelling

Treadmill

EMG_TA_L
\[ y = -0.18 \times + 1.9e+002 \]
Dec Perc = 4.25 %

EMG_LGS_L
\[ y = -0.39 \times + 1.7e+002 \]
Dec Perc = 5.38 %

EMG_RF_L
\[ y = -0.36 \times + 1.7e+002 \]
Dec Perc = 4.5 %

EMG_LH_L
\[ y = -0.24 \times + 1.6e+002 \]
Dec Perc = 4.4 %

EMG_VL_L
\[ y = -0.3 \times + 1.3e+002 \]
Dec Perc = 5.0 %

EMG_TA_R
\[ y = -0.26 \times + 1.4e+002 \]
Dec Perc = 7.3 %

EMG_LGS_R
\[ y = -0.49 \times + 1.3e+002 \]
Dec Perc = 12.5 %

EMG_RF_R
\[ y = -0.43 \times + 1.2e+002 \]
Dec Perc = 10.7 %

EMG_LH_R
\[ y = -0.31 \times + 1.5e+002 \]
Dec Perc = 10.9 %

EMG_VL_R
\[ y = -0.31 \times + 1.2e+002 \]
Dec Perc = 0.52 %
Adding the information on quantities that are not directly measurable: Musculoskeletal Modelling and Finite Element Modelling

Possibility of developing subject-specific models starting from the MRI of the subjects [7]

Simulate not directly measurable in-vivo data (e.g., internal stress-strain) [8]

Simulate not directly measurable in-vivo data (e.g., internal stress-strain) [9]

Musculoskeletal Models [10-11]
Very few works combined Diabetic Foot Biomechanics with MSM and didn’t involve diabetic subjects

Gait analysis revealed alterations and there is a relationship between altered gait and plantar ulcers: but only few models considers subject specific boundaries conditions deriving form gait analysis

MSM revealed important alterations in muscle forces and there is a relationship between altered muscles forces and plantar ulcers

Fem revealed important alterations in internal stresses and material properties and there is a relationship between internal stresses and plantar ulcers

Still validation of FEM results against experimentally plantar pressure reveals important discrepancies

Combining Gait Analysis and Musculoskeletal Modelling

Diabetic foot 3D Gait analysis (Sawacha et al 2012)

6DOF & Intrinsic Muscles Foot Musculoskeletal Model (MSM) (Malaquias et al 2017)

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Scarton et al 2017

Diabetes Association recommends:
- Annually if you have diabetes
- Daily if you have neuropathy nerve damage that affects your feet

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Scarton et al 2017
Background – Musculoskeletal Modelling

IK: Kinematics

Pelvic Tilt Angle

Pelvic Obliquity Angle

Pelvic Rotation Angle

Hip Flexion/Extension Angle

Hip Adduction/Abduction Angle

Hip int/ext Rotation Angle

Knee Flexion/Extension Angle

Ankle Dors/Plantarflexion Angle

Subtalar Inversion/Eversion Angle

Legend:
- DPNS
- DPNS mean
- CS
- CS mean

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Background – Musculoskeletal Modelling

IK: Kinetics

Pelvic Tilt Moment

Pelvic Obliquity Moment

Pelvic Rotation Moment

Hip Flexion/Extension Moment

Hip Adduction/Abduction Moment

Hip Int/ext Rotation Moment

Knee Flexion/Extension Moment

Ankle Dorsi/Plantarflexion Moment

Subtalar Inversion/Eversion Moment

\[
\text{[DPNS]} \quad \text{[DPNS mean]} \quad \text{[CS]} \quad \text{[CS mean]}
\]
Background – Musculoskeletal Modelling

SO: Static Optimization
SO: Static Optimization

- Rectus Femoris Force
- Vastus Medialis Force
- Vastus Intermedius Force
- Lateral Gastrocnemius Force
- Gemellus Force
- Soleus Force
- Peroneus Brevis Force
- Peroneus Longus Force
- Tibialis Anterior Force
- Tibialis Posterior Force
- Flexor Digitorum Force
- Flexor Hallucis Force
- Extensor Digitorum Force
- Extensor Hallucis Force
Results suggest that the process of injury in diabetic feet is very likely to initiate not on the skin surface, but in deeper tissue layers.

