Inertial Measurement Units and their applications for Human Performance Analysis

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E-Just
Limitations of current Skill Training Systems:

<table>
<thead>
<tr>
<th></th>
<th>Reality Trainer</th>
<th>VR Simulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>skill evaluation</td>
<td>subjective</td>
<td>objective (only time, error evaluation)</td>
</tr>
<tr>
<td>objective evaluation system</td>
<td>none</td>
<td>embedded with training systems (cannot be used for other systems)</td>
</tr>
<tr>
<td>used for operation room or clinical treatment</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

Strong needs:
- objective skill evaluation methods both for reality and VR training system
- common skill evaluation methods for various medical training applications
- skill evaluation methods which might be further implemented in real operation room and clinical treatment
Objectives

Develop an Objective Skill Training System

- Objective skill evaluation and quantitative feedback
- Implementation in Reality training, VR training, and operation room
- Assisting clinical diagnosing and treatment
- Common, adaptive for multiple medical applications
Conventional Method (1/2)

Problems:
- subjective scoring by expert, using vague criteria
- No quantitative feedback
Conventional Method (2/2)

Problems:
- low level analysis, without detailed quantitative feedback
- skill analysis system embedded with the training system, which can be used only for that specific training system
Methodology Proposal

Hypothesis:

- This methodology could provide more objective and quantitative information to subjects than conventional methods.
- This methodology can be implemented in regular training, operation room and clinical treatment.
- The evaluation method is separated from training system, which can be extended to various medical fields.
Motion Capture Techniques

- **Measurement**
  - Volume
  - Inertial-based
  - Acoustic-based
  - Electromagnetic-based
  - Inertial-based
  - Camera-based
  - Mechanical-based

- **Accuracy**
  - Inertial-based
  - Camera-based
  - Mechanical-based
  - Acoustic-based

- **Cost**
  - Camera-based

- **Outdoor**
  - Inertial-based
  - Acoustic-based

- **Home**
  - Acoustic-based
  - Inertial-based
  - Camera-based

- **Operation Room**
  - Inertial-based
  - Camera-based

- **Training Room**
  - Inertial-based
  - Camera-based
Optical Capture Systems (2/2)

**Pros**
- Accurate and fast (0.3mm and up to 10,000 fps)
- Not affected by metal
- No electromagnets
- Mature technology
- Flexible placement of markers

**Cons**
- Needs dedicated space
- Not available for portable rental
- Expensive
- Markers need to be reapplied each session
- Expensive, bulky, and not sufficient for measuring small object’s orientation

http://www.inition.co.uk/
Inertial Measurement Units (IMUs) are a very promising frontier on the wearable and reliable Motion Capture system because they can be virtually used everywhere.

**Pros**
- Self-contained
- Cost and reliability (improving)
- Mature technology (sensors)
- Uses Earth’s magnetic field rather than transmitter
- Flexible placement
- Simple calibration

**Cons**
- Size and weight are still critical for some applications
- Affected by metal
- Drift
- Accuracy
- 3dof natively – attitude only
Objectives

- **Realize** an ultra-miniaturized IMU for application where size and weight of the sensor is critical

- **Compare** the performance of the new IMU with Vicon and other commercial systems

- **Verify** that IMU can provide precise and reliable results also in dynamic conditions (RMS error less than 2 Deg)
WB-3 (Waseda Bioinstrumentation ver. 3) (2/2)

![WB-3 Diagram](image)

<table>
<thead>
<tr>
<th>Component</th>
<th>3-Axis Accelerometer</th>
<th>2-axis Gyroscope</th>
<th>1-axis Gyroscope</th>
<th>3-axis Magnetometer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range</strong></td>
<td>±2 g</td>
<td>±500 deg/s</td>
<td>±300 deg/s</td>
<td>±4 Gauss</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>12 bit</td>
<td>12 bit</td>
<td>12 bit</td>
<td>12 bit</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>40 Hz</td>
<td>140 Hz</td>
<td>88 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td><strong>Linearity</strong></td>
<td>±2%</td>
<td>&lt;1%</td>
<td>±0.8%</td>
<td>±0.1%</td>
</tr>
<tr>
<td><strong>Noise level</strong></td>
<td>&lt;1 bit</td>
<td>&lt;2 bit</td>
<td>&lt;1 bit</td>
<td>&lt;1 bit</td>
</tr>
</tbody>
</table>

**WB-4** (**Waseda Bioinstrumentation ver. 4**)
WB-4 (Waseda Bioinstrumentation ver. 4)

Two-layer configuration

WB-4 Wireless IMU (7g)
EKF Quaternion Based (1/5)


