ACCURACY AND PRECISION OF MICROELECTRONIC MEASURING SYSTEMS (MEMS)

STATIC AND DYNAMIC ASSESSMENT OF THE ACCURACY AND PRECISION OF FOUR SHIMMER 2r MICROELECTRONIC MEASURING SYSTEMS (MEMS)

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A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirements for the Degree Master of Rehabilitation Science

McMaster University MASTER OF SCIENCE (2015) Hamilton, Ontario

(Rehabilitation Science)

TITLE:	Static and Dynamic Assessment of the Accuracy and Precision of Four Shimmer 2r Microelectronic Measuring Systems (MEMS)
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NUMBER OF PAGES :	xiii,110

LAY ABSTRACT

The overall objective of this thesis was to determine if four Shimmer 2r Microelectronic Measuring Systems (MEMS) were accurate and precise enough in static and dynamic conditions prior to their use in a future study to assess seven activities of daily living (including level walking, ramp walking and stairs) in individuals with a unilateral transtibial amputation in a clinical environment. To understand the effect the environment has on the MEMS, they were assessed in both a rural environment to reduce the effect of building materials, as well as the clinical environment where they will eventually be used for research. This study confirmed that the clinical environment affected the MEMS outputs, although these effects were deemed to be clinically insignificant for the intended purpose of these MEMS. Calibration as well as accuracy and precision assessment of MEMS should be executed in the conditions and environments in which they are to be utilized.

ABSTRACT:

Microelectronic Measuring Systems (MEMS) are being used to capture kinematic data in real-world environments. The benefits of using MEMS are their small size, relatively low cost (compared to an Optical Motion Capture System) and the ability to capture real-time data in almost any environment. The accuracy and precision of MEMS can be influenced by elements in their surrounding environment such as building materials (i.e., reinforced steel) and structural components (i.e., elevators). Recognizing the influence of the environment on MEMS output is important if the MEMS are to be used in real-world environments where subjects could navigate between various environments. MEMS can also be affected by dynamic motion therefore testing of the MEMS in the same conditions in which they are to be used will help to identify any issues prior to data collection.

The overall purpose of this thesis was to determine if the outputs of four Shimmer 2r MEMS were accurate and precise enough in static and dynamic conditions to use in a future study to assess gait activities of daily living in individuals with a unilateral transtibial amputation. In order to understand the effect of the environment on the MEMS, accuracy and precision were assessed in a rural environment (to reduce the effect of building materials and structural components) as well as the clinical environment where they will eventually be used for research. The MEMS were also evaluated in static and dynamic conditions to better understand how motion affected accuracy and precision.

The results of this study confirmed that the clinical environment affected the MEMS outputs. During the dynamic condition, the gyroscope output of one MEMS sensor was significantly different than the other devices indicating recalibration or possible exclusion from future studies. Prior to using MEMS in research, it is advisable to investigate the effects of the environment on the sensor outputs as well as assess the performance of the individual sensors.

ACKNOWLEDGEMENTS

This thesis would not have been possible without the guidance, patience and understanding of Dr. Michael Pierrynowski. Dr. Pierrynowski's vast knowledge and attention to detail is awe-inspiring.

A heartfelt thanks to:

My Supervisor Dr. Norma MacIntyre and my committee members Dr. Monica Maly, Professor Paul Stratford and Dr. Stephen Perry for their guidance, input and support.

The staff, patients and volunteers at Hamilton Health Sciences Prosthetic and Orthotic Department for their support and understanding

The Ontario Association of Prosthetists and Orthotists (OAPO) for funding support.

My fellow graduate students for their friendship, support, guidance and encouragement.

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LIST OF ABBREVIATIONS

ANOVA – analysis of variance

DC – direct current

FFT – Fast Fourier Transform

Hz – hertz

LED – light emitting diode

MEMS – microelectronic measurement system

MSE – mean square error

OMCS - optical motion capture system

rad - radians

rpm- revolutions per minute

SD – standard deviation

SEM – standard of the mean

3D – 3 dimensional

9DoF – 9 degrees of freedom

Chapter 1: INTRODUCTION

1.1 Background

Microelectronic Measuring Systems (MEMS) are a classification of electronic devices that may include accelerometers, gyroscopes, and magnetometers. When placed on the body, MEMS can be used to capture kinematic data and measure participation in real-world environments with little interference to the individual (Kavanagh & Menz, 2008). Benefits of using MEMS are their low cost (relative to an Optical Motion Capture System (OMCS)), small size and ability to capture real-time data over a larger number of strides in most environments (Hanlon & Anderson, 2009). These characteristics make MEMS useful and practical for capturing data in a real-world environment when the subject forgets they are being monitored (Samà, Angulo, Pardo, Català, & Cabestany, 2011).

