Comparison of vision-based and sensor-based Systems for Joint Angle Gait Analysis

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Abstract—Gait analysis has become recently a popular research field and been widely applied to clinical diagnosis of neurodegenerative diseases. Various low-cost sensor-based and vision-based systems are developed for capturing the hip and knee joint angles. However, the performances of these systems have not been validated and compared between each other. The purpose of this study is to set up an experiment and compare the performances of a sensor-based system with multiple inertial measurement units (IMUs), a vision-based gait analysis system with marker detection, and a markerless vision-based system on capturing the hip and knee joint angles during normal walking. The obtained measurements were validated with the data acquired from goniometers as ground truth measurement. The results indicate that the IMUs-based sensor system gives excellent performance with small errors, while vision systems produce acceptable results with slightly larger errors.

Keywords—gait analysis; inertial measurement unit; vision; goniometer; joint angles;

I. INTRODUCTION

Gait analysis is the systemic study of the human locomotion during walking. The analyzed results are widely used for the early detection of neurodegenerative diseases which are observable from gait patterns, and the evaluation of the rehabilitation progress [1]. The most influential gait features are composed of temporal-spatial parameters, e.g. stride time, stance time, step length; kinematic parameters, e.g. joint angles of hip and knee, joint velocity, joint acceleration; kinetic parameters, e.g. joint moment, foot pressure; and electromyography. Among all types of parameters, the kinematic parameters are the most visible and contain rich information. The angles of hip and knee joint in sagittal plane are semi-periodic during a normal walking and the example joint positions of hip, knee and ankle joints of a normal gait cycle are illustrated in Fig. 1.

Fig. 1. A normal gait cycle and the movement of hip, knee, ankle and metatarsophalangeal (MTP) in a gait cycle.

Two types of systems are commonly used in order to obtain the hip and knee joint angles from the measurements: vision-based systems and sensor-based systems. However, the performance of some exiting low-cost vision and sensor systems are not yet evaluated and compared.

Vision-based systems can be divided into marker-based and markerless systems. Many advanced marker-based systems employ four to eight cameras in a pre-designed environment and detect the active markers attached on specific positions of human body. These systems are able to provide precise measurements but have obvious drawbacks, for instance, expensive, large space requirement, disturbing to patients; other marker-based systems utilize passive markers and detect the position of the markers with color-based or shape-based segmentation algorithms. These systems provide cheaper solutions, but the effectiveness of the systems is highly influenced by the correct placement of markers and the relative view angle of the camera. Markerless vision gait capture systems were recently becoming a popular and challenging topic; they are considered as a fast and effective way to obtain the measurements according to the proportion of the human body segments without any knowledge of the individual human joint locations.

Another low-cost method to measure the joint angle is to use wearable inertial measurement units (IMU) based on MEMS 1 technology. A 6-axis IMU can measure the acceleration using accelerometers and the angular velocity by gyroscopes. Some IMUs have in addition magnetometers in 3 axes. The magnetometer measures the vector of the earth magnetic field and uses the measurement as a reference for the calibration against drifting in orientation. The output of the IMU is the acceleration (a, b, c) and the angular velocity ( \( \dot{\theta}, \dot{\phi}, \dot{\psi} \) ) (mostly after onboard calibration). Some IMUs have additional outputs, such as roll, pitch and heading (yaw) angles and they are called Vertical Reference Unit (VRU) if the heading angle is low-drift unrefereenced, or Attitude and Heading Reference System (AHRS) if heading angle is accurate [2] [3]. Table I shows a comparison between few IMUs with different functionalities, different number of axis and different accuracies for orientation.

Different studies have proposed different number of IMUs, for measuring the gait features [5] [6] [7]. The method can be low-cost depending on the number of the sensors and on the

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1 MEMS-Micro-Electro-Mechanical System
model of the IMU. Additionally the accuracy of the measurements also depends on the model of the IMU.

**TABLE I**

Comparison between different IMU models [2] [3] [4]

