Evaluation of a 3-dimensional inertial tracking system for quantifying human movement

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EVALUATION OF A 3-DIMENSIONAL INERTIAL TRACKING SYSTEM FOR QUANTIFYING HUMAN MOVEMENT.

by

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Bachelor of Science
Indiana University
1998

A thesis submitted in partial fulfillment of the requirements for the

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ABSTRACT

Evaluation of a 3-Dimensional Inertial Tracking System for Quantifying Human Movement

by

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The purpose of this study was to evaluate an inertial tracking unit (ITU) by comparing it to an optical tracking system. The ITU was attached to a bowling ball along with reflective markers for the optical system. Each trial started with the ball at rest on a pedestal. The ball was then hung from a steel cable 10 feet long and set in motion in an elliptical pattern for approximately 25 seconds. The ball was then removed from the cable and returned to the pedestal so as to end each trial at rest. This was repeated 10 times with 5 trials chosen for analysis. A 10 second section starting with the ball at rest was taken from each data set for analysis. Maximum and minimum values for position and acceleration were compared between the two systems. Correlation coefficient and Root Mean Square were calculated for position and acceleration between the two systems. Maximum and minimum displacements in the Z plane were different between the two systems, while maximum acceleration in the Y plane and maximum and minimum acceleration in the Z plane were different. Only acceleration in the Z plane was strongly correlated between the two systems. As configured for this experiment the ITU did not reliably track the same motion as the optical system most likely due to slight misalignment of the gyroscopes.
I would like to thank Dr. Richard Kant for his help and guidance during the course of this project.
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CHAPTER 1

INTRODUCTION

Evaluation of a 3-Dimensional Inertial Tracking System for Quantifying Human Movement

As technology advances and new research tools become available it is imperative that the strengths and weakness of each new tool are assessed in order to determine the validity of using the tool for a particular application. The type of particular tool or tools chosen to answer questions depends greatly on the nature of the question being asked. A tool that may work very well for one study may not be the right choice for another.

In the field of biomechanics, researchers use tools to quantify different aspects of human movement. Tools which can quantify kinematics are necessary. Kinematics is the branch of mechanics concerned with the motions of objects without being concerned with the forces that cause the motion. Kinematic measurements that describe motion such as position, velocity, and acceleration of a segment are of interest. Using these measurements to describe the movement of a segment allows angles, angular velocity, and angular acceleration to be calculated, for example. In order to describe the motion of a human body, the kinematics of each relevant segment of the body needs to be tracked and measured. The most common approach to measuring kinematics is to measure position of a segment with respect to time. From these data velocity (the time rate of change of position) and acceleration (the time rate of change of velocity) can be derived. For example, the position of a segment can be tracked using common optical technology such as video cameras. A camera (2-dimensional analysis) or cameras (3-dimensional analysis) track the movement of markers or landmarks through a calibrated space.
Coordinate data of the markers can be calculated by hand digitizing the images or by using a computerized motion tracking system available on the market today. Companies such as ViconPeak, Motion Analysis, and Qualsis manufacture systems which use cameras and reflective markers to generate position coordinate data of segments. In order for a segment to be defined in three dimensions, it must have a minimum of three reflective markers placed on it. The measured positions of these markers are used to calculate the position and orientation of the segment.

Another tool that is starting to be used in laboratories to quantify kinematics is an inertial tracking system. These systems use micro electro-mechanical systems such as accelerometers and gyroscopes that are both small and inexpensive. They have higher sampling rates than most optical tracking systems, and they can be placed on a subject without concern for possible occlusions. Position of the unit is calculated by taking the double integral of acceleration in each axis, while gyroscopes, which measure the angular rate about a given axis, track the orientation of the unit.

Similar technology has been used successfully in virtual reality systems (Lang, Kusej, Pinz, Brasseur, 2002), navigation systems (Walchko 2002), and has been evaluated for 2-dimensional kinematic analysis (Mayagoitia, Nene, Veltink, 2002). These studies have shown there is some promise for the use of this technology in biomechanics, however none of the studies address the question as a three dimensional evaluation of quantifying human movement. Therefore, the purpose of this study is to evaluate a three dimensional inertial tracking units’ ability to quantify the kinematics of a moving body.
Definitions

ac·cel·er·a·tion n.

1. a. The act of accelerating.
   b. The process of being accelerated.

2. The rate of change of velocity with respect to time.;

ac·cel·er·om·e·ter n.

An instrument used to measure acceleration.;

an·gle n.

1. Mathematics
   a. The figure formed by two lines diverging from a common point.
   b. The figure formed by two planes diverging from a common line.
   c. The rotation required to superimpose either of two such lines or planes
      on the other.
   d. The space between such lines or surfaces.

angular acceleration

The rate of change of angular velocity with respect to time. Angular acceleration
is measured in revolutions per minute squared or in radians per second squared.;

angular velocity n.

(Physics / General Physics) the velocity of a body rotating about a specified axis
measured as the rate of change of the angle subtended at that axis by the path of
the body. Symbol ω;
bi-o-me-chan·ics n.

1. (used with a sing. verb) The study of the mechanics of a living body, especially of the forces exerted by muscles and gravity on the skeletal structure.

2. (used with a pl. verb) The mechanics of a part or function of a living body, such as of the heart or of locomotion.;

dei·riv·a·tive  n.

1. Mathematics
   a. The limiting value of the ratio of the change in a function to the corresponding change in its independent variable.
   b. The instantaneous rate of change of a function with respect to its variable.
   c. The slope of the tangent line to the graph of a function at a given point.

Also called differential coefficient, fluxion.;

dis·place·ment n.

A vector or the magnitude of a vector from the initial position to a subsequent position assumed by a body.

gy·ro·scope n.

A device consisting of a spinning mass, typically a disk or wheel, mounted on a base so that its axis can turn freely in one or more directions and thereby maintain its orientation regardless of any movement of the base.
in·er·tia n.

1. Physics The tendency of a body to resist acceleration; the tendency of a body at rest to remain at rest or of a body in straight line motion to stay in motion in a straight line unless acted on by an outside force.

2. Resistance or disinclination to motion, action, or change;

in·te·gra·tion n.

The process of computing an integral; the inverse of differentiation.;

kin·e·mat·ics(n. (used with a sing. verb)

The branch of mechanics that studies the motion of a body or a system of bodies without consideration given to its mass or the forces acting on it.;

meas·ure·ment n.

1. The act of measuring or the process of being measured.

2. A system of measuring: measurement in miles.

3. The dimension, quantity, or capacity determined by measuring;

move·ment n.

1. a. The act or an instance of moving; a change in place or position.

   b. A particular manner of moving.;

o·ri·en·ta·tion n.

1. The act of orienting or the state of being oriented.

2. Location or position relative to the points of the compass.

3. The direction followed in the course of a trend, movement, or development.;

po·si·tion n.

1. A place or location.
2. a. The way in which something is placed: the position of the clock's hands.
   b. The arrangement of body parts; posture: a standing position.

3. A situation as it relates to the surrounding circumstances;

quantify r.v. quantified, quantifying, quantifies
To determine or express the quantity of;

quaternion n.
Any number of the form a + bi + cj + dk where a, b, c, and d are real numbers, ij = k, i2 = j2 = -1, and ij = -ji. Under addition and multiplication, quaternions have all the properties of a field, except multiplication is not commutative;

three-dimensional adj.
1. Of, relating to, having, or existing in three dimensions
2. Having or appearing to have extension in depth;

valid adj.
1. Well grounded; just: a valid objection.
2. Producing the desired results; efficacious: valid methods.
3. Having legal force; effective or binding: a valid title.
4. Logic
   a. Containing premises from which the conclusion may logically be derived: a valid argument.
   b. Correctly inferred or deduced from a premise: a valid conclusion.

velocity n. pl. velocities
1. Rapidity or speed of motion; swiftness.
2. Physics A vector quantity whose magnitude is a body's speed and whose direction is the body's direction of motion;
CHAPTER 2
REVIEWS OF RELATED LITERATURE

There are a number of different measurement tools appropriate for kinematic analysis of human movement. These instruments directly or indirectly measure one of the key variables in Newton’s Second Law of Motion (i.e. $\Sigma F=ma$), which is at the core of research in the field of biomechanics. The purpose of this literature review is to summarize the research conducted to date on the use of accelerometers as a tool to measure kinematic parameters.

First, two commonly used tools in the field of biomechanics, motion capture systems and accelerometers will be introduced. Then research comparing these systems will be reviewed. The following method will be used to review each article. First the purpose of each study will be stated. Followed by the number of subjects tested, the type of instruments used for data collection and the procedures used to collect data. Procedures will include the type of movement the number of trials collected and the number of separate conditions each study used. Relevant data reduction techniques will be described along with the variables of interest. The type of statistical analysis used will be listed along with the key results from each paper. The authors’ conclusion and an interpretation of the conclusion will follow. If any of this information was not included in a particular article it will be noted as not reported.

Accelerometers

There are many styles of accelerometers varying in size and purpose. Two types of accelerometers that will be discussed in this paper are piezoelectric and integrated
The main components of a piezoelectric accelerometer are a mass and a piezoelectric crystal. Piezoelectric crystals produce a voltage proportional to the force applied to the crystal. In a piezoelectric accelerometer, the mass sits on the crystal in such a way that when the mass is accelerated it exerts a force on the crystal. The voltage change generated by the crystal can be amplified and measured by a computer. Since the mass is constant and since force exerted is proportional to acceleration, the piezoelectric accelerometer measures acceleration.