OMCS's are considered to be the gold standard in gait analysis (Buganè, Benedetti, D'Angeli, & Leardini, 2014; Esser, Dawes, Collett, & Howells, 2009). Gait data collection using an OMCS often involves several walking trials on a treadmill or level surface that require an individual to pass through a calibrated area (Mayagoitia, Nene, & Veltink, 2002). Walking is initiated prior to data collection in order to ensure the gait pattern is in a steady state; however, this can become fatiguing for individuals with pathological gait (Ballaz, Raison, & Detrembleur, 2013). Utilizing OMCS to assess gait on a level surface in a clinical environment does not necessarily inform gait of an individual once they are in the various environments they traverse during their vocational and avocational activities. MEMS offer an alternative that allows unencumbered analysis of gait in real world environments.

When a newer measurement instrument (such as a MEMS) is introduced in rehabilitation, its reliability and validity are often compared against the current gold standard, in this case an OMCS. Reliability and validity are frequently used terms when assessing a measurement instrument utilized in rehabilitation while precision and accuracy are terms often used in engineering to assess similar attributes. The term reliability refers to the consistency of the measures obtained from the measurement device (Gavin, 1996; Streiner & Norman, 2006). Precision refers to the repeatability of a measure under the same conditions on a second occasion (Gavin, 1996; Streiner & Norman, 2006). Precision does not have the ability to differentiate between inter and intra rater reliability or reflect how a measurement instrument will differentiate between people. Precision is a component of reliability.

Validity refers to how well the measurement instrument accurately reflects what is being measured (Gavin, 1996; Streiner & Norman, 2006). Validity needs to be put into the context of how the measurement instrument was used and the population it was used on. Validity of a measurement instrument, utilized in rehabilitation, will be different depending on the context. Accuracy refers to how close an observed measure is to the real or known value (Gavin, 1996; Streiner & Norman, 2006). Accuracy is often used in engineering where measurement instruments are tested against known values.

There is a lack of known acceleration values in human gait to compare the accelerometer data (Kavanagh & Menz, 2008). Acceleration using an OMCS is obtained by differentiating displacement data twice. Any noise or errors present in the displacement data are multiplied during the differentiation process (Esser et al., 2009; Kavanagh, Morrison, James, & Barrett, 2006). To reduce noise in the displacement signal, the data are initially low-pass filtered. This has the potential to attenuate the true displacement signal therefore introducing inaccuracies within the calculated acceleration (Kavanagh & Menz, 2008). Directly collecting accelerometer data with a MEMS eliminates issues associated with differentiating displacement data to acceleration data that occurs in OMCS (Kavanagh & Menz, 2008). It would be ideal to assess accuracy and precision of the MEMS outputs in conditions that allow direct comparison to known values such as using gravity to assess the vertical component of the accelerometer.

Manufacturers publish datasheets regarding acceptable output tolerances expected when their device is operating within specified conditions. The datasheet for the accelerometer contained within the Shimmer 2r MEMS provides a sensitivity value of ± 0.002 m/s^2 (Freescale, model MMA7361L, Arizona, USA). Manufacturer expectations may be more stringent than what is required or clinically relevant for the intended purpose of the sensors. Force platforms are comparable to MEMS in that both are instruments used in gait assessment to measure acceleration. The manufacturing tolerances of force platforms have been reported to be ± 0.1% (AMTI, model Optima HPS, Massachussets, USA) and ± 0.5% (Riemer, Hsiao-Wecksler, & Zhang, 2008). Gill et al. found that there was a 1.3-2.8% error in vertical force output when 20 to 40 lbs. were applied to a force plate (Gill & O'Connor, 1997). Using a force platform to assess ground reaction forces in children without gait impairments, Ballaz et al. found a relative mean error of 3.8% that they considered to be acceptable (Ballaz et al., 2013). When using MEMS to study acceleration during gait there will be variability in acceleration during normal human motion.

MEMS accuracy to 0.001% may not be a clinically relevant accuracy to strive toward as this level of accuracy and precision exceeds that generally acknowledged to be required to assess human motion. Therefore an *a priori* MEMS accuracy of 1% was deemed to be sufficient to show accuracy of the sensors while keeping their intended use in mind. The datasheets provided by the manufacturer should be used as a guideline to assess the MEMS accuracy; but the intended use of the sensors should be kept in mind when interpreting accuracy results.

1.2 Literature Review

Several studies have compared accuracy and precision to manufacturer datasheets and have concluded that the datasheets should not be explicitly trusted (Brodie, Walmsley, & Page, 2008a; Büsching, Kulau, Gietzelt, & Wolf, 2012). Individual assessment of the MEMS should be completed in order to identify MEMS that may need to be excluded prior to data collection (Deluzio, Wyss, Li, & Costigan, 1993; Picerno, Cereatti, & Cappozzo, 2011). Picerno et al. statically assessed 9 commercially available MEMS to determine intra- and inter-MEMS precision in detecting a global frame (Picerno et al., 2011). Their results indicated that the intra-MEMS accuracy was different depending on the axes within the MEMS and that this may influence the orientation of the sensors in future studies (Picerno et al., 2011). They also determined that intra-MEMS accuracy was dependent on calibration (Picerno et al., 2011). The assessment of inter-MEMS precision identified MEMS that measured significantly different values compared to their counterparts (Picerno et al., 2011) suggesting they should be excluded or recalibrated.

