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Motion Estimation Using Inertial Sensor Technology with Applications to Sporting Exercises
1 Introduction

It’s becoming increasingly important among performance athletes and physical trainers to track the displacement or specific motion profiles of various exercises. This permits trainers to perform a further quantitative analysis in order to prevent injuries or to enhance the efficiency of the exercises performed. Traditionally the measurement of elite athlete performance is mostly done in a laboratory environment [1], where specific testing of physiological indicators can take place. Laboratory testing, however, places limits on how the athlete performs, as the testing environment is different to the training environment. In addition, performance characteristics are further augmented during competition when compared to regular training. By better understanding athlete performance during the competition environment, coaches can more effectively work with athletes to improve their performance [2]. In testing athletes outside a highly controlled laboratory environment a number of factors and tradeoffs need to be considered. These factors include what test or measure is desired, what technologies can be used to obtain the measure, the practicality of obtaining the measure, and others related to the specific sport under consideration. In the case of sprint running one of the considerations is the weight of the apparatus, if it is too heavy it could disturb the runner.

The testing and monitoring of athletes in their natural training environment is a comparatively new field of development that has been facilitated by advancements in in the field of microelectromechanical systems (MEMS) technology [2]. Inertial measurement units (IMUs), which consist of a three-axis accelerometer, a three-axis gyroscope and a three-axis magnetometer, have been used as a sensing unit for motion determination by measuring acceleration, rotation angles and magnetic field [3]. However, calculating orientation and displacement using these miniaturized inertial systems has limited capabilities. The main problem is that displacement is computed by time-integrating the signals from gyros and accelerometers, including any superimposed sensor drift and noise. Therefore, the estimation errors tend to grow indefinitely. Solutions for mitigating the drift problem usually consist of additional sensors such as magnetometers [4] or on problem-specific knowledge, for example gait cycle for drift error correction [5]. Nevertheless, the reductions in size, power and weight as well as the handiness are very important factors when considering sport specific systems. Hence, IMUs have the big advantage to fulfil these requirements and thus are a preferable option for this application [3][6].

During walking and running, body segments go through a cyclic motion and the movement pattern of each segment repeats every stride cycle. The term “gait” is used to describe the way of walking or running [7]. As shown in Figure 1.1 during each gait cycle a sequence of events take place that mark the transitions from one gait phase to another. While walking, each gait cycle begins and ends by definition with the heel strike. Whereas a running gait involves landing farther forward on the foot, which is referred to as midfoot strike in most cases, with more forefoot landing as running speed increases. The cyclic motion of a body segment generates periodic acceleration, which can be detected by the attached inertial sensors. The embedded features in the measurements enable the possibility in estimating different parameters to analyse the running performance [9].
Foot-ground contact time, illustrated as the red arrow in Figure 1.1, is one of the most important variables that influence top running speed, with athletes that have shorter contact times typically being faster sprinters [10]. Foot-ground contact time is also known to be affected by leg stiffness, with higher leg stiffness associated with reduced contact times [11]. Sprinters attempt to reduce contact times during sprinting through training regimes, focusing on explosive development of force during stretch-shorten cycle muscle contractions that mimic the stance phase of running, which are designed to enhance leg stiffness. From a coaching perspective it would therefore be of benefit to be able to measure foot-ground contact times during sprinting. Such information could be used to monitor sprint performance and evaluate the effect of training on sprinting technique.

On a trainers request the analysis of running performance is conducted by the use of PARTwear, which is a microcontroller-based sensor system used to monitor the activity of human beings in different areas of sport. The intended contribution of this system is to be applied to numerous sports like football, tennis as well as track and field athletics et cetera, to provide the athlete an objective feedback of his performance in realtime.
2 Methods and Algorithm Design

As a first step, acceleration data was recorded by the use of PARTwear. The experiments were carried out on a treadmill as well as on a 50 m track in an outdoor environment. The experiments aim was to analyse the acceleration signal which represents the foot-ground contact time when jogging and sprinting. Data was collected in real-time and post-processed using a program written in MATLAB/ Simulink® [12] from Mathworks. The final goal was to find an appropriate algorithm, which can be implemented in PARTwear.