Integrated circuit accelerometers use a very small mass located between two plates on the surface of a computer chip. When there is acceleration the mass moves which changes the capacitance of the circuit. These types of accelerometers are sensitive to the acceleration due to the force of gravity which can help determine the orientation of the unit in space.

Optical Motion Capture Systems

Optical marker motion capture systems that use cameras to record the movement of reflective markers allow the user to quantify the location in space of specific markers. These data can then be double differentiated to yield the acceleration— and the accelerations can be incorporated in subsequent analyses (e.g., calculation of joint moments). Acceleration values therefore are measured indirectly. Accelerometers on the other hand measure acceleration magnitude directly, but in order to use the measurements for dynamics analysis the magnitude and direction of the acceleration must be known. Optical tracking systems have been used to describe the mechanics of running between
genders and propulsive adaptations to changing gait speed (e.g., Ferber 2003, e.g., Riley 2000).

Validity of Accelerometers for Kinematic Analysis

The development of new instrumentation techniques generally begin by establishing the validity and reliability of the instrument. Validity is defined as the degree to which a test or instrument measures what it purports to measure (Thomas 2005). Concurrent validity involves correlating an instrument with some criterion that is administered at the same time. Using this approach a researcher will measure a movement using two systems concurrently. This allows the researcher to quantify any differences in the measurement of the movement and to empirically evaluate the validity of the instrument. Validity can be quantified using Root Mean Square Error (RMSE) which is a statistical technique used to measure the magnitude of a varying quantity. The purpose of this paper is to compare the validity of an inertial tracking unit to an optical tracking system.

Van den Bogert et al. (1996) attached four triaxial accelerometers to a semi-rigid frame which was worn on the upper body of a single subject. They compared calculated hip joint forces and moments during single stance phase of walking and running, using both accelerometry and kinematics collected using an optical tracking system along with ground reaction force. The number of trials was not reported. Optical tracking data were smoothed with a cutoff frequency of 10 Hz for walking and 20 Hz for running while no smoothing was done to data collected from accelerometers. The authors reported a difference of about 20% in intersegmental force while the difference in moment data
were described as “somewhat less” than 20% between the two techniques. Average accelerometer RMS during walking was reported to be 0.32 ms² while average RMS during running was 1.07 ms² (SD were not reported). The authors reported that the rigidity of the accelerometer system was poor during the impact phase of running where RMS values reached peaks between 5.0 and 5.5 ms². The authors noted that a limitation of the study was that the accelerometer data provided force and moment on the upper body, while the optical tracking system with force plate provides information about the left hip so their experiment is not complete apples to apples comparison. They hypothesized that forces from the swing leg which were neglected in the accelerometer analysis could have contributed to the differences found between the two systems. They also point out that assuming the body as rigid added error in both methods especially during the impact phase of running. They concluded that using accelerometers for dynamic analysis is an appropriate use of the tool, but caution that the technique they used underestimated forces and moments by about 20% because forces from the swing leg were neglected. This paper highlights some of the limitations found when using accelerometers for dynamics analysis, but suggests that with improved technique using accelerometers could be appropriate.

Acceleration data can be integrated to find velocity and position. Giansanti et al. (2003) devised an analytical model to test the ability of two different multi-accelerometer systems to track the position and orientation of a segment. They used both a six and nine uni-axis accelerometer model and estimated the error propagation for each system. The authors did not perform a physical experiment only a theoretical model so subject data were not reported. They reported that errors in the estimation of position during three
simulated conditions grew over time and that the largest contributors of error were found in the inaccuracies of the orientation of the active axes of each accelerometer and the offset error of an accelerometer. The overall conclusion was that neither of the accelerometer models they studied would be appropriate for both position and orientation tracking. However they hypothesized that offset errors could be reduced to a minimum through an accurate calibration process.

A limitation of using accelerometers during human movement is identifying the orientation of the acceleration. To address this limitation, a micro machined gyroscope can be paired with an accelerometer to measure the change in angular rate about a specific axis, thus giving the orientation of the acceleration.

Baten et al. (1996) compared an accelerometer/gyroscope unit, also called an inertial tracking unit, to a 3D motion capture system for estimation of absolute back inclination angle in the sagittal plane. The accelerometer was mounted tangentially along with a gyroscope on a strip of orthoplast material on the skin above the spine at the level of L5/S1 for 9 subjects. Optical markers were placed on L5/S1 and T1 and the line between these markers were used to calculate absolute back angle. The subjects performed a lifting experiment which started from a flexed position at approximately 90 degrees, and moved to an extended position of about 0 degrees. The number of trials and conditions each subject performed were not reported. The authors reported the inertial unit estimated absolute back inclination angle with a typical relative error of 10% compared to the motion capture system. Data reduction techniques and statistical techniques were not reported. They concluded that the main source of error was the gain/conversion factor of the gyroscope. This conversion factor was derived by rotating the unit at three
90 degree intervals (-90°, 0°, and 90° with respect to gravity) and holding the unit still for 2 seconds at each interval. At each of these stopped positions the output signal from the gyroscope should be zero. They averaged the output signal over 4 intervals and 2 calibration trials to calculate the conversion factor for the gyroscope. They noted that improvements in calibration technique could improve the accuracy of the inertial unit, but that even using the current technique, the estimated back angle estimation in a single plane was reliable.

Heyn et al. (1996) compared an accelerometer/gyroscope unit to a 3D motion capture system for measuring sagittal plane kinematics during the swing phase of gait. The system used in their study consisted of two aluminum strips one for the thigh and one for the shank. On each strip were two pairs of uni-axial accelerometers, each pair having one accelerometer oriented radially and one oriented tangentially, and one gyroscope. These strips were placed anteriorly on the left shank and thigh of 8 male subjects. Reflective markers were placed on the centers of rotation of the hip, knee and ankle. The two systems were used to measure absolute shank angle and shank angular acceleration during walking. The number of trials and conditions performed were not reported. The correlation coefficient for absolute shank angle between the two systems was 0.995; the Root mean square (RMS) error was 0.026 deg. The correlation coefficient for shank angular acceleration between systems was 0.989 the RMS error was 128.5 deg/s/s. Data reduction techniques were not reported. The final conclusion was that the inertial sensors provide an accurate representation of all values necessary for the calculation of net moment about the knee during swing phase.
Mayagoitia et al. (2002) compared the validity of an accelerometer and gyroscope system to a motion capture system on 10 subjects walking at five different speeds on a treadmill. Each condition was recorded for at least 10s. The inertial system consisted of an aluminum strip with two pairs of uni-axial accelerometers and one gyroscope. Each accelerometer pair had one accelerometer oriented radially and one accelerometer oriented tangentially. One inertial system was attached to the shank and one was attached to the hip, using Velcro straps. Reflective markers for the motion capture system were placed on the lateral maleolus, lateral condyle, and greater trochanter. All data was smoothed using a sixth order Butterworth low pass filter using a cutoff frequency of 3 Hz. They compared the two systems by using the motion capture system as the gold standard, and calculating RMS and coefficients of correlation for all parameters at each of the five different walking speeds. They calculated percent error as the ratio of RMS error to average peak to peak values from the optical tracking system. They reported the percent error to be less than 7% in 75% of the cases with an overall mean of 6.64% and a standard deviation of 4.13%. They also observed high coefficients of correlation between the inertial units and the optical tracking system in 100% of the cases with an overall mean of 0.9812 and standard deviation of 0.02. The highest percent error (11-15%) and lowest coefficient of correlation (0.93) was knee linear acceleration. The authors noted that the RMS values for knee linear acceleration were dependent on the distance from the sensors to the knee joint and they attribute the higher error to small amounts of slippage of the aluminum strip, which hold the sensors, during movement. The authors reported that the inertial sensor units were able to accurately measure the following kinematic parameters in the sagittal plane: shank angle, thigh angle, knee
angle, shank angular velocity, thigh angular velocity, knee linear acceleration, shank angular acceleration, and thigh angular acceleration. The authors presented results for the following parameters: shank angle, shank angular velocity, knee linear acceleration, and shank angular acceleration. The authors concluded that “the body mounted sensors are accurate inexpensive and portable and allow long-term recordings in clinical, sport, and ergonomics settings.”

Simcox et al. (2001) compared accelerometer and gyroscope sensor packs to a motion analysis system for trunk and lower limb movements during normal walking. One subject was instructed to walk at a self-selected pace for “multiple trials” with each trial lasting 10 seconds. Each inertial sensor pack was comprised of two bi-axial accelerometers and one gyroscope. One sensor pack was fitted to each thigh, shank, and trunk of the subject, along with retro reflective markers aligned on bony landmarks in order to identify limb segments. Sagittal plane angle was compared between the two systems using the optical system as the gold standard. Other data reduction techniques were not reported. The authors reported the RMS error for each segment as follows: trunk-1.45 deg, left thigh-4.24 deg, right thigh-2.92 deg, left shank-2.97 deg, and right thigh-3.00 deg. The correlation coefficients for the entire data set between systems were as follows: thigh-0.970, left thigh-0.971, right thigh-0.998, left shank-0.991, and right shank-0.900. The authors concluded that the use of accelerometers and gyroscopes are accurate and reliable for measuring trunk and lower limb sagittal plane orientation.