<table>
<thead>
<tr>
<th>Model</th>
<th>Manufacturer</th>
<th>Accelerometer</th>
<th>Gyroscope</th>
<th>Magnetometer</th>
<th>on-board processing</th>
<th>Functionality</th>
<th>Typical attitude and heading accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navigation IMU</td>
<td>AIMS</td>
<td>3</td>
<td>3</td>
<td>-</td>
<td>no</td>
<td>IMU</td>
<td>Pitch and Roll</td>
</tr>
<tr>
<td>Navigation VRU</td>
<td>AIMS</td>
<td>3</td>
<td>3</td>
<td>yes</td>
<td>VRU</td>
<td>Static accuracy: ±0.1° / Dynamic accuracy: ±0.2°</td>
<td></td>
</tr>
<tr>
<td>MTi-100 IMU</td>
<td>Xsens</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>no</td>
<td>IMU</td>
<td></td>
</tr>
<tr>
<td>MTi-200 VRU</td>
<td>Xsens</td>
<td>3</td>
<td>3</td>
<td>yes</td>
<td>VRU</td>
<td>Static accuracy: ±0.2° / Dynamic accuracy: ±0.3°</td>
<td></td>
</tr>
<tr>
<td>MTi-300 AHRS</td>
<td>Xsens</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>yes</td>
<td>AHRS</td>
<td>Accuracy: ±1.0°</td>
</tr>
<tr>
<td>FSM-9</td>
<td>Hill crest labs</td>
<td>3</td>
<td>1</td>
<td>yes</td>
<td>AHRS</td>
<td>Static accuracy: ±1.5° / Dynamic accuracy: ±1.5°</td>
<td></td>
</tr>
</tbody>
</table>

Goniometer is an instrument that is able to measure angles or allow an object to be rotated to a precise angular position. In physical therapy and occupational therapy, the range of motion of joint angles of specific body parts are measured from a goniometer and used to track the rehabilitation progress of diseases. Since the electrogoniometer is capable of providing accurate measurement of motion angles, there have been a lot of researches recently regard the electrogoniometer as a ground truth data. A goniometer and used to track the rehabilitation progress of diseases. Since the electrogoniometer is capable of providing accurate measurement of motion angles, there have been a lot of researches recently regard the electrogoniometer as a ground truth data.

The purpose of the study is to evaluate and compare three types of low-cost gait joint angle capture tools, namely, Reha@home, a markerless vision-based system; Kinovea, a marker-based vision gait analysis system; and a sensor-based system with IMUs. The results will be used in future to design new combined low-cost gait capture and analysis systems that can provide more reliable measurements.

II. METHODS FOR GAIT JOINT ANGLE ACQUISITION

Four types of tools were employed in this study to obtain the hip and knee joint angles. The description for each device and the proper experimental setup are explained in this section in detail. Since the experiment and procedures in the paper are newly developed, only two authors of this article are recruited in this study as participants and more subjects will be involved for testing when more stable system is ready. Each participant was requested to stand still in the beginning of the experiment for the calibration of the goniometers and IMUs, and walk normally in a straight line for 2.5 meters afterwards. The walking patterns were recorded with all the four systems at the same time, and the hip and knee joint angles were computed from the raw data with a human leg model.

A. Goniometers

Two goniometers have been used for recoding. For the hip measurement, the two-axis flexible goniometer SG150 from Biometrics Ltd. is used with accuracy of ±2 degrees (°) [9]. For the knee measurement, the goniometer PS-2138 from PASCO is used with accuracy of ±1 degree (°) after calibration [10]. The goniometers measurements were used in this study as the ground truth data.

B. Vision-based Gait Capture System

Two types of low-cost vision-based gait capture systems, namely Kinovea and Reha@home, were investigated in this study.

Kinovea [11], a motion video analysis software, is able to detect and track the markers in a given motion video. Markers are attached on the hip, knee and ankle joint with tapes in the experiments. The joint angles are computed from the detected positions of the joints with the human model illustrated in Fig.3.

Reha@home [12] is a robust markerless gait capture system developed by the Institute of Automation (IAT) of University of Bremen. It is based on one Kinect I, a low-cost camera, but equipped with specific software because the original Kinect software had a low accuracy for the intended use [13] [14]. Markers are useful tools to help with the positioning of the specific joints on the human body, however could cost more efforts on setting up the experiments, and bring drifting errors by an inappropriate placement. Therefore Reha@home was involved in the study for comparison. The detection algorithm of Reha@home starts with extracting the contour and silhouette of the walking subject in the range of interest (ROI) from each frame of the video, and continues with detecting the head, hip, knee, and ankle locations according to the proportion ratios of human body. The joint angles are calculated based on the detected joint positions in the image, and smoothed with a cascade of filters afterwards. A sticker marker with a red line representing the leg close to the camera and a blue line representing the other leg is visualized in the image additionally. The detected angles of hip (θhip) and knee (θkne) from Reha@home system are illustrated in Fig. 3.
C. IMU-based Joint Angle Measurement

The IMUs have been widely used for motion tracking and detection. The IMU, which has been selected for this research study, is the 9-axis attitude and heading reference system FSM-9 from Hillcrest labs and contains 3-axis gyroscope, 3-axis accelerometer and 3-axis magnetometer. The FSM-9 is equipped with on-board motion engine that performs the data fusion. The motion engine takes as input the raw data from the accelerometer, the gyroscope and the magnetometer and gives as output orientation of the sensor, with dynamic accuracy of 1.5 degrees (°) [4]. For this study, the data from the motion engine have been used and will be presented in the next section.