While assessing the accuracy and precision, Picerno et al. (2011) completed MEMS data collection in a meadow to reduce any ferromagnetic influence. The outputs of MEMS have the potential to be influenced by the environment in which they are used (de Vries, Veeger, Baten, & van der Helm, 2009; Haverinen & Kemppainen, 2009). Buildings have their own ambient magnetic field that could interfere with the magnetometer (Haverinen & Kemppainen, 2009). The material in the building (i.e. reinforced steel) and metallic structural components (i.e. door frames, elevators, stairs, pipes under floors) will influence a building's magnetic field (de Vries et al., 2009). Electrical components, such as electrical outlets, industrial machinery and appliances can also affect the local magnetic field as can local variations in the composition of the Earth's crust (Haverinen & Kemppainen, 2009). Recognizing the influence of the environmental and building magnetic fields on data is important if the MEMS are to be used in real-world environments where subjects could navigate between numerous environments. Although manufacturers of MEMS provide information regarding the accuracy and precision of their devices, the environment and application in which the MEMS ultimately will be used for data collection can affect their accuracy and precision (Brodie et al., 2008a; De Pasquale & Somà, 2010; Picerno et al., 2011).

DePasquale et al. found that the homogeneity among the 3 axes within MEMS sensors was lost after dynamic testing and that there was decreased precision after dynamic excitation (De Pasquale & Somà, 2010). Their results may have been caused by damage to the internal structures due to the dynamic activity (De Pasquale & Somà, 2010). Although a vibration table was used in this study, it does reiterate that testing of the MEMS in the same conditions they are to be used will help to identify any issues prior to data collection.

Brodie et al. assessed the dynamic accuracy of MEMS attached to a custom constructed pendulum (Brodie et al., 2008a). During human gait, angular motion of some segments is similar to a pendulum (Brodie et al., 2008a) and will utilize the gyroscope (angular velocity) and accelerometer (tangential and radial (centripetal)) MEMS outputs (Esser et al., 2009; Mayagoitia et al., 2002). Two MEMS were placed along the shaft of a pendulum to assess two dynamic conditions: continuous motion, where the pendulum was allowed to come to rest naturally, and stopped motion, where the pendulum was stopped and started abruptly. This study compared the MEMS data with data collected from an OMCS and reported errors of up to 30^{o} (Brodie et al., 2008a). Errors are multiplied when differentiating displacement data to obtain acceleration therefore it would be ideal to assess accuracy and precision of the MEMS outputs in conditions that allow direct comparison to known values.

Customizing a turntable has been used as an inexpensive and convenient way to assess accelerometers (Büsching et al., 2012). Turntable speed was used to calculate expected turntable radial accelerations using known acceleration values (Büsching et al., 2012). Measured accelerometer values of six accelerometers were found to be lower than their expected values during higher accelerations (Büsching et al., 2012). Large measurement errors were also detected at accelerometer values below 2 m/s^2 (Büsching et al., 2012). Accuracy and precision assessment of MEMS should be completed in similar conditions and environment(s) they are ultimately going to be used for research data collection.

1.4 Systematic and Random Errors

Known and potential sources of systematic and random error need to be identified and controlled as much as possible when assessing accuracy and precision. Systematic errors are sometimes difficult to detect but if known can be controlled by making adjustments to the research protocol.

Systematic errors can be unidirectional and bias the data in one direction (Norman & Streiner, 1986) therefore tend to affect accuracy of a measurement. Common types of systematic error include instrumental error, operator error and method error (http://www.udel.edu/pchem/C446/error.pdf).

Systematic instrumental error occurs when there is something wrong with the instrument or it is not being used or functioning as the manufacturer intended. MEMS manufacturers provide a calibration protocol and publish specifications regarding an error range within which they guarantee their device will operate. Instrumental errors using MEMS can result from the accelerometer, gyroscope and magnetometer triaxial components within the MEMS being non orthogonal or misaligned with the outside casing, or the outside casing sides not being perpendicular to each other. Calibrating the MEMS will help to reduce the influence of instrumental errors.

Systematic operator errors are errors introduced into a study by human factors. In this thesis, operator error may have impacted accuracy and precision by the researcher’s ability to level of the MEMS as well as accuracy of placement and orientation of sensors. To reduce the impact of operator errors, an acrylic cube was used in the study (described in chapter two) to ensure that levelness and the orientation of the four sensors were maintained while simultaneously collecting data.

Systematic method errors are errors that are introduced by the study protocol. For example, it is known that electrical activity as well as any ferrous material may affect the magnetometer output (Roetenberg, Luinge, Baten, & Veltink, 2005) therefore data were collected in a rural home environment where building structures would have minimal effect on the various sensor outputs prior to data collection in a clinical environment. Calibrating the MEMS in the environment where they are to be used will reduce the influence of instrument as well as method errors. Another source of method error is found in the study described in chapter three in which a motorized (electrical activity) turntable is used to assess the accuracy and precision of the gyroscope output. An ethafoam block was used to elevate the MEMS above the turntable to increase the distance between the motor and the MEMS.

The electrical mains (60 Hz frequency) used to operate the turntable can be a source of random error. Random errors are difficult to identify as each time a measurement is taken a different value is observed. Although the errors are random, they tend to fluctuate around the mean therefore having a larger sample size will help to reduce the influence of the random error (Norman & Streiner, 1986). Random errors tend to affect precision.