Veltink et al. (1996) used two uni-axial accelerometers and a gyroscope to measure shank angle in the sagittal plane during cyclical flexion/extension movements while a subject was sitting. The number of trials was not reported. All data were
smoothed with a fourth order Butterworth filter using a cutoff frequency of 5 Hz. They used two different methods of processing the accelerometer/gyroscope data and compared both results to information collected from a bi-axial flexible goniometer. The first method they used estimated shank angle by integrating the signal from the gyroscope. They reported that the integration drift occurred shortly into the data collection (2 sec) resulting in an RMS error of 13.3 deg compared to the goniometer. The second method combined the radial and tangential components of acceleration with the measurements from the gyroscope and the distance of the sensors from the knee axis to calculate shank angle. They reported this method to be more reliable resulting in an RMS error of 4.4 deg.

All of the papers reviewed in this section have reported that the use of accelerometers and gyroscopes are appropriate for use in kinematic analyses. The following section reviews papers that involve three dimensional analyses.

**Quaternion Analysis**

In order to track movement in three dimensions a system must be capable of measuring, organizing, and processing spatial data. Local reference frame position and orientation data, for each time interval in each plane must be identified. Local coordinates from each interval are converted to global coordinates in the global reference frame using mathematical rotation techniques.

In 1843 an Irish mathematician named William R. Hamilton was the first to describe quaternions. Quaternions are complex numbers which provide us a simple representation for describing finite rotations in space (Hamilton 1853). Chou (1991)
noted that quaternions have been used successfully in a variety of applications such as, kinematic analysis, rigid body dynamics, robot trajectory planning, robot dynamics, spacecraft control, camera calibration, and photogrammetry.

A quaternion is a type of complex number with a real and imaginary part. The real part of the quaternion contains one value while the imaginary part contains three values. This gives it both a vector and scalar quantity. A quaternion can be defined mathematically in the form of $q = a + xi + yj + zk$ where $a$ represents the magnitude (real) and the other three values represent the orientation (imaginary) where $x$, $y$ and $z$ are orthogonal unit vectors. A quaternion is able to represent one rotation about one rotation axis in space. In order to perform a rotation about a specific axis the quaternion representation is:

$$Q_a = \cos(\theta/2) \quad Q_{x,y,z} = \sin(\theta/2)$$

Where $\theta$ is the amount of rotation about each specific axis. It should be mentioned that using quaternions to represent rotations is more computationally efficient than rotating in Euler space because there are fewer trigonometric functions called (Hamilton 1853).

Bachmann et al. (2001) used quaternions to track human segment motion for the arm and leg. They used a combination of 3 accelerometers, 3 magnetometers, and 3 gyroscopes each mounted orthogonal to each other. They used the information from the accelerometers combined with the information from the magnetometers to help stabilize the drift found in the gyroscope data. The authors applied these data to their quaternion rotation process to help reduce orientation errors. The authors preformed three separate experiments. Experiment 1 compared the instrument to a static reference frame of which the spatial coordinates were measured for one hour and found the average total RMS drift
was about 1%. Experiment 2 compared the instrument during a dynamic task by placing the sensor unit on a Haas rotary tilt table and repeatedly cycled the sensor through various angles of pitch, yaw, and roll at rates from 10 to 30 deg/sec. The reported achieved results of better than 1 degree accuracy of orientation. Experiment 3 consisted of testing the unit during human movement by attaching three sensors to three human segments with elastic bands and doing a qualitative comparison between the sensors and video data. They report that segment orientation appeared accurate and showed very little time lag. The authors conclude that the combination of the sensor pack and the quaternion representation of rotation can continuously track orientation of limb segments through all attitudes without singularities.

Lang et al. (2002) studied the effectiveness of an inertial tracking system for use in real time virtual reality. Their system used 3 accelerometers and 3 gyroscopes mounted orthogonally to each other. Orientation was calculated using quaternions and drift was adjusted by using a visually based tracker updated at 10 Hz. They preformed translation tests manually, and rotation tests with a pan tilt unit that allowed controlled simultaneous independent rotation in two axes. They compared the inertial tracking unit to an optical tracking system. The authors reported good agreement between the two systems in the translational experiment (simultaneous movement in the x and y direction) with an average XYZ position RMS error of (0.1mm ± 4.1, 2.9mm ± 9.4, 0.4mm ± 1.8). The rotation experiment consisted of a simultaneous 30 deg rotation about the y-axis and a 90 deg rotation about the z-axis at a 50 deg/s rate. Average XYZ orientation RMS error was (0.18 deg ± 0.29, 0.20 deg ± 0.29, 0.20 deg ± 0.31). The authors conclude the inertial
tracking system is capable of performing applications in virtual reality, especially when coupled with a visual tracking system.

Optical Motion Capture Validity

Richards (1999) tested the validity of seven optical tracking systems. A device was constructed with 7 reflective markers. The device consisted of a rotating bar on a base for the test the bar rotated in a horizontal plane at 60 rpm. Two markers were placed on the top of the bar 50 cm apart so as to always be in view of the cameras. At the end of the bar a plate with 3 markers in a triangle was placed perpendicular to the bar. A stationary marker was placed on the floor on a post, and the final marker hung by a post from the bottom of the bar at the same height as the stationary marker. Position data were collected with a six camera optical tracking system at 60 Hz for six trials. The first test compared the measured distance between the top 2 markers to the known distance of 50 cm. The author reported the optical tracking system had an average measurement of 49.953 cm with an RMS error of 0.062 cm ± 0.183. The second test compared the measured distance between 2 markers on the plate to the known distance of 9 cm. The author reported the optical tracking system had an average measurement of 8.980 cm with an RMS error of 0.129 cm ± 0.557. The next test compared the measured angle between the 3 markers on the plate to the known angle of 95.8 deg. The author reported the Vicon system had an average measurement of 94.543 deg with an RMS error of 1.421 deg ± 4.632. The authors reported that an optical tracking system can accurately track markers to within 3 mm.
Summary

Inertial tracking systems are a developing technology and the validity of the instrument has been explored. The studies reviewed in this paper provide evidence that the use of accelerometer and gyroscope based inertial tracking systems can be used to quantify movement. While there has been success using these instruments for two dimensional studies, progress still needs to be made using these devices for three dimensional measurements. The study I propose attempts to answer some of the basic questions that arise when a novel approach to instrumentation is undertaken.
CHAPTER 3

METHODOLOGY

Instrumentation

Inertial data were collected using a combination of a 3-axis Analog Devices ADXL335 (range: +/- 3g, sensitivity: 300 mV/g, frequency response: X and Y 1600 Hz, Z 550 Hz) accelerometer and 3 uni-axis Analog Devices ADXRS150 (range: +/- 150 deg/s, sensitivity: 12.5 mV/deg/s, frequency response: 40 Hz) gyroscopes. The accelerometer was mounted on an acrylic cube and gyroscopes were mounted orthogonal to each other on the same cube. Each instrument was fixed to the cube using epoxy. The cube was mounted onto the rotating axis of an isokinetic dynamometer. This was done by drilling holes through the cube so that each axis of the instrument could be rotated about the axis of the dynamometer. Data used for scaling factors for both the accelerometer and the gyroscope were collected concurrently for each axis. Each axis of the accelerometer was run through a 2 g tip over test to establish the scaling factor in g/volt along with the offset voltage which is the voltage at zero g. A 2 g tip over test is appropriate because the accelerometer is sensitive to the acceleration due to gravity the voltage can be measured when the accelerometer sensitive axis is parallel to gravity and then turned over so that the sensitive axis is parallel to gravity in the negative direction. The difference in voltage is equal to 2 g’s and the midpoint between the maximum and minimum voltages was considered to be equal to zero g’s which is the offset voltage. The scaling factor for each gyroscope was obtained by rotating them at 75 deg/s. The gyroscopes measurement range was 150 deg/s so since 75 deg/s was at the midpoint of the range it was chosen as the calibration angular velocity. While 150 deg/s would only
relate to a slow human movement such as walking it was appropriate for the movements in this study. The isokinetic dynamometer used for calibration does not move at a constant angular velocity throughout the entire range of motion. Therefore a 1 second portion of data were selected from the middle section of the data were angular velocity was constant, and used for calibrating the gyroscope. Degrees per volt was calculated and converted to radians/volt for further calculations. Data were collected at 1210 Hz using Bioware 3.0 data acquisition software.

Optical data were collected using a 120 Hz 12 camera Vicon system. Eight cameras were mounted along the walls of the lab space approximately 12 feet from the floor. Four cameras were mounted on tripods on the floor so that overall camera arrangement resembled an oval around the capture volume for a total of 12 cameras. The cameras were calibrated so that no camera had a mean residual error of over 3.00 mm. The XYZ reference frame was established using the right hand rule with X being horizontal along the width of the lab, Y being horizontal along the length of the lab, and Z being vertical. Data were collected using Workstation 3.24 software. Data from the two systems were time synchronized with a square wave sent simultaneously to each data acquisition system. A procedural flowchart is included in Appendix IV.

Procedures

In order to evaluate the inertial tracking unit in three dimensions a mechanical device that could move in 3 planes was necessary. A swinging pendulum met this requirement, and one was constructed using a bowling ball and steel cable. The inertial tracking unit was attached to the outside of the bowling ball. Also attached to the
bowling ball were three 25 mm reflective markers. The markers were placed on the acrylic cube with one placed on the same sides as the gyroscopes. The ball started each data collection on a pedestal so that it would be at rest at the beginning of each trial. The ball was marked on three sides so that it could be placed back on the pedestal in the same orientation at the end of each trial (Figure 2). After the data collection had begun in each trial, the ball was picked up and placed on a steel cable by a hook. The pendulum was set in motion in an elliptical path and data were collected for 30 sec. A total of 10 trials were collected in order to get 5 trials of complete data. Trials were excluded from analysis if they were missing data from the optical system.