Section 2.1 describes the PARTwear-Sensor-System. The acceleration data was compared with a video signal as explained in Section 2.2. The data was then analysed and an applicable algorithm is designed, see Section 2.3 for more details. Finally, additional measurements were conducted to validate the algorithm comparing other measuring devices, as described in Section 2.4.

2.1 PARTwear-Sensor-System

PARTwear is an accelerometer based system to monitor the activity of human beings in different areas of interest such as Sports and Medicine. In its most simple setup, raw data from the accelerometer is recorded to the internal flash memory of the device. It is possible, however, that the accelerometer data are processed online and only certain features of interest are recorded. In addition to the accelerometer data, the heart rate can be received from a commercially available heart rate belt by means of a wireless connection. What separates the PARTwear system from its concurrence is the ability to synchronously record data from multiple devices, sent over the wireless connection to one recording node. Furthermore it is designed to easily integrate feature extraction algorithms tailored to the customers requirements.

- Measurement of acceleration in the range of +/-16 g at up to 3200 Hz sampling rate
- Wireless sensor network for synchronous recording of multiple sensor nodes
- Easily adaptable online signal processing
- Autonomous operation from single battery up to 14 days
- Small, robust and biomechanically neutral to the athlete due to flexible silicone casing

Figure 2.1: PARTwear - Performance Analysis Research Technology
The PARTwear device can be configured to play different roles. The most basic role is **Stand-alone**, in which data from the accelerometer and optionally data from a heartrate belt can be processed and recorded to the local memory. In the **Recorder** role, a device collects data from other sensor nodes, processes the data and records it to the local memory. In the various sensor roles, the devices are configured to collect data and send them to the recorder. Role specific signal processing on the sensor nodes is possible. When the recorder node is plugged to a host computer via USB a live stream of the data recorded can be sent for real time analysis. The sensor platform consists of two rigid circuit boards connected by a flexible part (Figure 2.2). Thus it is flexible and can be integrated in round forms or folded in half. The battery can be mounted below or besides the PCB. The standard is a thin, flexible battery mounted below the PCB in a casing made of silicone. Custom casings and integrations (e.g. in protectors) are possible.

![PARTwear unfolded](image1)

![PARTwear with casing](image2)

![PARTwear folded](image3)

**Figure 2.2:** PARTwear unfolded without casing (left), with silicone casing (center) and folded (right).

### 2.2 Measurement

For each measurement run the PARTwear sensor was worn at the right foot of the test person (Figure 2.3). 3D acceleration data of the MEMS based sensor ADXL345 from Analog Devices were sampled by a MSP430 16-bit microprocessor from Texas Instruments at 2000 Hz per channel and recorded to the internal flash memory. The test person was required to run first on a treadmill and secondly along a runway using a forefoot strike pattern. Each test run has been filmed with a GoPro HERO3® camera in 240 frames per second for being able to compare the measured accelerations to the real movement of the subjects right foot.

![PARTwear sensor](image4)

![GoPro HERO3® camera](image5)

**Figure 2.3:** PARTwear sensor attached to the right foot. Positive directions of the three acceleration axes are superimposed. (left), and GoPro HERO3® camera (right).
2.3 Data Analysis and Algorithm Design

For being able to synchronize the recorded video with the acceleration data a sync pattern was generated at the beginning of each test run. The red LED on the PARTwear device was blinking three times. Additionally this current LED state was stored on the internal memory of the device as shown in Figure 2.4.

![Figure 2.4: The red LED on the PARTwear sensor platform is generating a sync pattern.](image)

The tool which was used in this project to evaluate the algorithm was MATLAB/ Simulink® [12] from Mathworks. The main approach to extract the contact time between the foot and ground was to detect peaks in the signal (global maxima and minima above a certain threshold) and measure the distance between these peaks, as can be seen in Figure 2.5.

![Figure 2.5: Detecting foot-ground contact time using a peak detection algorithm.](image)

A number of criteria were developed and tested to determine the contact time. The first part of the algorithm was finding positive and negative peaks in the repetitive acceleration pattern of the Z axis, denoted as the red and black dots in Figure 2.5.
According to the video analysis two events appeared to be appropriate for determining the initial foot contact and the toe-off moment. These two events were used to calculate the contact time. The first event was the minima in the Z acceleration axis which occurred near the beginning of ground contact. For detecting its ending a second event was observed using again the Z accelerations, which experience a second local minima near toe-off. Each ground contact found is indicated with the blue line, as can be seen in Figure 2.5.