Eigen analysis is one way to work around operator and instrumental errors in alignment and manufacturing. Eigen analysis is a method that aims to simplify coordinates. The largest eigenvalue identifies the eigenvector that indicates the mean direction of the signal. It is anticipated that the eigenvector will coincide with gravity (accelerometer) and magnetic north (magnetometer). Using an eigenvector to realign <u>static</u> output data minimizes the impact of alignment errors including: non-orthogonal axes of the accelerometer or magnetometer inside the sensor, alignment of accelerometer or magnetometer inside the sensor and cube, non-orthogonal surfaces of the sensor casing or cube as well as a non-level surface. More detail of the Eigen analysis will be found in chapter 2.

Fast Fourier Transform (FFT) was utilized to reduce the impact of the systematic method error of using a motorized turntable as well as other unknown sources of noise. To accomplish this, the signal was spectral decomposed to identify the harmonic that contained the largest part of the signal. The bias, amplitude and frequency of this signal were then used to reconstruct a new signal that contained the largest part of the original signal thereby removing noise. It is not always possible to eliminate the cause of systematic or random errors therefore methods such as Eigen analysis and FFT were used to reduce the impact of errors.

1.5 Significance of thesis

Understanding how prostheses are being used in everyday situations outside the clinic and laboratory is paramount to optimizing the prosthetic prescription. MEMS provide an advantage over OMCS in that they provide an unencumbered way to collect data on individuals with pathological gait in almost any environment. MEMS are affected by their environment therefore accuracy and precision of the MEMS should be assessed in the environment they are to be used under similar conditions prior to their use in research to provide insight on their optimal orientation or exclusion. The intended purpose of the MEMS should be kept in mind so that a practical level of accuracy is set, this will reduce the chance that MEMS are excluded unnecessarily. Ultimately these MEMS will be utilized in a future study to assess seven activities of daily living (including level walking, ramp walking and stairs) performed by individuals wearing a transtibial prosthesis in a clinical environment. The MEMS outputs, if inaccurate and imprecise, will lead to distorted results and erroneous conclusions.

1.6 Thesis objectives and organization

The purpose of this thesis was to determine if the output of the triaxial accelerometer, gyroscope and magnetometer in four Shimmer 2r MEMS were accurate and precise in static and dynamic conditions prior to their use in a future study to identify gait activities in individuals with a unilateral transtibial amputation. Chapter two describes the accuracy and precision of the accelerometer and magnetometer outputs in a static condition in a rural and clinical environment. Chapter two comprises a research study addressing three objectives: to assess the accuracy and precision of the accelerometer and magnetometer outputs, to determine if data collection can be collected simultaneously using an acrylic cube and to determine if the clinical environment where the sensors ultimately will be used affects the above mentioned outputs. Chapter three describes the accuracy and precision of the triaxial gyroscope and triaxial accelerometer (radial and tangential) outputs in four Shimmer 2r MEMS in a dynamic condition. Chapter three comprises a research study addressing two objectives: to determine if the gyroscope and accelerometer outputs were accurate and precise in a dynamic condition and quantify the influence of the electrical mains in the signal. Chapter four summarizes the extent to which thesis objectives were met and provides implications on future research.

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Chapter 2

Assessment of the Accuracy and Precision of Four Shimmer 2r MEMS Accelerometer and Magnetometer Outputs in a Static Condition Simultaneously in a Rural and Clinical Environment.

Abstract

Simultaneous data collection of four Shimmer 2r Microelectronic Measuring Systems (MEMS) was used to statically assess the accuracy and precision of the accelerometer and magnetometer outputs in two environments (rural and clinical) prior to their use in clinical research. The known local gravity value of 1.00000 g and magnetic local value of 1.00000 were used for the accelerometer and magnetometer gold standards, respectively. Using an eigenvector to realign static accelerometer and magnetometer output data minimizes the impact of alignment errors. In the clinical environment, significant differences in the accuracy of the accelerometer outputs at two heights (0.15 m and 1.0 m above floor) were found ($t_{(25199)} = -9.0352$, $p < 0.001$). There was no effect of the building environment on the precision of the accelerometers. A significant difference in magnetometer output was found in height of the sensors ($t_{(25199)} = -3.9702$, $p < 0.001$). Results suggest that the materials in the building altered magnetometer and accelerometer outputs. Therefore it is advisable to investigate the effects of the environment on the sensor outputs where they are to be used as well as the individual sensors themselves.

Key Words: accelerometer, magnetometer, accuracy, precision.

2.1 Introduction

Microelectronic Measuring Systems (MEMS) are a classification of electronic devices that include triaxial accelerometers, gyroscopes and magnetometers within one sensor. MEMS will capture kinematic data when placed on a body segment. Benefits of using MEMS to collect gait data are their low cost (relative to an optical motion capture gait lab), small size (allowing for unencumbered walking) and ability to capture real-time data over a larger number of strides in most environments (Hanlon & Anderson, 2009). MEMS can be used in real-world environments with little interference to the individual (Kavanagh & Menz, 2008). Directly collecting accelerometer data with a MEMS eliminates issues associated with differentiating displacement data to acceleration data that occurs in optical capture systems (Kavanagh & Menz, 2008). These characteristics make MEMS useful and practical for capturing gait data in a real-world environment where there is the potential that a subject may forget they are being monitored (Samà et al., 2011).

