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Development of an economic wireless human motion analysis device for quantitative assessment of human body joint

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ABSTRACT

In recent years, the study of human body dynamics has been attracting a significant amount of attention. Currently there are many camera or active sensor based motion analysis systems available on the market. They have been extensively adopted and used by the film and animation or entertainment industries such as film and video game producers. More recently their potential in studying human dynamics/motion for medical purposes has been realised to the extent that they are now used to study full body human biomechanics in the form of gait analysis systems. Most orthopaedic surgeries are usually about joint repair or implants. According health line, revision surgery is usually due to infection, continued pain, joint stiffness, wear, instability, loosening. Apart from infection, the rest can be linked to the operation itself. Currently, surgical planning and placing implants is performed in a subjective manner, relying on the surgeon's experience and instinct, current systems to help the surgeon to place implant are also bulky, expensive, slow and not user friendly. The aim of this project is to develop an economic and portable motion assessment system which involves a wireless inertial measurement unit (IMU) dedicated to study and assess body joints. Through the data collected from the IMU, the system is capable real time measurement of relative position and orientation of the human joint. Several tests were conducted to validate the data extracted from gyroscope and accelerometer of the IMU. The joint motion results analysed using the device was compared with the results analysed using commercial video motion analysis software and it shows good correlation. It is found that the gyroscope of the IMU under DMP sensor fusion algorithm and calibration capability is able to give the angular velocity with less than 5% error. This has led to a more accurate orientation data which gives 7% error in average bending angle.

1. Introduction

Motion analysis of human body parts is an important area in the medical field, where motion analysis is often required for medical diagnosis and physiotherapy. According to National Joint Registry (NJR) 10th annual report as at 31 March 2013, a total of 1,456,756 hip, knee, ankle, elbow, and shoulder replacement procedures had been reported to the NJR. There were 196,403 procedures submitted in 2012/13. Total of 2225 shoulder replacement procedures were recorded in 2012 including 1968 primaries and 257 revisions. Osteoarthritis was the primary diagnosis in 61% of cases. 24% of patients were reported to have cuff tear arthropathy. Of the 257 revision procedures, the indications for surgery were variable: 14% out of total needed revisions are aseptic loosening, 30% were conversion of hemi to total and 25% were revision for cuff insufficiency. Knee replacement surgery (arthroplasty) involves replacing a damaged, worn or diseased knee with an artificial joint. In 2012, 90,842 knee replacement procedures were entered into the NJR. Total of 6009 knee revision procedures were reported in 2012 representing an increase of 17% compared to 2011. Indications for revision surgery were recorded as aseptic loosening in 32% of cases [1]. According to a meta-analysis of worldwide joint registry databases, published in the Journal of Bone & Joint Surgery in 2011, the long term revision rate is 6% after 5 years and 12% after 10 years [2]. Although most of the joint revision can be linked to complications associated with infection, circulation, rejection, etc., some are linked directly to implants mechanical properties, poor locating, poor kinematics, reference able or repeatable positioning, poor materials, design, properties, etc. Problem arises when in many cases identical procedure for different individuals can result in dissimilar outcomes. This indicates that there is existence of other relevant parameters that currently a surgeon is either unaware of or has no means of determining, assessing or measuring before the operation [3].

The traditional approach used to analyse gait parameters during clinical applications are subjective. The specialist usually carried out an

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observation or survey to evaluate the quality of patients' gait. These subjective observational measurements are particularly lacking of accuracy and precision, which can have adverse effect on the diagnosis, follow-up and treatment of the pathologies. Progress in new technologies has given rise to creation of new devices and techniques which allow a more objective evaluation of various gait parameters, resulting in more efficient and reliable measurement hence providing specialists with larger amount of reliable and quantitative information about the patients' gaits. This in turn reduces the error margin caused by traditional and subjective techniques.

In practice, motion analysis of human body parts is dominated by visual based motion analysis systems, where one or multiple cameras are used to track the motion of the subject attached with reflective markers. These images are then processed and analysed using specialised software to derive kinematic data [4–7]. Visual based motion analysis systems have a widespread use and they have remarkable performances on measuring displacements and paths of motion [8]. However, they are weak in measuring high frequency and low amplitude motion because of the lack of resolution. Therefore, a more precise kinematics data is necessary for better assessment of the human joint before and after surgery. High resolution kinematics data is also needed for better assessment on the performance of joint after implant surgery. Besides the lack of resolution in visual based motion analysis system, this type of system usually requires high cost for a certain gait laboratory test. Furthermore, visual based motion analysis systems are usually not portable and the test is limited to a certain area covered by the range of the camera. Thus, the application of the visual based motion analysis system is limited, as it cannot be done outside of the instrumented environment.