Figure 1. Inertial tracking unit with optical markers affixed to a bowling ball.

Figure 2. Bowling ball resting on start/stop pedestal.
Data Reduction

The data from the inertial tracking unit were processed using a custom program (Matlab ver. 6.1, Appendix I) to calculate acceleration data in the X, Y, and Z directions. This processing started with the raw voltage data from the instruments converted into g’s and radians/volt. Voltage offset was subtracted from accelerometer data. DC Bias was removed from all ITU data by averaging the first 0.6 sec of data from each instrument and subtracting that value from each data point in each axis. The data during this time were stable for each trial. The frequency of the pendulum was less than 1 Hz therefore gyroscope data were filtered with a Butterworth filter with a cutoff frequency of 4 Hz. All data from the ITU were filtered using a 5 point moving window. Initial basis vectors for the ITU were computed. Local reference (ITU) accelerations were transformed to global reference (Lab) accelerations using quaternion transformation. 1 g was then subtracted from the Z direction to correct for gravity, and then all accelerations were converted to meters per second. Mean trend was removed from acceleration data by subtracting the mean of all data points from each data point. Acceleration data were
integrated using the trapezoidal rule to calculate velocity and velocity data were integrated using the trapezoidal rule to calculate position.

Position data from the three markers used for the optical system were filtered using a Butterworth filter with a cutoff frequency of 4 Hz. Vector addition was used to calculate X, Y, Z position data for a virtual marker which represented the location of the accelerometer. This was done using a custom program (Matlab ver. 6.1. Appendix II). The position data were used to derive velocity and velocity data were used to calculate acceleration, using first central difference. The optical motion capture data for position, velocity, and acceleration were then resampled to 1210 Hz using linear interpolation in Matlab, so that there would be an equal number of data points in each data set.

A 10 second span from each trial was used for analysis between the two systems. Each 10 second span began while the ball was at rest, and included the motion of the ball being hooked onto the cable along with the elliptical motion of the ball moving through space.

Statistical Analysis

Minimum and maximum positions, along with minimum and maximum acceleration in each direction (i.e., x, y, and z) were recorded for a total of 12 dependent variables for each instrument. Each dependent variable was compared between instruments using a paired t-test ($\alpha = .05$). In addition, coefficient of correlation was calculated for position in each plane (x, y, and z) between the two systems for each trial. Coefficient of correlation was calculated for acceleration in each plane (x, y, and z) between the two systems for each trial. The correlation coefficients from each trial were
averaged to one composite correlation coefficient for each parameter in each direction. Root mean square (RMS) was calculated for position and acceleration data in each plane (x, y, and z) using the data from the optical system as the standard for the position data and data from the ITU as the standard for the acceleration data. The RMS from each trial was averaged to one composite RMS for each parameter in each direction.
CHAPTER 4
FINDINGS OF THE STUDY

Maximum and minimum displacement values are presented in Table 1. Maximum displacement in the X direction was not different between instruments (p=0.202). Minimum displacement in the X direction was not different between instruments (p=0.085). Maximum displacement in the Y direction was not different between instruments (p=0.234). Minimum displacement in the Y direction was not different between instruments (p=0.182). Maximum displacement in the Z direction was different between instruments (p=0.007). Minimum displacement in the Z direction was different between instruments (p=0.018).

Maximum and minimum acceleration values are presented in Table 2. Maximum acceleration in the X direction was not different between instruments (p=0.188). Minimum acceleration in the X direction was not different between instruments (p=0.638). Maximum acceleration in the Y direction was different between instruments (p=0.005). Minimum acceleration in the Y direction was not different between instruments (p=0.058). Maximum acceleration in the Z direction was different between instruments (p=0.018). Minimum acceleration in the Z direction was different between instruments (p=0.007).

Average correlation coefficients for X, Y, Z displacement between systems were 0.147, 0.083, and -0.623 respectively (Table 3). Average correlation coefficients for X, Y, Z acceleration between systems were 0.578, 0.457, and 0.740 respectively (Table 4). Correlation coefficients above 0.7 were considered strong, with only one (Z acceleration) meeting that criteria.
Average RMS errors for X, Y, Z displacement were 0.288 m, 0.692 m, and 0.196 m respectively (Table 5). Average RMS errors for X, Y, Z acceleration were 1.258 m/s/s, 1.836 m/s/s, and 0.790 m/s/s respectively (Table 6).

Because all of the trials had similar outcomes, position, velocity, and acceleration in x, y, and z planes (Fig. 4-12) for trial 1 are presented below, graphs for the remaining trials can be found in Appendix III.
Figure 4. Trial 1 displacement in the X plane, optical system (blue) compared to the inertial tracking unit (pink).

Figure 5. Trial 1 velocity in the X plane, optical system (blue) compared to the inertial tracking unit (pink).

Figure 6. Trial 1 acceleration in the X plane, optical system (blue) compared to the inertial tracking unit (pink).
Figure 7. Trial 1 displacement in the Y plane, optical system (blue) compared to the inertial tracking unit (pink).

Figure 8. Trial 1 velocity in the Y plane, optical system (blue) compared to the inertial tracking unit (pink).

Figure 9. Trial 1 acceleration in the Y plane, optical system (blue) compared to the inertial tracking unit (pink).
Figure 10. Trial 1 displacement in the Z plane, optical system (blue) compared to the inertial tracking unit (pink).

Figure 11. Trial 1 velocity in the Z plane, optical system (blue) compared to the inertial tracking unit (pink).

Figure 12. Trial 1 acceleration in the Z plane, optical system (blue) compared to the inertial tracking unit (pink).
Table 1. T-test results from maximum and minimum values for displacement. (* denotes difference (P = .05))

<table>
<thead>
<tr>
<th>Device</th>
<th>Mean (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X Max Displacement</strong></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>1.23±0.37</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>4.32±4.50</td>
</tr>
<tr>
<td><strong>X Min Displacement</strong></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>0.06±0.45</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>-1.99±2.42</td>
</tr>
<tr>
<td><strong>Y Max Displacement</strong></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>3.08±0.27</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>5.17±3.43</td>
</tr>
<tr>
<td><strong>Y Min Displacement</strong></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>0.39±0.32</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>-5.18±7.64</td>
</tr>
<tr>
<td><strong>Z Max Displacement</strong></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>1.77*±0.10</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>1.11*±0.20</td>
</tr>
<tr>
<td><strong>Z Min Displacement</strong></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>0.75*±0.00</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>-9.21*±5.72</td>
</tr>
</tbody>
</table>

Table 2. T-test results from maximum and minimum values for acceleration. (* denotes difference (P = .05)).

<table>
<thead>
<tr>
<th>Device</th>
<th>Mean (m/s/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X Max Acceleration</strong></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>5.47±1.18</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>4.36±1.37</td>
</tr>
<tr>
<td><strong>X Min Acceleration</strong></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>-7.22±5.95</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>-6.97±5.39</td>
</tr>
<tr>
<td><strong>Y Max Acceleration</strong></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>8.94*±1.75</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>5.76*±0.95</td>
</tr>
<tr>
<td><strong>Y Min Acceleration</strong></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>-10.14±3.90</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>-6.88±1.69</td>
</tr>
<tr>
<td><strong>Z Max Acceleration</strong></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>5.51*±1.43</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>2.81*±0.35</td>
</tr>
<tr>
<td><strong>Z Min Acceleration</strong></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>-4.67*±1.11</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>-2.86*±0.40</td>
</tr>
</tbody>
</table>
Table 3. Correlation Coefficient column represents each individual trial while Average Correlation Coefficient is the average for all trials in each direction.

<table>
<thead>
<tr>
<th></th>
<th>X Displacement Correlation Coefficient</th>
<th>Y Displacement Correlation Coefficient</th>
<th>Z Displacement Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>-0.044</td>
<td>-0.160</td>
<td>-0.603</td>
</tr>
<tr>
<td>Trial 3</td>
<td>0.159</td>
<td>-0.258</td>
<td>-0.638</td>
</tr>
<tr>
<td>Trial 6</td>
<td>0.401</td>
<td>0.209</td>
<td>-0.745</td>
</tr>
<tr>
<td>Trial 9</td>
<td>-0.164</td>
<td>0.331</td>
<td>-0.442</td>
</tr>
<tr>
<td>Trial 10</td>
<td>0.382</td>
<td>-0.260</td>
<td>-0.687</td>
</tr>
<tr>
<td>Average Correlation Coefficient</td>
<td>0.147</td>
<td>0.083</td>
<td>-0.623</td>
</tr>
<tr>
<td>SD (+/-)</td>
<td>0.252</td>
<td>0.230</td>
<td>0.114</td>
</tr>
<tr>
<td>Average Correlation Coefficient (Converted to Z-score)</td>
<td>0.154</td>
<td>-0.027</td>
<td>-0.633</td>
</tr>
<tr>
<td>SD (+/-)</td>
<td>0.261</td>
<td>0.221</td>
<td>0.121</td>
</tr>
</tbody>
</table>

Table 4. Correlation Coefficient column represents each individual trial while Average Correlation Coefficient is the average for all trials in each direction.