EKF Quaternion Based (2/5)

Accelerometer

Gyroscope

\[ \mathbf{u}_k = [\omega_x, \omega_y, \omega_z] \]
\[ \mathbf{z}_k = [a_x, a_y, a_z] \]

Input vector

Measurement vector

\[ \hat{\mathbf{x}}_k = [\hat{q}_0, \hat{q}_1, \hat{q}_2, \hat{q}_3, \hat{b}_{\omega x}, \hat{b}_{\omega y}, \hat{b}_{\omega z}] \]
\[ \hat{\mathbf{x}}_k = [\hat{q}_0, \hat{q}_1, \hat{q}_2, \hat{q}_3, \hat{b}_{\omega x}, \hat{b}_{\omega y}, \hat{b}_{\omega z}] \]

Predicted State vector

Updated State vector

Prediction

Roll-Pitch Update

\[ \mathbf{z}_k \]

Updated State vector

\[ \mathbf{x}_k \]
Prediction step

- State prediction:
  \[ \hat{x}_k = f(x_{k-1}, u_{k-1}) + w_k \]

- Covariance matrix prediction:
  \[ \hat{P}_k = A_{k-1} P_{k-1} A_{k-1}^T + Q_{k-1} \]
EKF Quaternion Based (4/5)

**Correction step**

- Sensor model:

\[
\begin{align*}
\vec{\omega} &= G_g \omega_r + \vec{b}_\omega + \vec{v}_g \\
\vec{a} &= G_a \left[ C_n^b (q)(\vec{g}) \right] + \vec{v}_a
\end{align*}
\]

\[
C_n^b (q) = \begin{bmatrix}
q_1^2 - q_2^2 - q_3^2 + q_4^2 & 2(q_1q_2 + q_3q_4) & 2(q_1q_3 - q_2q_4) \\
2(q_1q_2 - q_3q_4) & -q_1^2 + q_2^2 - q_3^2 + q_4^2 & 2(q_2q_3 + q_1q_4) \\
2(q_1q_3 + q_2q_4) & 2(q_2q_3 - q_1q_4) & -q_1^2 - q_2^2 + q_3^2 + q_4^2
\end{bmatrix}
\]

The acceleration acting on the body is negligible compared to the gravity acceleration

December 14, 2010

EKF Quaternion Based

Correlation step
- Kalman gain:
  \[ K_k = \hat{P}_k H_k^T (H_k \hat{P}_k H_k^T + R_k)^{-1} \]
- State update:
  \[ x_k = \hat{x}_k + K_k (z_k - h(\hat{x}_k)) \]
- Covariance matrix update:
  \[ P_k = (I - K_k H_k) \hat{P}_k \]

Accelerometer

Gyroscope

Prediction

Roll-Pitch Update

\( Z_k \)

\( u_k \)

\( \hat{x}_k \)

\( x_k \)

December 14, 2010
Limitations

The acceleration sensor model is valid only when:

“the acceleration acting on the body is negligible compared to the gravity acceleration”

\[ K_k = \overline{P}_k H_k^T (H_k \overline{P}_k H_k^T + R_k)^{-1} \]

The Measurement Covariance Matrix represents the noise level of the accelerometer and is often choose as constant matrix.

**Hypothesis:** The lack on the sensor model for the effects of external acceleration acting on the body can be compensated with a dynamic choice of the Measurement Covariance Matrix.

**R-Adaptive algorithm**
R-Adaptive Algorithm (1/2)

- **Accelerometer**
  - \( z_k \)

- **Gyroscope**
  - \( u_k \)

- **Prediction**
  - \( \hat{x}_k \)

- **Roll-Pitch Update**
  - \( R_k \)
  - \( x_k \)

- **R-Adaptive algorithm**
R-Adaptive algorithm (2/2)

\[ \sigma_k^2 = \frac{1}{N+1} \sum_{k-N}^{k} \left( \| z_k \| - \| z_{k-1} \| \right)^2 \]

N=10 (100 ms)

Human movements less than 10Hz

\[ R_k = \begin{bmatrix} \sigma_k^2 & 0 & 0 \\ 0 & \sigma_k^2 & 0 \\ 0 & 0 & \sigma_k^2 \end{bmatrix} \]

\[ K_k = \hat{P}_k H_k^T (H_k \hat{P}_k H_k^T + R_k)^{-1} \]

\[ x_k = \hat{x}_k + K_k (z_k - h(\hat{x}_k)) \]

Adjust the Kalman gain with a term dependent to the variance of the acceleration module


Experimental Setup (1/2)