The output of MEMS have the potential to be influenced by the environment in which they are used (de Vries et al., 2009; Haverinen & Kemppainen, 2009). Buildings have their own ambient magnetic field that could interfere with the magnetometer (Haverinen & Kemppainen, 2009). The magnetic field of a building is influenced by the material in the building (i.e. reinforced steel) as well as the metallic structural components (i.e. door frames, elevators, stairs, pipes under floors) (de Vries et al., 2009). Electrical components, such as electrical outlets, industrial machinery and appliances can affect the local magnetic field as can local variations in the composition of the Earth's crust (Haverinen & Kemppainen, 2009). Recognizing the influence of the environmental and building magnetic fields on data is important if the MEMS are to be used in real-world environments where subjects could navigate between numerous environments. Although manufacturers of MEMS provide information regarding the accuracy and precision of their devices, it is important to evaluate the MEMS under the conditions and environments in which they are to be used. The MEMS outputs, if inaccurate and imprecise, will lead to skewed results and misinformed conclusions.

Accuracy and precision are terms used when there is a definite gold standard or known value. Accuracy refers to how close a measure is to the real or known value (Gavin, 1996; Streiner & Norman, 2006). Accuracy is defined as the observed value compared to a known value. The accelerometer and magnetometer outputs of MEMS lend themselves to the assessment of accuracy because the outputs can be compared to known values. The vertical component of the accelerometer can be compared to the known value of gravity. The magnetometer output will be equal to 1.00000 when the axis is aligned with true magnetic north. Precision refers to the repeatability of a measure under the same conditions on a second occasion (Gavin, 1996; Streiner & Norman, 2006). Static evaluation of the accelerometer and magnetometer outputs over a time period can provide repeatability data in order to assess precision.

The overall purpose of this work was to simultaneously assess the accuracy and precision of four Shimmer 2r MEMS sensor accelerometer and magnetometer outputs under static conditions in a rural and clinical environment. The known local gravity value of 1.00000 g (to 5 decimal places) was used as the accelerometer gold standard. When the magnetometer axis is aligned with true magnetic north the magnetic local value is equal to 1.00000, this value was used as the magnetometer gold standard. There was no attempt to align the X, Y and Z axes parallel to the Earth's magnetic north axis. Three experiments addressed the overall purpose. Study I assessed the static MEMS outputs in a rural home environment. Study II determined whether an acrylic cube, used to simultaneously collect data, affected the MEMS outputs. Study III determined if the clinical environment where the sensors will be ultimately used, affected the MEMS outputs. These three experiments were conducted in preparation for using the sensors in a clinical environment to assess seven activities of daily living (including level walking, ramp walking and stairs) of individuals wearing a transtibial prosthesis.

2.2 Materials

Data collection was performed using four Shimmer 2r sensors each with an integrated 9DoF platform (Shimmer, Dublin, Ireland). The Shimmer 2r MEMS incorporate a tri-axial accelerometer, gyroscope and magnetometer. The accelerometer and gyroscope allow for 3D orthogonal measurement of linear acceleration and angular velocity respectively. The magnetometer measures the orientation of the local frame with respect to an earth fixed global frame, magnetic north (Picerno et al., 2011). Detailed characteristics of the Shimmer 2r MEMS can be found in Appendix A.

Calibration of the sensors was accomplished in each of the data collection locations using the manufacturers recommended procedure and the Shimmer 9DoF Calibration software application (Shimmer, Dublin, Ireland). Configuration and synchronization of the four MEMS during data collection were achieved utilizing the Multi Shimmer Sync for Windows application (Shimmer, Dublin, Ireland). Ultimately these sensors will be utilized to asses human gait therefore data were collected at 102.4 Hz, which greatly exceeds the Nyquist sampling theorem requirements of doubling the highest frequency expected during gait (Hamill, Derrick, & Caldwell, 1996).

The accelerometer range was set at the maximum setting of ± 6 g as this exceeds the tangential and radial accelerometer range expected during gait activities with individuals wearing a prosthesis (Van Jaarsveld, Grootenboer, & De Vries, 1990).

Commercially available MEMS units use proprietary fusion algorithms to determine the global frame using gravitational and magnetic field vectors (Picerno et al., 2011). Allowing the MEMS to remain stationary for 15 minutes prior to data collection allows the fusion algorithm an initialization period to establish the sensors orientation to the global frame (Picerno et al., 2011). MEMS sensors are also sensitive to temperature changes therefore allowing the sensors to be on for 15 minutes also ensures stability of the sensor temperature (De Pasquale & Somà, 2010). The sensors were turned on and remained static for a minimum of 15 minutes prior to data collection to establish the sensor's orientation to the global frame (Picerno et al., 2011). Data from all experiments were analyzed starting one second after sampling commenced to ensure that start up transients were minimized.