<table>
<thead>
<tr>
<th></th>
<th>X Acceleration Correlation Coefficient</th>
<th>Y Acceleration Correlation Coefficient</th>
<th>Z Acceleration Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>0.728</td>
<td>0.534</td>
<td>0.883</td>
</tr>
<tr>
<td>Trial 3</td>
<td>0.476</td>
<td>0.401</td>
<td>0.802</td>
</tr>
<tr>
<td>Trial 6</td>
<td>0.510</td>
<td>0.333</td>
<td>0.828</td>
</tr>
<tr>
<td>Trial 9</td>
<td>0.636</td>
<td>0.607</td>
<td>0.548</td>
</tr>
<tr>
<td>Trial 10</td>
<td>0.541</td>
<td>0.408</td>
<td>0.689</td>
</tr>
<tr>
<td>Average Correlation Coefficient</td>
<td>0.578</td>
<td>0.457</td>
<td>0.740</td>
</tr>
<tr>
<td>SD (+/-)</td>
<td>0.103</td>
<td>0.111</td>
<td>0.122</td>
</tr>
<tr>
<td>Average Correlation Coefficient (Converted to Z-score)</td>
<td>0.587</td>
<td>0.462</td>
<td>0.773</td>
</tr>
<tr>
<td>SD (+/-)</td>
<td>0.112</td>
<td>0.107</td>
<td>0.128</td>
</tr>
</tbody>
</table>
Table 5. Displacement Root Mean Square column represents each individual trial while Average Root Mean Square is the average for all trials in each direction.

<table>
<thead>
<tr>
<th></th>
<th>X Displacement RMS (m)</th>
<th>Y Displacement RMS (m)</th>
<th>Z Displacement RMS (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>0.097</td>
<td>0.728</td>
<td>0.183</td>
</tr>
<tr>
<td>Trial 3</td>
<td>0.602</td>
<td>0.610</td>
<td>0.212</td>
</tr>
<tr>
<td>Trial 6</td>
<td>0.207</td>
<td>0.796</td>
<td>0.200</td>
</tr>
<tr>
<td>Trial 9</td>
<td>0.357</td>
<td>0.498</td>
<td>0.205</td>
</tr>
<tr>
<td>Trial 10</td>
<td>0.178</td>
<td>0.827</td>
<td>0.179</td>
</tr>
<tr>
<td>Average RMS (m)</td>
<td>0.288</td>
<td>0.692</td>
<td>0.196</td>
</tr>
<tr>
<td>SD (+/-)</td>
<td>0.507</td>
<td>0.136</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Table 6. Acceleration Root Mean Square column represents each individual trial while Average Root Mean Square is the average for all trials in each direction.

<table>
<thead>
<tr>
<th></th>
<th>X Acceleration RMS (m/s/s)</th>
<th>Y Acceleration RMS (m/s/s)</th>
<th>Z Acceleration RMS (m/s/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>0.695</td>
<td>1.991</td>
<td>0.627</td>
</tr>
<tr>
<td>Trial 3</td>
<td>1.564</td>
<td>1.555</td>
<td>0.754</td>
</tr>
<tr>
<td>Trial 6</td>
<td>0.953</td>
<td>1.936</td>
<td>0.653</td>
</tr>
<tr>
<td>Trial 9</td>
<td>1.967</td>
<td>1.902</td>
<td>0.800</td>
</tr>
<tr>
<td>Trial 10</td>
<td>1.111</td>
<td>1.794</td>
<td>1.116</td>
</tr>
<tr>
<td>Average RMS (m/s/s)</td>
<td>1.258</td>
<td>1.836</td>
<td>0.790</td>
</tr>
<tr>
<td>SD (+/-)</td>
<td>0.507</td>
<td>0.173</td>
<td>0.196</td>
</tr>
</tbody>
</table>
CHAPTER 5
DISCUSSION

The purpose of this study was to evaluate an inertial tracking unit by comparing data to an optical motion tracking system to quantify the kinematics of a moving body. Compared to the optical tracking system, the accelerometer and gyroscope based inertial tracking unit (ITU) did not measure similar values for discrete kinematic parameters. It was observed that over a 10 second analysis the ITU measured differently than an optical motion tracking system in 5 of 12 parameters. However for 7 of the 12 parameters analyzed there was no difference. These statistical similarities between systems will be discussed and refuted in the following sections. To further illustrate the two systems differences only 1 of 6 (Acceleration in the Z plane) correlations between XYZ position and acceleration were considered strong while tracking the same motion.

The accelerometer had 3 sensitive axes and accelerations along those linear axes were measured. There was no adjustment made for centripetal accelerations. The motion that was measured was a pendulum traveling in an elliptical shape with a displacement of about 3 m along the major axis a displacement of about 2 m along the minor axis and a vertical displacement around 1 m. The trajectories for each of the trials can be found in figure 13.

After inspecting figures[4-12], the lack of difference in 7 of 12 parameters compared appears to be a limitation of comparing maximums and minimums between instruments rather than an affirmation that the two systems were measuring the same motion.
Figure 13. Three dimensional traces (from the optical system in meters) of the path of the ball for each trial that was analyzed, with the red line representing data that were used for analysis and the blue line representing the remainder of the trial.

There was no difference between instruments in the maximum and minimum values for displacement in the X or Y planes. Average maximum displacement in the X plane was 1.23 +/- 0.37 m for the optical system and 4.32 +/- 4.50 m for the ITU. Average minimum displacement in the X plane was 0.39 +/- 0.32 m for the optical system and -1.99 +/- 2.42 m for the ITU. Average maximum displacement in the Y plane was 3.08 +/- 0.27 m for the optical system and 5.17 +/- 3.43 m for the ITU. Average
minimum displacement in the Y plane was 0.39 +/- 0.32 m for the optical system and 5.18 +/- 7.64 m for the ITU.

To explore whether or not the statistical analysis represents the relationship in displacement data between instruments, the analysis was extended to compare discrete displacement data at different points of time. From this analysis, the differences in displacement between the two systems at t=1 sec in XYZ plane were 0.183 m, -0.863 m, and 0.139 m respectively for trial 1. The difference in displacement between instruments at t=10 sec for the XYZ plane were -6.05 m, -5.96 m, and 10.74 m respectively. The greater difference in position between instruments at 10 s vs. 1 s indicates that the maximum and minimum values for each data set happen at different points in time, with the last point of each data set from the inertial tracking unit being either a maximum or minimum value. As an example, the Z plane displacement data for trial one has a minimum value at t=10 sec for data collected with the ITU while the minimum value for the optical tracking system occurs at t= 0.629 sec. For some trials the displacement data collected with the ITU would drift in a positive direction making the last data points artificially high, while other trials would drift in a negative direction making the last data points artificially low. This drift in the data resulted in comparisons of discrete values from different moments in time.

Comparing the data from the two systems is confounded by the processes applied to each original data set. First there are sources of error in the process of calculating position data from acceleration data for the ITU. Second there are errors from the instruments themselves in measuring what is supposed to be measured. Finally there are
errors calculating acceleration data from position data for the optical system. Sources of these errors are discussed below.

Sources of Error in Determining Position Data from Acceleration Data

In order to understand the relationship between the data sets it is necessary to examine possible sources of error during the processing of the data. For example, a source of error is due to the algorithm used to estimate the area under the curve when integrating acceleration data. Acceleration data from the ITU were integrated twice using the trapezoidal rule twice to yield displacement data. Integration using the trapezoidal rule uses trapezoids to provide an approximation of the area under the curve for a particular interval. When the areas for all of the intervals are summed the output will not be the same as the true value of the area, with the difference being the integration error due to summation. Since the general motion being measured was elliptical the slope of the line oscillated from positive to negative which could minimize the effects of error from summation. For this study the ball began and ended each trial in approximately the same position and orientation. This step also helps minimize the effects of summation errors because if position and orientation are known for both time initial and time final, then any summation errors can be and were removed. To test the influence of integration method on the data, displacement data were reprocessed using an alternate integration method using rectangles to approximate the area under the curve and the results were nearly identical to the trapezoidal method. If summation errors were primarily responsible for the drift found in the displacement data from the ITU then changing the integration method should change the displacement curve. Since the curves are nearly
identical to each other it follows that summation errors have little impact on the displacement curve.

Integration Method (Trapezoids vs. Rectangles)

![Graph of displacement in the Y direction for one trial for comparing integration methods. Rectangular method is blue while Trapezoidal method is pink.](image)

Figure 14. Graph of displacement in the Y direction for one trial for comparing integration methods. Rectangular method is blue while Trapezoidal method is pink.

Another possible source of error when integrating acceleration data is using an incorrect initial velocity. If the initial velocity is incorrect, the pattern of the velocity curve resulting from integrating acceleration is not influenced: however, the magnitude and direction of velocities are. This means that errors in displacement data can result when the wrong initial velocity is used. Figure 15 illustrates the same integration with the exception of different initial velocities.

For this study each trial began with the ball at rest on a pedestal and the integration technique assumes initial velocity to be zero. In order to start the integration of acceleration data with an initial velocity of zero processing began while the ball was still on the pedestal. This resulted in the integration of acceleration data from the motion...
required in getting the ball from the pedestal onto the cable. While including this motion
was not ideal it allowed the initial velocity to be established with certainty.