Despite the widespread use of visual based motion analysis systems such as the Vicon, Qualysis, Codamotion, Motek, Biometrics, ETB Gaitsmart motion analysis systems, body mounted sensors are sometimes used as an alternative to collect kinematics data from human body parts for the purpose of motion analysis [9–12]. This method has the advantage of identifying human motion in a wide variety of environments without taking into account the camera distance, capture range, resolutions, frame rate, etc. [9]. Body mounted sensors are also suitable to measure high frequency motion with low amplitude, which is hard for visual camera to capture [8]. Some researchers have started to use micro-electro-mechanical system (MEMS) accelerometer, gyroscope and combined unit of them or IMU as an alternative for visual based human motion analysis system [13–19]. Inertial measurement unit, when used together with analysis techniques could be useful in providing an economic and portable solution in locating the implants. It could be used to provide information such as original anatomical differences, magnitude and orientation of body segments, initial muscle tension and etc. The use of this sensor in biomedical applications to study body movements has been frequently discussed. However, the major challenge in this method is to translate data which are in the form of acceleration and angular velocity into three dimensional data such as joint angles, and position in 3D space [9].

Theoretically, performing single integration on angular velocity data and double integration on acceleration data would enable us to obtain the orientation and position of an inertial sensor mounted to the body parts. Tong and Grant have calculated lower limb body segments orientations using integration of measured angular velocity from the gyroscopes attached to the thigh and shank [5]. However, they also reported that noise in the gyroscopes data has caused integration errors. This could be caused by the signal noise in the raw data of acceleration and angular velocity. When integration is performed, the error will accumulate over time and this will cause significant error in the computed results. This is often referred as drift. In order to reduce the signal noise, cyclical properties of human gait have been used for developing signal filters. Liu et al. have developed a gait phase detection algorithm to correct gyro sensor drift by using inclination of lower body segments during mid-stance of gait [18]. Sabatini has also proposed calculation of body segment orientations from angular velocity data of a body mounted gyroscope using quaternions [20]. This proposed method also used the cyclic properties of gait to compensate for the drift in the results. Favre et al. [17] have also used acceleration data for compensation of the drift, but the method could only be used where the only force components measured is the gravitational acceleration. A research has also been done to estimate the acceleration signal output at the centre of rotation of the knee using inertial sensors attached to the thigh and shank separately. This method does not make cyclical properties of gait an assumption in the calculation and is shown useful in obtaining accurate knee joint measurements. This method is then further used in determination of positions of hip, knee and ankle joint centres. Despite its accuracy in measuring flexion-extension movements, internal-external rotation of the joint is not taken into consideration. This problem is not addressed until a sensor system which incorporates magnetometer is developed. Picerno et al. have reported high reliability and accuracy in using the sensors system for gait analysis with specific anatomical calibration [21]. However, Brodie et al. have reported that accuracy exists when the measurements using inertial and magnetic sensing sensors are compared with a camera based motion analysis system [15]. The errors could only be eliminated by recalibrating the sensors regularly and conducting the experiment in a homogeneous magnetic environment, which is not realistic in everyday situations [9]. Tadano et al. have reported a substantially reduce in error caused by noise by implementing sensor attachment error calibration and signal filtering on quaternion calculations. In their experiment, quaternions were implemented to better represent the joint motion while avoiding singularities. Body mounted sensors suffer from many factors such as attachment errors, calibration maintenance, signal noise, filtering errors and integration drift. It is reported that even commercially available motion tracking systems have significant errors [15]. Therefore, it is important to choose a method which could minimise the errors in motion analysis of human body parts.

The use of IMU in medical application provides a high resolution solution to motion analysis of human body parts, which enables better performance in surgery related to human body joints. The use of IMU in the motion analysis of human body parts enables the understanding of the shoulder biomechanics which has resulted in surgical modifications of the implant and eventually reduction of the rate of complications. Motion analysis of knee using IMU could be useful. It could be used to compare the recovery rate against national average to determine the effectiveness of new knee prosthesis. This will involve studying the kinetics and kinematics through quantifying the change in gait and joint forces over time. When possible the kinematics of gait before and after the surgery will be studied to measure the relative contribution of the intervention. This method could also be used to evaluate new knee prosthesis developed. The new implant could be assessed if it meets the functional demands of patients in the aims to improve the life, range of motion, stability, wear resistance, post operation complication such as joint failure, stability, detachment, tension settings and excess motion [19,21–24].

This eventually leads to the objective of this research, which is to develop a cost effective inertial measurement unit based human motion analysis device. This device is portable to qualitatively and quantitatively assess human body joints with 3D graphical tracking feature and its kinematics data, such as acceleration, angular velocity, orientation (angle), position and bending angle. The work presented here is a pilot study on an approach of extracting the 3-dimensional orientation data using quaternions from the Digital Motion Processor (DMP) of IMU. The DMP acquires data from accelerometers and gyroscopes and provides an integrated motion fusion output which is capable of computing quaternion data from sensor readings and performing device calibration. The DMP generated sensor fusion orientation data with the ability of device calibration is hypothesized to have relatively less errors or drifts compared with orientation data reported in previous studies.

In this study, a wireless human motion analysis device is first