Frames of reference

The accelerometer, gyroscope and magnetometer are fixed within the MEMS casing and are considered to be in the local frame of the MEMS (Picerno et al., 2011).

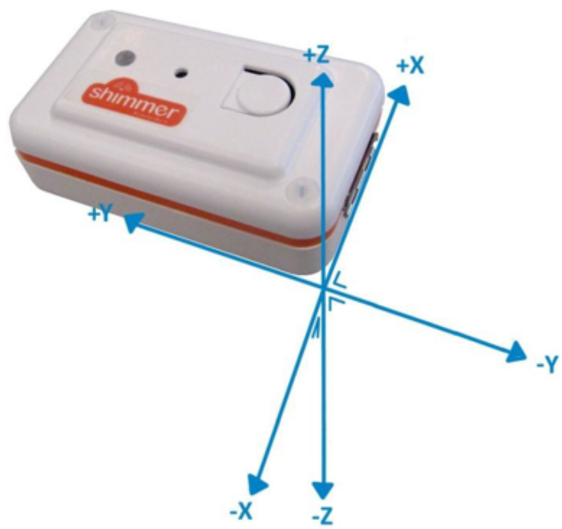

Figure 2.1. Alignment of the x, y and z axes within local frame of MEMS sensor.

2.3 Methods

Simultaneous sampling from all four sensors is more time efficient than sampling one sensor at a time. Therefore the four sensors were placed in an acrylic cube and held in place using ethafoam (Vitacare, Canada). One sensor was placed along each of the four sides of the acrylic cube and oriented such that positive X was oriented upward, positive Y to the right and positive Z toward the inside of the acrylic cube (Appendix B). A spirit level was used to level the acrylic cube. The cube was then statically positioned to align the positive and negative X, Y and Z axes parallel to the Earth's gravitational field (total of six orientations). Eight seconds of data were acquired for each of the six orientations.

2.3.1. Study I and II

Studies I and II were performed in a rural environment in Southern Ontario on a wooden desk to minimize any influence from metal and ferromagnetic building structures. After the data were collected with the sensors inside the acrylic cube, the sensors were then placed outside the acrylic cube mimicking their orientation within the cube. The experiment was duplicated with the sensors out of the cube.

2.3.2. Study III

Study III was performed in a clinical environment within a hospital where data collection on subjects will occur in future studies. The orientation and location of the sensors in the acrylic cube as well as the order of static positioning were maintained from Study I. Data collection, with the four sensors in the acrylic cube, was repeated while the cube was placed on a level piece of wood 0.15 m and 1.00 m above the floor (Appendix C) at 3 locations throughout the clinical environment. Locations included the bottom of a ramp, level walkway and a stairwell (Appendix D).

2.4. Statistical Methods

All statistical analyses were performed using R (version 0.97.248, R Core Team, 2012). Values were truncated after analysis to 5 decimal places in order to display an adequate level of accuracy and precision. The level of significance was set at $p < 0.05$.

Force platforms are comparable devices to MEMS in that both are devices used in gait assessment to measure acceleration. The manufacturing tolerance of a force platform is ± 0.5% ("Optima Human Performance System," n.d.; Riemer et al., 2008). This level of accuracy and precision exceeds that generally acknowledged to be required to assess human motion. Gill et al. (1997) found that there was a 1.3-2.8% error in vertical force output when 20 to 40 lbs were applied to a force plate (Gill & O'Connor, 1997). Therefore an *a priori* MEMS accuracy of 1% was deemed to be sufficient to show accuracy of the sensors while keeping their intended use in mind. Therefore, only MEMS acceleration and magnetometer accuracy and precision values that exceed ± 1 % are investigated further using post hoc Tukey HSD tests.

2.4.1. Accelerometer Accuracy

To determine accelerometer accuracy, a known value is required to compare with the measured values. Although the known accelerometer value where the data collection occurred was (9.80597 m/s^2 or 0.99993 g) (Henderon, 2010), the sensors were calibrated at this same location therefore a local gravity value of 1.00000 g was used for analysis. The time series samples of the X, Y and Z components of the acceleration provided by the tri-axial accelerometer were explored graphically to determine features of the data. The data were then organized within a 3 x n matrix A, where n is the number of samples. The 3 x n matrix A were then multiplied by its transpose (n x 3 Matrix A^T (where superscript T defines the matrix transpose)) to create a 3 x 3 matrix B. The spectral decomposition of matrix B into three eigenvectors and their corresponding eigenvalues provides measures of direction and dispersion, respectively. The largest eigenvalue (τ_{max}) identifies the eigenvector that indicates the mean direction of the accelerometer signal. The transpose of the 3 x 3 eigenvector matrix was used to realign the acceleration data (referred to as realigned accelerometer output) thereby correcting for misalignment of the sensor and acrylic cube. To determine accuracy, τ_{max} from the realigned acceleration orientation tensor, in the various cube orientations, were calculated. A z-test was used to statistically infer if τ_{max} was different than the known local calibrated gravity value (1.00000 g).