Effects of Different Initial Velocities on Displacement Curves

![Graphs illustrating different initial velocities](image)

Figure 15. Three graphs to illustrate the effect of different initial velocities on position
curves after integration. The first graph has an initial velocity of 0 m/s, the second 10
m/s, and the third -10 m/s. The red line represents acceleration, the black line represents
velocity, and the green line represents position.

An unknown constant in a data set being integrated could also be a possible
source of error during processing. If a constant is being added to each data point during
integration the resulting curve will drift.

Effect of an Added Constant on Integration

![Graphs showing integration with and without constant](image)

Figure 16. The first graph illustrates integration without an added constant and the
second is integration with a constant added. The red line represents acceleration, the
black line represents velocity, and the green line represents position.
An example of something that may be affecting the data for this experiment is a DC bias, a non zero value for the mean of the signal. Similarly a value that is changing at a constant rate could cause a drift in the signal once it is integrated. An example of a constantly changing value would be a loss of voltage over time in either of the battery packs used to power the instruments. The instruments were calibrated at a particular voltage and a small change in voltage could explain the drift seen in the displacement data from the ITU. In addition to errors due to integration, another source of error for the ITU is the orientation of the gyroscopes. The accelerometer used was three dimensional, while three one directional gyroscopes were mounted on an acrylic cube using epoxy. In the present study, although every effort was made to construct the ITU such that the gyroscopes were orthogonal to each other, it seems that this may not have been accomplished. This would result in small offset errors that could lead to a DC bias which would show up in data that had been integrated. It would be preferable to have the gyro machine mounted orthogonally on a single PC board with the accelerometers. Also each of the accelerometers and gyroscopes were hard wired to both a battery pack and to a Cat 5 hub for data transmission. Even though the wires were taped together and then taped to the bowling ball, there was still some wire movement artifact during data collection. Wireless data transmission and integrated power would be welcomed improvements to this version of the ITU. Also, in regards to the power source, it would be beneficial to add a voltage regulator especially if a battery pack is used. Since the calibrations for the accelerometers and gyroscopes relate a known input to an output voltage a constant voltage is important. While the accelerometers and gyroscopes draw low amounts of power, the battery packs were still slowly losing charge during the experiment. This
would have a very small effect on output voltage, but when integrating over time a very small effect can lead to larger errors in position data due to the double integration of acceleration data.

Another source of error when the integration time is very long is rounding. At each point in time the area under the curve is estimated and then summed with the area at every other point in time. At each point in time the last digit is rounded and with a large data set this may lead to an incorrect estimation of the total area under the curve. To test the influence of rounding method on the data, displacement data were reprocessed using acceleration data that had been rounded to 3 decimal places before being integrated; the original data were rounded to 15 decimal places. If rounding method had been a primary contributor to the drift in the displacement curve then changing the method should alter the curve. Since the two curves are nearly identical it follows that rounding method was not a significant contributor to the drift seen in the displacement curve.

Different Rounding Levels (3 vs. 15 Decimal Places)

![Graph of displacement in the Y direction for one trial for comparing rounding methods. Rounding to 3 decimal places is blue while rounding to 15 decimal places is pink.](image)

Figure 17. Graph of displacement in the Y direction for one trial for comparing rounding methods. Rounding to 3 decimal places is blue while rounding to 15 decimal places is pink.
To summarize, possible sources of error during integration are the specific algorithm used, an incorrect initial velocity value, an unknown constant present in the data, and the accumulation of rounding errors. After running alternate analyses it appears that the most likely source of error in this experiment is the presence of a constant in the acceleration data from the ITU.

Sources of Error in Determining Acceleration Data from Position Data

Displacement data collected from the optical tracking system were double differentiated to yield acceleration data. Differences in acceleration data between the two systems could be caused by a number of factors. First, the effects of double differentiation of the displacement data from the optical system could account for the differences between the acceleration data from the two systems. This is because differentiation amplifies high frequency noise that is present in the signal. Figure 18 illustrates the increase in amplitude of a sine wave after double differentiation.

Second, just as in integration, the accumulation of rounding errors during the Euler transformations used by the optical system may explain some of the difference, especially in the Z plane. This is because; during an Euler transformation the rotation occurs about each axis independently and in succession. So any rounding errors that occur will have the least impact about the first axis, in this case X, while the second axis (in this case Y) will be affected more, and the third axis (Z) will be impacted the most.

There is also error in the measurement of the data from each data acquisition system. For this study the optical system was calibrated with a residual error of less than 3mm for each camera.
Figure 18. These three graphs illustrate how high frequency noise is amplified when differentiated.

Comparison Studies

Other studies have compared accelerometer and gyroscope based inertial tracking units to optical tracking systems for measurement of joint angles in two dimensions (References). The authors of these studies found strong correlations ($r > 0.9$) in joint angles between the two systems. The present study compared acceleration and displacement measurements in 3 planes, between the two systems with only one parameter showing a strong correlation (acceleration in the Z direction).
When using an accelerometer and gyroscope based system, the time length of a data capture is of critical importance especially if displacement data are of interest. As discussed before, the displacement data from the ITU began to drift after a short period of time as a result of a drift in the acceleration data set. This drift was not as noticeable in the acceleration data which may allow for acceleration data to be robust for longer data capture sessions. It is important to restate that the unit must start and stop in the same position and orientation to help stabilize the acceleration signal.

Bachmann (2001) and Lang (2002) evaluated ITU’s for use in virtual reality, and instead of comparing the ITU to an optical system they used instruments that moved in known directions and at known velocities. The ITU’s RMS XYZ orientation errors were less than one degree, while average RMS XYZ position errors were less than 3 mm. The average RMS XYZ position errors in this current study were 0.29 m, 0.69 m, and 0.20 m respectively. The ITU’s used in these previous experiments were different from the ITU used in the present study, in that one study added magnetometers and the other combined and optical tracking system, while this study used accelerometers and gyroscopes alone.

Static Analysis

Data from a static trial were collected from the ITU only and processed in the same manner as previous ITU data after the experiment was finished. Global position, velocity, and acceleration (x, y, z) data are found in Figure 19.

These data suggest a problem transforming the accelerations from the local reference frame to the global reference frame. Acceleration values should be start at zero and ideally would remain at zero. The acceleration values drift in a generally linear
fashion. Another issue is that the initial velocity is non zero. The ITU was static throughout the trial and initial velocity should be zero. As discussed previously accurate initial velocity is critical in the determination of position. It appears as if the mean trend removal affected the calculated initial velocity.

Static Trial PVA

![Graph of static trial PVA](image)

Figure 19. Global position, velocity, and acceleration (x, y, z) data for 10 seconds during a static (no motion) trial.

Practical Application

The accelerometer and gyroscope based inertial tracking system could be a low cost alternative for human biomechanics analysis. Ideally a system using this type of technology could be used to track human movement outside of a lab setting, giving researchers new insights into the way people move in the real world. The accelerometers used in this study have a measurement range of +/- 3 g. While this range is too small for many human studies it was adequate for the movements in this study. Accelerometers are built in varying sizes and measurement ranges and can be applied depending on the
movement of interest. The small size of the ITUs allow them to be placed directly on the body of the subject and combined with wireless technology give the researcher a great deal of freedom in how to collect data. Placing subjects in settings outside the lab can lead to new insights into how and why we move the way we do. ITUs could be placed inside of equipment such as golf clubs to provide feedback to the player or inside pads or helmets to quantify the force of an impact during a game. This could lead to better diagnosis of injuries such as concussions and better understanding how different levels of force are handled by the body.

It appears that there could be an improvement in the data from the ITU by using more/different bias removal. It would also be beneficial to compare both systems to a known movement, such as using a pan/tilt machine or other controlled device. Future experiments could shorten the data capture time. For this experiment data were collected for 30 seconds with 10 seconds of data analyzed for each trial. Part of this time was spent taking the ball from its stand and hanging it on the cable, then removing the ball from the cable and placing it on the stand. Improving the process of starting and stopping the ITU in the same position would make for a simpler data collection. It would also be of interest to know how long a data capture could be and have the variable of interest be reliable. In other words could one collect robust acceleration data for 10 to 20 seconds, while displacement data were good for 1-3 seconds? This information would help researchers apply these tools in an effective way for their research interests.

The ITU used in this experiment did not measure similar values for discrete kinematic parameters for the motion in the experiment when compared to an optical system. Calibrated alignment of the gyroscopes, voltage monitoring and wireless data
transmission would improve the quality of the data collected. Future experiments could
determine if these changes would be enough to use the analysis procedures for research in
biomechanics.
APPENDIX I

ITU SOFTWARE

The following code was used to process the ITU data in Matlab version 6.1.

function QUBE
'QUBE.m version 1'
clear all ;close all;clc

% SELECT an input file
Dfile='biocal1-1short 3cycle.txt','	'
Dfile= 'T9a.txt','	'
A = importdata(Dfile);% reads entire data file
SizeA=size(A);% number of data pts
npts=SizeA(:,1)

% PLOT INPUT >>
figure % #1 raw omega (volts) as fnc of time
% npts rows of omega vectors
plot(A(:,1), A(:,6:8))
title('raw omega (volts)');

figure % #2 raw acceleration (volts)
plot(A(:,1), A(:,2:5))
title('raw acceleration (volts)');

% All about time
t=zeros(npts,1);
t=A(1:npts,1);  % save the original time data
dt=A(2,1)-A(1,1);  %dt=1/100;

% acceleration scale factors (g's/volt)
asf=[1/.2605 1/.2688 1/.2479 1/.2688] ;

'Subtraction of previously measured acc. offset voltages is ON'
oV=[1.2136 1.2449 1.2233 1.2449];
for n=1:npts
A(n,2:5)=A(n,2:5)-oV; %subtract offsets
end

% omegas's scale fators (radians/volt)
wsf=[48.0366 56.0598 63.2366]/10;

% Angular velocity vectors
w=zeros(npts,3); % create and initialize

'Averaging of first sdnpts points is ON,'

%--------------------------------------
%
% sdnpts=.6*1210% sec of stable data * samples/sec
%Replace the first row of values with the average of the first 50 samples
% of the corresponding col.
% Note: The cube is assumed to be stationary
% over the first second of data
% We'll use these later to define the
% initial orientation of the cube.