The IMU-based system for the gait analysis is composed of two IMUs, in order to measure the two angles (hip and knee). One is placed on the thigh (upper leg) and one is placed on the shank (lower leg). The exact setup of the IMU-based system is shown in Fig. 2.

Fig. 2. Placement of the IMU-based system: hip IMU is placed on the thigh and knee IMU is placed on the shank.

Each IMU measures one angle; the hip and knee IMU measure the inclination of the hip (\( \varphi_{\text{hip}} \)) and knee (\( \varphi_{\text{knee}} \)) with respect to the inertial position of the hip and knee (standing position), respectively (Fig. 3). The angles are positive when the IMU sensor is tilted up, as shown in Fig. 3.

The hip angle is measured with the same reference in the IMU-based system and the previous 3 methods (Goniometer and the two Vision-based gait capture systems) with equation (1), while the knee angle is measured differently. The conversion between the two measured knee angles is given in the equation (2).

\[
\vartheta_{\text{hip}} = \varphi_{\text{hip}} \tag{1}
\]

\[
\vartheta_{\text{knee}} = | \varphi_{\text{hip}} - \varphi_{\text{knee}} | \tag{2}
\]

III. EXPERIMENTAL RESULTS AND DISCUSSION

In this section, the experimental results of one subject from the above four methods are presented. The computed joint angles of hip and knee from the above methods are illustrated in Fig. 4 and Fig. 6, respectively. The output of the two IMUs used for the calculation of the knee angle is shown in Fig. 5. The joint detection results from Kinovea and Reha@home in one selected frame are presented in Fig.7 (a) and Fig.7 (b) respectively.

As presented in Fig. 4, the difference was ±3 degrees (°), between the measurement from the goniometer and the IMU-based system. This difference is acceptable because in the IMU-based system there is no measurement for the upper body, which has some small movements during walking. Additionally the goniometer’s accuracy is 2 degrees (°) and the accuracy for the IMU is 1.5 degrees (°). Compared with the results from goniometer, Reha@home measurement had ±10 degrees (°) of difference and Kinovea gave ±15 degree (°) of difference. Additionally, the detection from Reha@home had approximately 0.2 second delay. Besides, the trajectories obtained from vision systems had more spikes than from the IMU-based system with integrated motion engine.

As depicted in Fig. 6, the difference was ±3 degrees (°), between the measurement from the goniometer and the IMU-based system for the knee angle detection. This difference is in the acceptable range; the accuracy for each IMU is 1.5 degrees (°) and the accuracy of the goniometer is 1 degree (°). Regarding vision-based systems, Kinovea gave ±5 degree (°) of difference while Reha@home had ±10 degree (°) of difference. The Kinovea detection contained noises caused by the unstable tracking of markers, while the Reha@home detection contained errors during the stance walking phase which may arise from the occlusion of the two legs. The knee measurements had smaller error than the hip measurements in general for all three systems.
Fig. 4. Hip angle trajectories from goniometer (black line), IMU system (blue line), Reha@home (green line) and Kinovea (red line)

Fig. 5. Measurements from the hip IMU (a) and the knee IMU (b)

Fig. 6. Knee angle trajectories from goniometer (black line), IMU system (blue line), Reha@home (green line) and Kinovea (red line)

Fig. 7. Joint detection results for one selected frame from recorded video of a subject walking from left to right: (a) using Kinovea; (b) using Reha@home

IV. CONCLUSION AND FUTURE WORK

From the above experiments, it can be concluded that the IMU-based system gives accurate and reliable results in comparison to the goniometers. The yielded results have maximum ±3 degree of difference. For the hip joint angle measurement, it is enough to use one IMU attached on the thigh, presumed an upright gait with low upper body inclination; the measurement of knee angles needs two IMUs with one placed on the thigh and one on the leg. The IMUs can be used as powerful tools for capturing gait joint angles.

Vision-based systems, Reha@home and Kinovea, are able to provide acceptable results as well compared with goniometers. However, slightly larger errors were observed from the detection when the two legs are having occlusion for Reha@home system, and when marker tracking is unstable for Kinovea system. The errors of Reha@home system may also come from the body shape, clothing, and walking speed of the person, the lighting condition, and an unstable walking. The errors of Kinovea may be caused by the imperfect placement of markers, relative position and distance of camera to the subject, and the inaccurate detection and tracking of markers as well.

In summary, the low-cost IMU system that has been used in this study seems to be more reliable on capturing gait patterns than the low-cost vision-based system. The vision-based systems have the advantage that the setup is less complex (the subject needs to only walk in front of the camera without any wearable sensors). In future work we will consider the different effects in more detail and consider statistically relevant group of participants in order to come up with statistically significant data.

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