2.4.2. Magnetometer Accuracy

During sensor calibration the magnetometer aligns the orientation of its local frame with respect to an Earth fixed global frame. Therefore the known value for the static MEMS magnetometer triaxial output is (1, 0, 0) in the X, Y, and Z local directions since the initial calibration and cube calibration experiment were performed at the same location. In a manner identical to the accelerometer spectral decomposition, the 3 x 3 matrix B was used to realign the magnetometer output. The largest eigenvalue, in the various cube orientations, was used to test the hypothesis, using the z-test, that the dominant magnetometer eigenvalue was equal to 1.00000.

2.4.2.1. Accelerometer and Magnetometer Accuracy Study I and II

Three-way analysis of variance (ANOVA) was used to determine whether there was a main effect on accelerometer and magnetometer output means due to the sensors, their orientation and location (in and out of the cube). To determine the effect of placing the sensors inside the acrylic cube, a paired t-test was used on the realigned outputs to determine if there was a difference between the two sensor locations (out and in the acrylic cube). As discussed above, tolerance was set at 1 % *a priori* therefore any results within 1 % were not investigated further.

2.4.2.2. Accelerometer and Magnetometer Accuracy Study III

All sensors were recalibrated in the clinical environment to minimize potential errors due to that environment. An ANOVA was used to determine if there was a main effect in accelerometer and magnetometer output means due to the 3 locations in the clinical environment. A t-test was used to determine if there was a difference in either accelerometer or magnetometer realigned output means between the 0.15 m and 1.00 m height regardless of location. As in study I and II, tolerance was set at 1 % *a priori* therefore any results within 1 % were not investigated further.

2.4.3. Accelerometer and Magnetometer Precision

The 3 × n accelerometer values were first normalized to be unit length. This removes the accelerometer magnitude whereas direction remains. A Q-Q plot was used to determine if the assumption of rotational symmetry about the primary direction was met. Dispersion is a measure of precision used in directional statistics to calculate how much the direction varies about the main direction. Dispersion is the resultant mean length of the unit vectors and its value would be 1.00000 if there were no dispersion. In studies I and II dispersion for each of the four sensors was assessed in and out of the cube. In study III dispersion was assessed for each of the three locations and two heights in the clinical environment.

2.5. Results

Visual observation of the data confirmed that a unimodal model could be used for accelerometer and magnetometer output data analyses.

2.5.1. Study I and II

Accelerometer Accuracy: The mean and standard deviation of the realigned accelerometer outputs out and in the cube were 0.99755 ± 0.02782 and 1.00037 ± 0.03333 g, respectively. A z-test determined there was a significant difference ($z = -9.64364$, SEM = 0.00025, $p \leq 0.05$) between the calibrated local gravity value of 1.00000 g and the realigned outputs out of the cube. A z-test comparing the means of data collected when the MEMS were in the cube determined there was no significant difference ($z = 1.22427$, SEM = 0.00030, $p \leq 0.05$) between these values. A paired t-test reveal that there was a significant difference ($t_{(11999)} = 17.40320$, $p < 0.001$) between the realigned accelerometer outputs out and in the acrylic cube. Table 2.1 displays individual sensor means and standard deviations, in the cube as well as out of the cube are all within 1 % of the expected value of 1.00000 g.

Table 2.1. Realigned accelerometer means and standard deviations for all four sensors out and in the acrylic cube.

	Accelerometer			
	Out Cube Only (all 6 orientations)		In Cube Only (all 6 orientations)	
	MEAN (g)	SD	MEAN (g)	SD
Sensor 1	0.99124	0.02864	0.99322	0.03350
Sensor 2	1.00446	0.02423	1.00733	0.02825
Sensor 3	1.00112	0.03376	1.00478	0.03976
Sensor 4	0.99338	0.02075	0.99615	0.02839
All 4 Sensors	0.99755	0.02782	1.00037	0.03333

Figure 2.2 displays the realigned accelerometer output means of the six orientations and two locations for each of the four sensors. Three-way ANOVA determined that there were main effects for all factors: sensors ($F_{(3,23990)} = 910.71$, $MSE = 0.25$, $p < 0.001$), orientation ($F_{(5,23990)} = 10880.32$, $MSE = 3.03$, $p < 0.001$) and locations ($F_{(1,23990)} = 171.35$, $MSE = 0.05$, $p < 0.001$). All post hoc Tukey's HSD tests showed significant interactions between all comparisons.