S=0;% temporary summing variable
for c=2:8
  for r=1:sdnpts
    S=S+A(r,c);
  end
  A(1,c)=S/sdnpts;
  S=0;
end

%subract offset from omwgas only
oV=[A(1,6) A(1,7) A(1,8)];
for n=1:npts
  A(n,6:8)=A(n,6:8)-oV; %subtract offsets
  A(n,6:8)=.1*randn(1,3)+[1 1 1]/1e-7;
end

[A(:,6)] = butterworth(A(:,6),1210,4);
[A(:,7)] = butterworth(A(:,7),1210,4);
[A(:,8)] = butterworth(A(:,8),1210,4);

%SymAveFilter % filters A(:,2:8) %function call commented out

'Filtering, (symetric uniform averaging), is ON.'
B=A;
for c=2:8
  for r=3:npts-3
    B(r,c)=A(r-2,c)*.2+A(r-1,c)*.2+A(r,c)*.2+A(r+2,c)*.2+A(r+1,c)*.2;
  end;end
A=B;
clear B; % release the memory used by B

DEFINE and SCALE acceleration and omega vectors
acc=A(1:npts,2:5); % all 4 accelerometers

w=A(1:npts,6:8);

% Apply scale factors% switching order could mean wrong scale factors
for r=1:npts
   acc(r,:)=acc(r,:).*asf ;
   w(r,:)=w(r,:).*wsf;
end

figure          % acceleration
plot(t,acc(:,1:3))
title(' raw acceleration (gs)  ');

% At this point accelerations still include effect of tilt in gravitational field

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Compute the INITIAL BASIS VECTORS for orientation at t=0.       %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% create the three unit vectors fixed in the cube
u=zeros(3,3);

% calc. the Z-component of each u
% from acc at t=0 (not moving) ...u dot (0,0,1) =u3
for r=1:3
   u(r,3)=acc(1,r);
end

% assign u1 to be in x-z plane => u(1,2)=0
u(1,2)=0;        % by definition
% cuz the norm of u1=1, we get
u(1,1)=sqrt(1-u(1,3)^2 ); % we got u(1,3) from acc(1,1)

% from u2 is perpendicular to u1, we get
u(2,1)=-u(1,3)*u(2,3)/u(1,1); % watch out if U(1,1)=0
% u(2,3) is from acc(1,2)
% and since the norm is u2 is one, we get
u(2,2)=sqrt( 1- u(2,1)^2 - u(2,3) ^2  );

% and cuz u3 is perpendicular to both u1 and u2, thus
u(3,:)=cross(u(1,:),u(2,:));
% PREPARE for main processing loop
%output files will contain 15 columns of data, first 9 represent basis vectors next 3 are components of net acceleration(resultant) at
%next three columns are omega vector win
fout = fopen('out.txt','w'); % fout is id of output file
ffmt = '%9.5f  %8.5f  %8.5f '; %file format #1
ffmt = '%8.2e	  %8.2e	  %8.2e	';%file format #2 "scientific"
win=zeros(1,3);% create and initialize current omega vector
wmag=0; % used to hold magnitude of current omega vector
Q=[0,0,0,0]; % create a zero Quaternion transformation
pb=zeros(7,3);% hold shapes for orientation movie
% set b's to initial u's; [cubes unit vectors]
'initial base vectors are:'
b1=u(1,:)
b2=u(2,:)
b3=u(3,:)

norm(b1)
norm(b2)
norm(b3)

am=zeros(3,3); % used to hold the 3 measured acceleration vectors
at=zeros(1,3); % A vector holding total acceleration
wv=zeros(3,3); % vectors along each b(i), of magnitude win(i)
wlast=0; % magnitude of previous omega vector
nframes=1;% for a movie of basis vectors
nfrm=0;

% THE FOLLOWING LOOP DOES THE REAL WORK
% for k=1:npts
tstart=2.4;
tstop=12.4;
sps=1210;
range=round(tstart*sps:tstop*sps);

newnpts=tstop*sps-tstart*sps+1;
for k=range;
% Compute the component of the cube's basis vectors, b, as fnc(time)
% using the angular velocity vectors, w and Qaternion transformations

win=w(k,:);% get current omega vector = the kth one
wmag = norm(win); % must be in radians/s
if (wmag) % norm is non-zero so rotate basis vectors... else skip it

% Re-express components of omega in Lab(Global) frame
wv(1,:) = b1*win(1);
wv(2,:) = b2*win(2);
wv(3,:) = b3*win(3);
for c=1:3
win(c)=wv(1,c)+wv(2,c)+wv(3,c);
end
A(k,6:8)=win; % save for plotting... by overwritting input to A matrix

% set the angle for the rotation and divide by 2
thby2=(.5*(wmag+wlast)*dt/2; % 0.5 is for ave. W and /2 for half angle
wlast=.5*(wmag+wlast);

% ---DEFINE The elements of Quaternion transformation---
Q(:,1)=-sin(thby2)*win(:,1)/wmag;
Q(:,2)=-sin(thby2)*win(:,2)/wmag;
Q(:,3)=-sin(thby2)*win(:,3)/wmag;
Q(:,4)=cos(thby2);

%calculate components of the b unit vectors after rotation
% of |win|*dt about the 'win' vector
b1=qvxform(Q,b1);
b2=qvxform(Q,b2);
b3=qvxform(Q,b3);
else % (if wmag=0 then leave b's alone)
% i.e., don't rotate b's, i.e., do nothing!
end % end of the else statements

% SAVE the basis vectors, b of the cube
fprintf(fout, ffmt,   b1);
fprintf(fout,  ffmt,   b2);
fprintf(fout,  ffmt,   b3); % don't close the line yet

% Compute the acceleration along each basis vector, b of the cube
% Components of unit vectors, b, are in Lab frame;
% acc's are in g's (uncorrected for gravity
for c=1:3
am(1,:) = b1*acc(k,1);
am(2,:) = b2*acc(k,2);
am(3,:) = b3*acc(k,3);
end

% Compute the TOTAL acceleration vector, 'at'
c=1:3; at(c) = am(1,c) + am(2,c) + am(3,c);

' Gravity subtraction is ON.';
at = at + [0, 0, -1];

% copy 'at' to acc and covert to m/s for subsequent plots
c=1:3; acc(k,c) = at(c)* 9.81;
% CAUTION: we're overwriting A(:,1) which was time

% SAVE total accelartion vector ( still in g's)
fprintf(fout, ffmt, at);
% SAVE omega too but here it is still in radians/s?
fprintf(fout, [ffmt , '\n'], win);

end % ---->>>>       END of main loop     <<<<<---------
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                     END of main loop                        %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'end of main loop'
hold off % end of movie
% movie(F);       % movie(F,[2,1:(nframes-13)])

%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                     END of main loop                        %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%-----------------------------
figure    % #3 acceleration
plot(t,acc(:,1:3)) % debug
title(' acceleration (g) **** XYZ frame');

%--------------------------------------
figure         % #4  omega as fnc of time
plot(t,A(:,6:8));
title('Omega (radians/second) ');
%--------------------------------------
figure % #5  graph theta(degrees) vs time
th=cumtrapz( t,A(:,6:8))*180/pi;
plot(t,th)
title('Angular Displacement ')

--------------------------------------

figure % #6 velocity

% bias=sum(acc(1:sdnpts,1:3))/sdnpts;
bias=sum(acc(range,1:3))/newnpts;
% remove bias
% % %
for (r=1:npts)
   for(c=1:3) % 2:5 are accel's and 6-8 are gyros
      acc(r,c)=acc(r,c)-bias(c);
    end
end

plot(t(range,1),v(:,1),'r',t,v(:,2),'g',t,v(:,3),'b')
xlabel('time')
ylabel('v2')
title('Velocity (m/s)');

--------------------------------------

figure % #7 position

%bias=sum(v(:,1:3))/newnpts;
bias=sum(v(:,1:3))/npts;
% remove bias

for (r=1:newnpts)
   for(c=1:3) % 2:5 are accel's and 6-8 are gyros
      v(r,c)=v(r,c)-bias(c);
   end
end
x=cumtrapz( t(range,1), v(:,:));
c=1:3; accf(:,c)=acc(range,c);

%jam 4/22/09
my_save('c:\biomech', 'ddelion9a.txt', [x v accf], 4);

plot(t(range,1),x)
%plot3(t,..+x(:,2)..+x(:,3))
xlabel('time')
ylabel('x2')
zlabel('x3')
title('Displacement');

%--------------------------------------
figure  % #8
% recall we stored at in acc
plot3(t,acc(:,1),acc(:,3))
title('A1 and A3')
xlabel('time')
ylabel('A1')
zlabel('A3')
title('Accelerations in x-Z plane vs time')