Using MATLAB’s Computer System Vision Toolbox® the raw data and the computed ground contact times as well as the step rates of a test run are visualized. As shown in Figure 2.6 the contact time of each step is displayed using a blue bar and the step rate with a corresponding orange bar. At the bottom of the video the raw data of the three acceleration sensor axes are synchronously plotted to the video image. It was concluded from this visualization that close estimates of foot-ground contact time during running can be obtained using body mounted accelerometers, with the best estimates obtained in conditions associated with the highest accelerations. At the beginning of a test run, where acceleration has not the same intensity peaks, the algorithm can miss some steps and in this only case not being able to compute the foot-ground contact time.

Figure 2.6: Acceleration data of each sensor axis and the computed foot-ground contact time as well as the step rate are displayed in a video file.
2.4 Algorithm Validation

2.4.1 Experiment A

The accuracy of the designed algorithm was studied by comparing the estimated ground contact time with two additional measuring devices. The first device was a force plate from KISTLER and the second device was OPTOJUMP which is an optical measurement system consisting of a transmitting and receiving bar. A RED high-speed camera was used as the reference signal which records video data in 350 Hz and in full HD resolution (1920 x 1080), see Figure 2.7. Details about the used measuring devices are shown below:

- **KISTLER** force plate: 0.90 x 0.90 m Quattro Jump, Winterthur, Switzerland. 500 Hz sampling rate.
- **OPTOJUMP**: Next Microgate, Bolzano, Italy. 1000 Hz sampling rate
- **RED** high-speed camera: Epic Mysterium-X, Red Digital Cinema Camera Company, Lake Forest, California, 350 Hz and full HD (1920 x 1080)

The test person conducting this experiment was a former top triathlon athlete (25.8 y, 182 cm, 67 kg) and still active runner with experience in midfoot and forefoot strike running. The described setup for this experiment allowed to measure one step. The test person was asked to run along a predefined 50 m runway. Each measuring sample was taken when the maximum running speed was reached. According to this procedure four test runs were recorded while jogging and sprinting. Afterwards the results were compared with the video data from the high-speed camera. Concerning the setting of the force plate, two measuring limits (5 N and 10 N) have been selected to avoid the influence of artefacts, due to ground vibrations.

![Figure 2.7: RED high-speed camera (left) and measurement setup with KISTLER force plate and OPTOJUMP (right).](image)

2.4.2 Experiment B

The second experiment was about to measure the ground contact time when sprinting along a 10 m runway. This time, the main goal was not to measure just one step and comparing it with several other measuring systems, as in experiment A, but to measure the contact time of every step involved and comparing it against the OPTOJUMP system. Measurements with four different test persons were made, which involved two elite sprinters and two recreational runners. This helped to evaluate the inter-subject variability.
3 Results

3.1 Results Experiment A

The results from experiment A are shown in Figure 3.1. The image on the left represents the ground contact times of the four measured steps when jogging, and on the right when sprinting, respectively. Statistical analysis is used to compare each measurement against the reference signal, obtained from the high-speed camera. When jogging, the ground contact times of the RED are in the range of minimum 177 ms and maximum 191 ms and when sprinting in the range of minimum 137 ms and maximum 160 ms. The mean absolute error and the maximum error of each measuring device is calculated, which is summarized in Table 3.1 and 3.2. When jogging, differences between the measuring devices of mean absolute error range between 0.9% and 4.0%, with a maximum error in the range between 2.3% and 6.2%. When sprinting, differences between the measuring devices of mean absolute error range between 1.5% and 3.9%, with a maximum error in the range between 2.1% and 6.6%.

Figure 3.1: Compare ground contact times when jogging (left) and sprinting (right).
Table 3.1: Comparing different measuring devices for ground contact time when jogging against RED.