Prevention programs’ objective should take into account muscle force together with joint angles and moments.
Outline

What is Motion Analysis

- Kinematics
- Kinetics
- Gait Analysis

Instruments

- Kinematics
- Kinetics
- Electromyography

New Frontiers

- Musculoskeletal Modelling
- Markerless
- Inertial Sensors
Markerless Motion capture

synchronized video sequences

segmented mesh model

non-controlled environments

encumbrance reduction

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With Courtesy of E. Ceseracciu

Markerless Motion capture

Silhouette

Visual hull

Model matching

3D surface

With Courtesy of E. Ceseracciu

Markerless Motion capture

Articulated
Iterative Closest Point
algorithm

LOCAL
needs initialization

ITERATIVE
finds pose for each body segment so that model mesh fits visual hull data
distances between corresponding points are minimized

ARTICULATED
segments respect kinematic chain (translation constraints)
INPUT: mesh surface of the subject (laserscan, visual hull...)

ITERATIVE SHAPE-POSE REGISTRATION WITH GENERIC SEGMENTED MODEL

OUTPUT: segmented mesh model with embedded joint centers iterative pose

**Human shape space** *(from database of shapes)*


*With Courtesy of E. Ceseracciu*
Markerless Motion capture
Model generation

With Courtesy of E. Ceseracciu

root of the kinematic chain
Simultaneous Markerless Markerbased
Ceseracciu and Sawacha et al 2014

Marker-based anatomical calibration

Markerless pose estimation

With Courtesy of E. Ceseracciu

for every segment \( s \)

for every segment \( s \), for every instant \( t \)

for all relative anatomical landmarks

relative transformation of technical frames

\[
\begin{bmatrix}
-ML_{R_s} & -ML_{T_s} \\
0 & 0 & 1
\end{bmatrix}^{-1} \cdot
\begin{bmatrix}
MB_{R_s} \\
MB_{T_s}
\end{bmatrix}
\]

\( R \) orientation matrix

\( T \) position vector

marker-based anatomical calibration

\[
AL_{glo} = R(t)_s \cdot AL_{loc} + T(t)_s
\]
Full-body markerset

Clusters of skin markers on pelvis, thighs, shanks

Anatomical calibration

- Pointer: ASIS, PSIS, GT
- Markers: LE, ME, LM, MM, HF, TT

Anatomical landmarks

- CA, IM, IIM, VM, C7,
- L5, RA, LA

1 healthy subject

- Static anatomical calibration
- Static video acquisition
- Markerless
- Technical frames

Protocol

With Courtesy of E. Ceseracciu
Experimental Set up

BTS Smart optoelectronic stereophotogrammetric system
8 cameras (200 Hz)

Grayscale images stored from 6 cameras (100 Hz)
Joint Angles

- **marker-based**
- **markerless**
Markerless In Clinics
Gait Analysis @ X Fragile

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Markerless In Clinics
Gait Analysis @ X Fragile

**Hip Angle Flex/Ext**
- ROM: comparable
- Profile: comparable
- Excessive hip flexion in static

**Knee Angle Flex/Ext**
- ROM: reduced
- Profile: comparable

**Ankle Angle Flex/Ext**
- ROM: comparable
- Profile: comparable

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- Reduced activity and less organized pattern at left distal plantar flexor muscles compared to right side muscles.

- Reduced activity at left proximal knee-hip joints flexor-extensor muscles compared to right side muscles.

- Worst activity at proximal muscles compared to distal muscles.
- Neurologic degenerative disease
- Unknown aetiology
- Reduction in dopaminergic recruiting: Reduced motor cortex stimulation

**NON – MOTOR:**
- Sensitive disturbances
- Bradyphreni
- Fatigability
- Hypomimia
- Poor Balance
- Freezing

**MOTOR:**
- Tremor
- Stiffness
- Bradykinesia
- Festination

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Subjects: 11 PD  age: 70 (+- 5.8)  BMI: 27.8 Kg/m²
9 CS: age 65.85 (+- 7.4)  BMI: 28.62 Kg/m²

**Hydrotherapy:** subjects were asked to walk at self-selected speed, back and forth with a level of immersion on the mamillary line, for 40 minutes on a daily basis at the same time each morning for a total of 3 weeks.

The pool was 8 meters long x 4 meters wide and has a depth, varying from 1.1 meters to 1.50 meters. The water temperature was set at 32 °C.
Markerless In Clinics Gait Analysis @ Parkinson Disease

Experimental set up

- 3D UW and OL gait analysis by means of Iorgait markerset (Leardini et al 2007)
- Emg Electrodes placement according to Blanc et al 2013:
  - Right tiabialis anterior
  - Left tiabialis anterior
  - Right rectus femoris
  - Left rectus femoris
  - Right biceps femoris caput longus
  - Left biceps femoris caput longus
  - Right gastrocnemius lateralis
  - Left gastrocnemius lateralis

UW set up

OL set up

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Do PDs walk differently?