%--------------------------------------
figure  % #9 shows 3D nature of omega
plot3(A(:,6), A(:,7), A(:,8) )
xlabel('wx')
ylabel('wy')
zlabel('wz')
title('Omega')
figure  % #8
% recall we stored at in acc
plot3(t,A(:,7),A(:,8))
title('A7 and A8')
xlabel('time')
ylabel('w7')
zlabel('w8')
title('Omega 7 and 8 vs time')

'-------------end of program------------------'
APPENDIX II

VIRTUAL MARKER SOFTWARE

clc;
clear all
% set to directory of data
% cd 'C:\Documents and Settings\me\My Documents\MATLAB\Accelerometers\Data Files'
cd 'C:\MATLAB6p1\Qcube'
%read data
'busy'

Dfile='data12.txt';
r=importdata(Dfile);
[npts sc]=size(r);
% Extract out time and marker vectors
t=r(1:npts,1);
M1=r(1:npts,2:4);
M2=r(1:npts,5:7);
M3=r(1:npts,8:10);

[M1(:,2)] = butterworth(M1(:,2),120,4);
[M1(:,3)] = butterworth(M1(:,3),120,4);
[M1(:,4)] = butterworth(M1(:,4),120,4);
[M2(:,5)] = butterworth(M2(:,5),120,4);
[M2(:,6)] = butterworth(M2(:,6),120,4);
[M2(:,7)] = butterworth(M2(:,7),120,4);
[M3(:,8)] = butterworth(M3(:,8),120,4);
[M3(:,9)] = butterworth(M3(:,9),120,4);
[M3(:,10)] = butterworth(M3(:,10),120,4);

%save some space
clear r
% get local unit vectors
b1=(M2-M1);
b3=(M3-M1);
for n=1:npts
b1(n,1:3)= b1(n,1:3)/ norm( b1(n,1:3));
b3(n,1:3)= b3(n,1:3)/ norm( b3(n,1:3));
end

% b1=(M2-M1)/norm(M2-M1);
% b3=(M3-M1)/norm(M3-M1);
%'set measured data'
c1=46.5;    % CAUTION - use same units as vicon
c2=33.04;
c4=2.27;
c5=36.9;
%calculate intermediate constants
c3= c4*c1/c2;
a=-sqrt(c3^2 +c4^2);
b=c3+c5;
% Calc.position of virtual marker. It is linear combination of vector to marker one
% and multiples of the unit vectors b1 and b3
%__________________ VIRTUAL MARKER LOCATION___________
p=M1+a*b1+b*b3;% all in mm

p=p/1000;% p is now in meters
%------------------DERIVATIVES---------------------------
%Form first derivatives...velocity of virtual marker vector'
dpdt(1:npts-1,1)=diff(p(:,1))./diff(t);
dpdt(1:npts-1,2)=diff(p(:,2))./diff(t);
dpdt(1:npts-1,3)=diff(p(:,3))./diff(t);
%form Second derivatives... accleration of virtual marker vector'
dvdt(1:npts-2,1)=diff(dpdt(:,1))./diff(t(1:npts-1));
dvdt(1:npts-2,2)=diff(dpdt(:,2))./diff(t(1:npts-1));
dvdt(1:npts-2,3)=diff(dpdt(:,3))./diff(t(1:npts-1));

%Show some plots just to see what they look like
figure
plot (t,M1/1000)
title('Position of marker M1')
xlabel('Time (s)')
figure
plot(t,M1-p*1000)
title('offset of Virtual marker')
xlabel('Time (s)')
ylabel('mm')
figure
plot(t(2:npts),dpdt)
title('Velocity of Virtual marker')
xlabel('Time (s)')
ylabel('(m/s)')
figure
plot(t(3:npts),dvdt)
title('Acceleration of Virtual marker')
xlabel('Time (s)')
ylabel('(m/s/s)')
%convert vicon time base 't' to accelerometer time base 't2'
t2=0:1/1210:(npts-1)*1/120;

%interpolate to get position (p2) of virtual marker in accelerometer time base 't2'
p2=interp1( t, p, t2 );

%compare the two
figure
plot(t,p(:,1),'o',t2,p2(:,1),'r')
title('original (o) and interpolated (.)')
ylabel('(m)')
xlabel('Time (s)')
%prepare data for saving
OutPut=[t2', p2];

% % %interpolate to get velocity (dpdt) of virtual marker in accelerometer time
dpdt2=interp1( t(1:npts-1), dpdt, t2 );
% append new data to previous
OutPut=[OutPut, dpdt2];

% % %interpolate to acceleration (dvdt2) of virtual marker in accelerometer time
dvdt2=interp1( t(1:npts-2), dvdt, t2);
% append new data to previous
OutPut=[OutPut, dvdt2];

% save data in OutPut data as tab-delimited ascii data in file called vicon
save vicon OutPut -ascii -tabs;
% clear all

% get data back -matlab puts data in variable with the same name as the
% ascii- file named in the load command.
load vicon

%verify data are really there by plotting a sample
figure
plot(vicon(:,1),vicon(:,8:10))
title('Acceleration')
xlabel('Time (s)')
ylabel('m/s/s')

'All done'
**APPENDIX III**

**SUPPLEMENTAL DATA**

**Trial 3 Data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>x acc</th>
<th>y acc</th>
<th>z acc</th>
</tr>
</thead>
<tbody>
<tr>
<td>vm</td>
<td>7.351227</td>
<td>6.396478</td>
<td>5.730238</td>
</tr>
<tr>
<td>acc</td>
<td>4.3266</td>
<td>4.3837</td>
<td>2.8558</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>xpos</th>
<th>y pos</th>
<th>z pos</th>
</tr>
</thead>
<tbody>
<tr>
<td>vm</td>
<td>1.792618</td>
<td>2.918623</td>
<td>1.81003</td>
</tr>
<tr>
<td>acc</td>
<td>0.671614</td>
<td>1.528486</td>
<td>0.961212</td>
</tr>
</tbody>
</table>
**Trial 6 Data**

<table>
<thead>
<tr>
<th></th>
<th>x acc</th>
<th>y acc</th>
<th>z acc</th>
</tr>
</thead>
<tbody>
<tr>
<td>vm max</td>
<td>3.233172</td>
<td>9.493312</td>
<td>3.875902</td>
</tr>
<tr>
<td>acc max</td>
<td>3.1707</td>
<td>6.4817</td>
<td>2.6844</td>
</tr>
<tr>
<td>x acc min</td>
<td>-3.28527</td>
<td>-8.2849</td>
<td>-3.80205</td>
</tr>
<tr>
<td>acc min</td>
<td>-3.0432</td>
<td>-6.5772</td>
<td>-2.4266</td>
</tr>
</tbody>
</table>

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Trial 1 Data

Graphs see Chapter 4

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APPENDIX IV

METHODS FLOW CHART

Accelerometer and gyroscopes mounted on cube

Cube bolted to rotating axis of isokinetic dynamometer

Each ITU axis rotated about dynamometer axis at 75 deg/s

Scaling factors and offset voltages calculated

Optical markers attached to cube

Optical system calibrated

Cube attached to bowling ball

Ball placed on pedestal marks on ball aligned with marks on pedestal

Data collection begins, ball starts at rest, then placed on cable and set into motion in an elliptical path

Ball removed from cable placed back onto pedestal and marks re-aligned, ball sits at rest, data collection ends
Raw voltage data converted into g’s and radians, voltage offset subtracted

DC bias removed

Gyro data filtered with butterworth filter

Position data filtered with Butterworth filter

Virtual marker position calculated using vector addition

All ITU data filtered with 5 point moving window

Initial basis vectors computed

Local accelerations transformed to global accelerations using quaternions

Position data used to derive velocity, velocity data used to derive acceleration

1 g subtracted from global Z axis

Mean trend removed from global accelerations

Acceleration integrated to velocity, velocity integrated to position

Position, velocity, acceleration data interpolated to 1210Hz
BACHMANN, EB. 2000 “Inertial and magnetic tracking of limb segment orientation for inserting humans into synthetic environments” Ph.D. dissertation, Naval Postgrad. School, Monterey, CA


Hamilton, SWR. 1853 “Lectures on quaternions” Hodges and Smith Dublin

Heyn, A, Mayagoitia, RE, Nene, AV and Veltink, PH. 1996” The kinematics of the swing phase obtained from accelerometer and gyroscope measurements” presented at the 18th Annu. Int. Conf. IEEE Engineering in Medicine and Biology Society—Bridging Disciplines for Biomedicine


Mayagoitia, RE, Nene, AV, Veltink, PH. 2002 “Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems” J. Biomech., 35, pp. 537–542


Riley, PO, Croce, UD, Casey, D, Kerrigan. 2000 “Propulsive adaptation to changing gait speed Journal of Biomechanics” Volume 34, Issue 2, Pages 197-202

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June 2005, 52nd Annual Meeting, American College of Sports Medicine, Nashville, TN. Zachry, TL, Wulf, G, Mercer, JA, Bezodis, N, DeLion, D. "Effects of Internal versus External Focus of Attention on EMG Activity During Basketball Free Throws"


Thesis Title: Evaluation of a 3-dimensional inertial tracking system for quantifying human movement

Thesis Examination Committee:
Chairperson, John Mercer Ph. D.
Committee Member, Janet Dufek Ph. D.
Committee Member, Mack Rubley Ph.D
Graduate Faculty Representative, Edward Neumann Ph. D.