<table>
<thead>
<tr>
<th>Measuring Device</th>
<th>Mean Abs Error [%]</th>
<th>Max Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kistler 10 N</td>
<td>4.03</td>
<td>6.215</td>
</tr>
<tr>
<td>Kistler 5 N</td>
<td>2.926</td>
<td>5.085</td>
</tr>
<tr>
<td>OptoJump</td>
<td>0.9783</td>
<td>2.26</td>
</tr>
<tr>
<td>PARTwear</td>
<td>1.258</td>
<td>3.056</td>
</tr>
</tbody>
</table>

Table 3.2: Comparing different measuring devices for ground contact time when sprinting against RED.

<table>
<thead>
<tr>
<th>Measuring Device</th>
<th>Mean Abs Error [%]</th>
<th>Max Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kistler 10 N</td>
<td>3.286</td>
<td>4.895</td>
</tr>
<tr>
<td>Kistler 5 N</td>
<td>1.909</td>
<td>3.497</td>
</tr>
<tr>
<td>OptoJump</td>
<td>1.525</td>
<td>2.098</td>
</tr>
<tr>
<td>PARTwear</td>
<td>3.947</td>
<td>6.569</td>
</tr>
</tbody>
</table>

3.2 Results Experiment B

The results from experiment B are shown in Figure 3.2. The four images represent the ground contact times of each of the four test persons. Statistical analysis is used to compare each measurement against the reference signal, obtained from Optojump. The ground contact times measured with Optojump are in the range of minimum 0.076 ms and maximum 0.203 ms. The mean absolute error and the maximum error of the designed ground contact time algorithm is calculated, which is summarized in Table 3.3. The mean absolute error ranges between 2.6% and 7.0%, with a maximum error in the range between 5.6% and 15.8%.

Table 3.3: Comparing ground contact times of four different persons against Optojump when sprinting.

<table>
<thead>
<tr>
<th>Test Person</th>
<th>Mean Abs Error [%]</th>
<th>Max Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.973</td>
<td>14.85</td>
</tr>
<tr>
<td>2</td>
<td>5.365</td>
<td>15.79</td>
</tr>
<tr>
<td>3</td>
<td>2.629</td>
<td>5.556</td>
</tr>
<tr>
<td>4</td>
<td>3.453</td>
<td>8.163</td>
</tr>
</tbody>
</table>
Figure 3.2: Comparing ground contact times of four different persons.
4 Discussion

In the first experiment the new designed algorithm has been compared against different measuring devices. The results of this study indicate that the maximum error of the found algorithm (3%) is similar to that of previous used laboratory equipment (2.2%), like Optojump. Since Optojump has the smallest error of all the involved measuring devices in the first experiment, it is used as reference instrument in the second experiment. The aim of this second experiment is to analyse the inter-subject variability of the designed algorithm, when sprinting along a 10 m runway. Instead of only analysing one step, as in the first experiment, contact time of every step involved is measured in second experiment. Although the current study is based on a small sample of participants, the findings suggest that the algorithm can be adopted to different persons. Even so, the algorithm could be further improved with an adaption factor, which can be found using the cross-validation method. C++ code of the current algorithm state has been generated with the Embedded Coder from MATLAB®/Simulink®. This allows to integrate and test the algorithm on the embedded processors of the PARTwear sensor.
5 Conclusion

Since foot-ground contact time is one of the most important variables that influence maximum running speed, it would therefore be of benefit to be able to measure foot-ground contact times during sprinting. Using inertial sensors for this purpose permits athletes and trainers to analyse running performance in their natural training environment, instead of only in the laboratory environment. This research has found that generally it is possible to measure ground contact time with the PARTwear acceleration sensor using the designed algorithm.
6 Recommendations

Traditionally the measurement of athlete performance is done in a laboratory environment, where specific testing of physiology takes place. Laboratory testing however places limits on how the athlete performs, as this environment is different to the training environment. Hence a new system is needed, which provides a rapid feedback in the normal training and competition environment. With PARTwear, every athlete has the possibility to improve his performance, e.g. running technique while exercising in his familiar training environment. The collection of data in every training enables the athlete to actually see the improvements and get additional motivation from it. PARTwear also shows strength and weakness and thereby helps to train the right thing, getting more reward out of the training time. By using a smartphone or tablet to control the sensors and visualize results, the usage will be very intuitive. High precision, low cost, minimal size and the ease of use make the PARTwear system the perfect fit both for the application in professional training and for the enthusiastic hobby sportist.
Bibliography