PD T1 OL (blue) CS OL (red).
Markerless In Clinics
Gait Analysis @ Parkinson Disease

Do PDs walk differently UW?

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Do CS walk differently UW?
Results UW vs OL T0

Ankle FE

Knee FE

Hip AA

Hip FE

Ankle FE

Knee FE

Hip AA

Hip FE

UW (blue) OL (red) (*) = p<0.05

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Results: T0 vs T1

Does water buoyancy improve PDs walking?

ankle FE

knee FE

Hip AA

Hip FE

PD T0 UW (blue) PD T1 UW (red) (*) = p<0.05

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TECHNOLOGY: UW gait needs improvement on transversal and coronal planes joints estimation. Artefacts are present OL and even more UW (markerless techniques require at least 9 cameras, not feasible in a clinical settings);

Underwater training seems to be effective in improving the joints ROM and improving stability: the unstable, weightless environment trains the neuro-muscular system, even if debilitated by PD, to better control the body balance and posture, leading to a more stable gait both UW and OL, and may reduce the fall risk.
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Inertial Sensors in gait analysis

Dinua et al 2016

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Inertial Sensors in gait analysis

\[ K_s \cdot x_0 + B \cdot \dot{x}_0 = M \cdot (a_i - \dot{x}_0) \]

\[ \ddot{x}_0 + \frac{B}{M} \cdot \dot{x}_0 + \frac{K_s}{M} \cdot x_0 = a_i \]

\[ G(s) = \frac{X(s)}{A_i(s)} = \frac{G_0}{s^2 + \frac{2\zeta \omega_n s}{\omega_n^2} + 1} \]

Damping ratio \( \zeta = \frac{B}{2\sqrt{K_s \cdot M}} \)

Natural frequency \( \omega_n = \sqrt{\frac{K_s}{M}} \)

\[ G_0 = \frac{1}{\omega_n} = \sqrt{\frac{M}{K_s}} \]
Inertial Sensors in gait analysis

- The spring applies a kinematics along a preferred axis (in the axis of sensitivity)
- Cross-talk must be avoided (cross-axis sensitivity)
- K depends from both spring geometry and material

- Three accelerometers are mounted at right angles to each other, so that acceleration can be measured independently in three axes: X, Y and Z.
- Three gyroscopes are also at right angles to each other, so the angular rate can be measured around each of the acceleration axes.
measurements are summarised as a resultant acceleration and a resultant angular acceleration by the acquisition Frequency
Ex 200 Hz IMU.

Errors

Ripetibility
Turn-on to Turn-on Bias: the signal differs in case of repeated measures

Stability
Same output over time with same input

Drift
Loutput varies over time in static condition
Inertial Sensors in gait analysis

by: Laura Rocchi, DEIS, UNIBO

<table>
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condition 0g, ±1g

CRITICAL !!

Compensation techniques
Inertial Sensors in gait analysis

- MEMS

Functioning principles

- Sensing axis (rotation)
- Rotational velocity of the reference frame (driving axis)
  \[ \Rightarrow \text{The transducer structure is driven orthogonally (Coriolis effect)} \]

The scalar governing equation of motion for a gyroscope device with a resonating mass in the y axis, rotated about the z axis is given by

\[ \ddot{x}_0 + \frac{B}{M} \dot{x}_0 + \frac{K}{M} x_0 = a_{Cor} = 2\Omega_z \cdot y \]

\( \Omega_z \) is the rate of rotation and \( y \) is linear velocity of the structure due to the drive.
Inertial Sensors in gait analysis

More sensors to compensate single sensor technological issues

**General purpose**

Movement analysis (2 examples)

by: Laura Rocchi, DEIS, UNIBO
First in vivo assessment of “Outwalk”: a novel protocol for clinical gait analysis based on inertial and magnetic sensors

Eight Xsens SUs and clusters positioned over the body of a subject. The white box is the Xsens data-logger (called Xbus Master)
Inertial Sensors in gait analysis

14 gait cycles for subject AF, as measured by Outwalk (bright plots) and CAST (dark plots). For each joint-angle, the $CMC_1$ and $CMC_2$ are provided. Since the knee varus–valgus and internal–external rotation will not be considered in the clinical routine due to their low accuracy, they are reported over a gray background.
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