Reflective Markers

Acquisition frequency (Vicon): 100 Hz

Experiments

- 50 sec: free rotations
- 100 sec: rotations around one axis ($X_1$)
Data Processing Model

WB-3 Raw Data
- Data Filtering
- EKF (R-Adaptive)
- Quaternion to RPY
- Local frame (WB-3) to Global frame (VICON)
- DTW for data synchronization

Vicon Raw Data
- Data Filtering
- Attitude calculation
- Quaternion to RPY

InterSense Raw Data
- Resampling (100Hz)
- Local frame (WB-3) to Global frame (VICON)
- DTW for data synchronization

WB-3 Error
InterSense Error
Sampling time comparison

(*) All the experiment (total 150 sec)

WB-3

99.98% of samples is received with the nominal sample time of 10 ms

InertiaCube

Only 77.00% of the samples is received with the nominal sample time of 25 ms
Data Synchronization

Free rotation
Rotations around one axis
Global Results

50 sec - Free rotations

<table>
<thead>
<tr>
<th></th>
<th>RMS Roll Error and standard deviation [Deg]</th>
<th>RMS Pitch Error and standard deviation [Deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>InertiaCube</td>
<td>5.2696 (22.5080)</td>
<td>2.3245 (2.5740)</td>
</tr>
<tr>
<td>WB-3</td>
<td>2.7388 (13.2622)</td>
<td>0.9040 (0.9282)</td>
</tr>
</tbody>
</table>

100 sec - 45 rotation from 0 to 90

<table>
<thead>
<tr>
<th></th>
<th>RMS Roll Error and standard deviation [Deg]</th>
<th>RMS Pitch Error and standard deviation [Deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>InertiaCube</td>
<td>0.9183 (0.7427)</td>
<td>2.2640 (1.6764)</td>
</tr>
<tr>
<td>WB-3</td>
<td>1.0739 (0.9301)</td>
<td>1.2337 (0.9446)</td>
</tr>
</tbody>
</table>
Results

- **R-Adaptive algorithm** allows the WB-3 to achieve better performance than the InertiaCube, especially when the hypothesis of negligible linear accelerations in respect to the gravity is not verified.

- **DTW techniques for data synchronization** among the different motion capture systems (WB-3, Intersense, Vicon) was successfully applied.

- **WB-3 can measure the human body movements virtually everywhere**, not only in a structured environment (Vicon).

- **No calibration procedures**
Single Sensor Demo
Kinematic Model (Upper Body)
Kinematic Model Demo
Objective

- Objectively evaluate operative skills during regular training
- Provide quantitative information feedback to subjects
- Further implemented in operation room for skill evaluation
Experimental Evaluation

- Box trainer: Endowork-pro II
- Training task:
  - peg-board training
  - pipe-cleaner training
- Subject:
  - Surgeon: 5
  - Novice: 11

* Cooperation with Prof. Hashizume at Kyushu University

Peg-board training platform
Pipe-cleaner training platform
Data Processing Model

Evaluated kinematics parameters:
- Joint angle
- Joint angular speed
- Joint angular speed frequency
- Power spectrum density of joint angular speed
### Results

**Peg-board training** (significant parameters: p<0.05)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>left side</th>
<th>right side</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shoulder</strong> average angular speed</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td><strong>Shoulder</strong> angular speed CDF</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td><strong>Shoulder</strong> peak frequency of angular speed</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td><strong>Shoulder</strong> used efficiency</td>
<td>×</td>
<td>○</td>
</tr>
</tbody>
</table>

**Pipe-cleaner training** (significant parameters: p<0.05)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>left side</th>
<th>right side</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shoulder</strong> angle standard deviation</td>
<td>×</td>
<td>○</td>
</tr>
<tr>
<td><strong>Shoulder</strong> angle range</td>
<td>○</td>
<td>×</td>
</tr>
<tr>
<td><strong>Shoulder</strong> peak frequency of angular speed</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td><strong>Shoulder</strong> used efficiency</td>
<td>×</td>
<td>○</td>
</tr>
</tbody>
</table>

- No significance found in the cases of wrist and elbow.
- The movements of shoulder are strongly related to the operative skills.
# Classification

## Peg-board training task

<table>
<thead>
<tr>
<th>Task</th>
<th>Subject</th>
<th>QUANTITY</th>
<th>Successful Case</th>
<th>Failed Case</th>
<th>Correct Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peg-board</td>
<td>expert</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>novice</td>
<td>11</td>
<td>10</td>
<td>1</td>
<td>90.9%</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td></td>
<td><strong>16</strong></td>
<td><strong>15</strong></td>
<td><strong>1</strong></td>
<td><strong>93.75%</strong></td>
</tr>
</tbody>
</table>

## Pipe-cleaner training task

<table>
<thead>
<tr>
<th>Task</th>
<th>Subject</th>
<th>QUANTITY</th>
<th>Successful Case</th>
<th>Failed Case</th>
<th>Correct Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe-cleaner</td>
<td>expert</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>novice</td>
<td>11</td>
<td>11</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td></td>
<td><strong>16</strong></td>
<td><strong>15</strong></td>
<td><strong>1</strong></td>
<td><strong>93.75%</strong></td>
</tr>
</tbody>
</table>

*TBME(submitted), ROBIO 2010*
Biomechanics Analysis

Data Filtering

Feature Extraction

Feature Normalization

Principal Component Analysis

Linear Discriminant Analysis

Pre-processing

Feature Processing

Expertise Classification
Objectives:

- analyze the biomechanics features of surgical gesture
- give more insight to the operation skills
Inverse Dynamics Sequence

Kinematics Data

measure joint angles by using WB-3 IMU on each human segment
Biomechanics Analysis

Angles → Velocities → Accelerations → Multi-Joint Dynamics → Musculoskeletal Geometry → Moments → Tendon forces

\[ \frac{d}{dt} \quad \frac{d}{dt} \quad \text{Multi-Joint Dynamics} \]

Shoulder
Triceps
- Long head
- Medial
- Lateral

Biceps
- Long head
- Short head

Elbow
Brachialis
Biomechanics Analysis

**Joint moment (N*m)**

- **Shoulder**
- **Elbow**

**Time (s)**

- 0
- 5
- 10
- 15
- 20
- 25
- 30
- 35

**Joint moment (N*m)**

- 0
- 5
- 10
- 15
- 20
- 25
- 30
- 35
Objective

- Objectively evaluate operative skills by analyzing hand motion
- Provide quantitative information feedback to subjects
- Further implementation in operation room for real time evaluation
Experimental Evaluation

Basic training: pick and place task

- **Microscope**
- **WB-3 IMU**
- **Bipolar Forceps**
- **Training platform**

**Experimental setup**

3 different training target

---

* Cooperation with Prof. Iseki at Tokyo Women Medical University*
Global Evaluation

\[ \text{Score}_{\text{SubjN}} = \frac{\text{Param}_{\text{Surgeon}}}{\text{Param}_{\text{SubjN}}} \]
Objective

- Objectively evaluate mastication pattern and skills
- Provide quantitative information for better diagnosis
- Assist jaw symptoms treatment
Experimental Evaluation

Experimental setup
- WB-3 attached to mandible by adhesive medical tape
- Subject’s head lean on wall during chewing the food

Task
- Free chewing of three types of food with different hardness

Three types of foods:
- marshmallow: 8.0 ± 1.0 g
- biscuit: 7.0 ± 0.1 g
- almond: 4.3 ± 0.4 g
## Results

### Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Marshmallow (soft)</th>
<th>Biscuit (intermediate)</th>
<th>Almond (hard)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chewing Time</td>
<td>▼</td>
<td></td>
<td>△</td>
</tr>
<tr>
<td>Chewing Frequency</td>
<td>▼</td>
<td></td>
<td>△</td>
</tr>
<tr>
<td>Rotation Energy (PSD of $</td>
<td>\omega_x</td>
<td>$)</td>
<td>▼</td>
</tr>
<tr>
<td>Translation Energy (PSD of $</td>
<td>a</td>
<td>$)</td>
<td>▼</td>
</tr>
<tr>
<td>Mouth Opening Angle</td>
<td></td>
<td>no significant difference</td>
<td></td>
</tr>
</tbody>
</table>

- △ Big Value
- ○ Intermediate Value
- ▼ Small Value

- Quantitative information to the doctors for realizing a better diagnosis
- Mastication performance information for jaw skill rehabilitation

*JCS 6(8) 2010, IRIS 2010*
Chewing frequency was analyzed from the Power Spectrum Density (PSD) of jaw’s angular speed about x-axis.

Frequency of the peak as the chewing frequency for each food.
All the subjects used more rotation energy when eating hard than soft food.
Subjects used significantly more rotation energy when they were eating hard food.

Mastication Skill Evaluation

Task:
- freely chew gum (60s)
- chew gum only using the teeth on right side (60s)
- chew gum only using the teeth on left side (60s)

Two WB-4 IMUs
- one for compensating the head motion (on forehead)
- one for measuring the jaw motion (on mandible)
Results

Evaluation parameters:
- chewing pattern
- chewing frequency
- mouth opening angle
- etc.
My research team

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