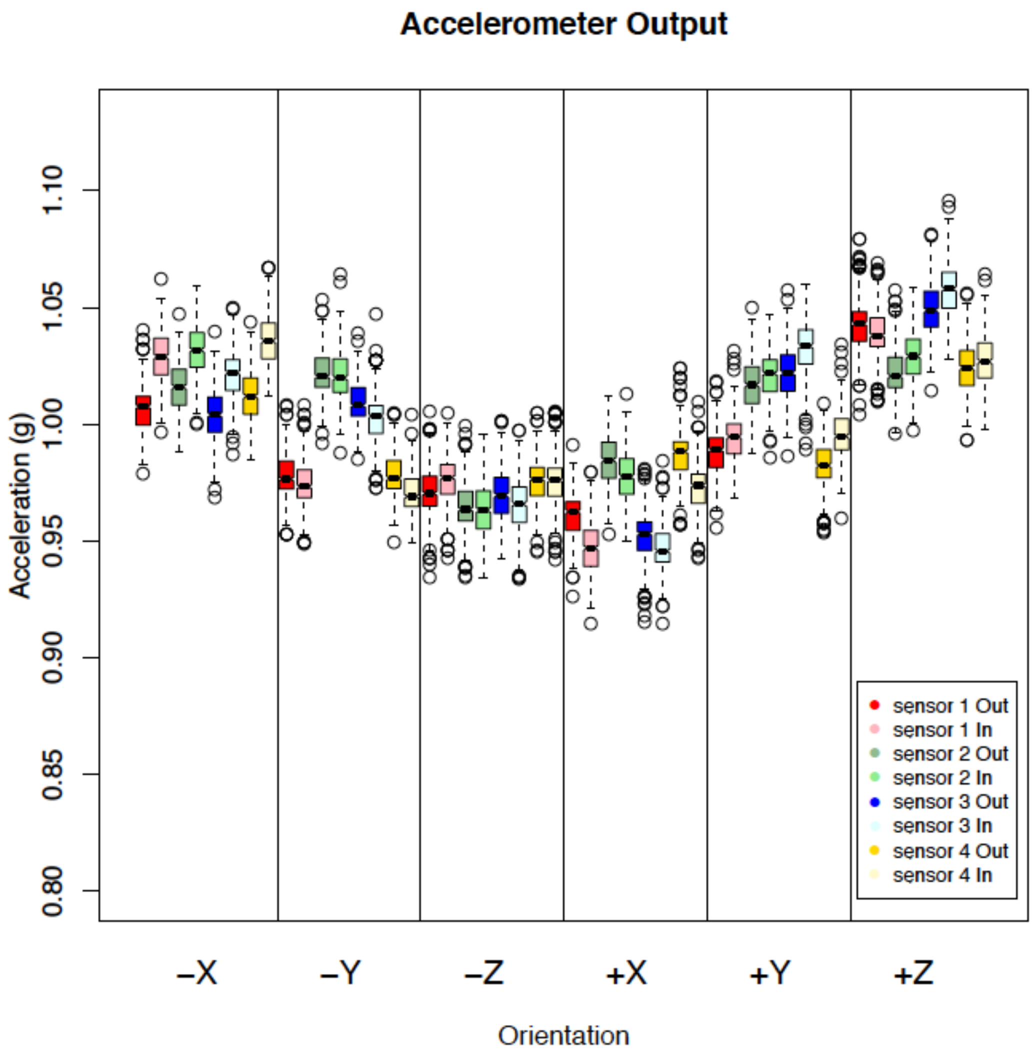

Figure 2.2. Boxplot graphs display realigned accelerometer data for all four sensors in each axis orientation out and in the acrylic cube. The thick black horizontal line reflects the median; the outer bounds of the boxes represent the interquartile range. The whiskers display the minimum and maximum values excluding the outliers that are represented by the circles.

Magnetometer Accuracy: The mean ± standard deviation of the realigned magnetometer outputs out and in the cube was 0.99217 ± 0.01715 and 0.99012 ± 0.02378 local value, respectively. A z-test determined that there were significant differences between the means and the known magnetic local value of 1.00000 when the MEMS were located outside of the cube ($z = -49.98041$, $SEM = 0.00016$, $p \leq 0.05$) as well as inside the cube ($z = -45.52334$, $SEM = 0.00022$, $p \leq 0.05$). A paired t-test between the realigned magnetometer outputs out and in the acrylic cube revealed that there was a significant difference ($t_{(11999)} = -8.2345$, $p < 0.001$) between the two locations. Individual sensor means and standard deviations are found in Table 2.2. Excluding sensor four, out and in the cube are all within 1 % of the calibrated expected local value of 1.00000.

Table 2.2. Realigned magnetometer means and standard deviations for each sensor and the grand mean and SD for all four sensors are shown for two locations (out and in the acrylic cube).

	Magnetometer			
	Out Cube Only (all 6 orientations)		In Cube Only (all 6 orientations)	
	MEAN	SD	MEAN	SD
Sensor 1	1.00490	0.00847	0.99965	0.01449
Sensor 2	0.99852	0.00994	1.00181	0.01368
Sensor 3	0.99323	0.01751	0.99388	0.02959
Sensor 4	0.97204	0.00956	0.96513	0.01112
All 4 Sensors	0.99217	0.01715	0.99012	0.02378

The realigned magnetometer output means of the four sensors, six orientations and two locations are displayed in Figure 2.3. Three way ANOVA determined that there were main effect interactions between sensors ($F_{(3,23990)}$ = 7779.34, *MSE* = 1.44, p < 0.001), orientations ($F_{(5,23990)}$ = 1681, *MSE* = 0.31, p < 0.001) and locations ($F_{(1,23990)}$ = 136.93, *MSE* = 0.03, p < 0.001). Tukey's HSD post hoc analysis revealed the only interactions that were not significant were between orientations positive Y and negative X as well as positive Z and negative X.

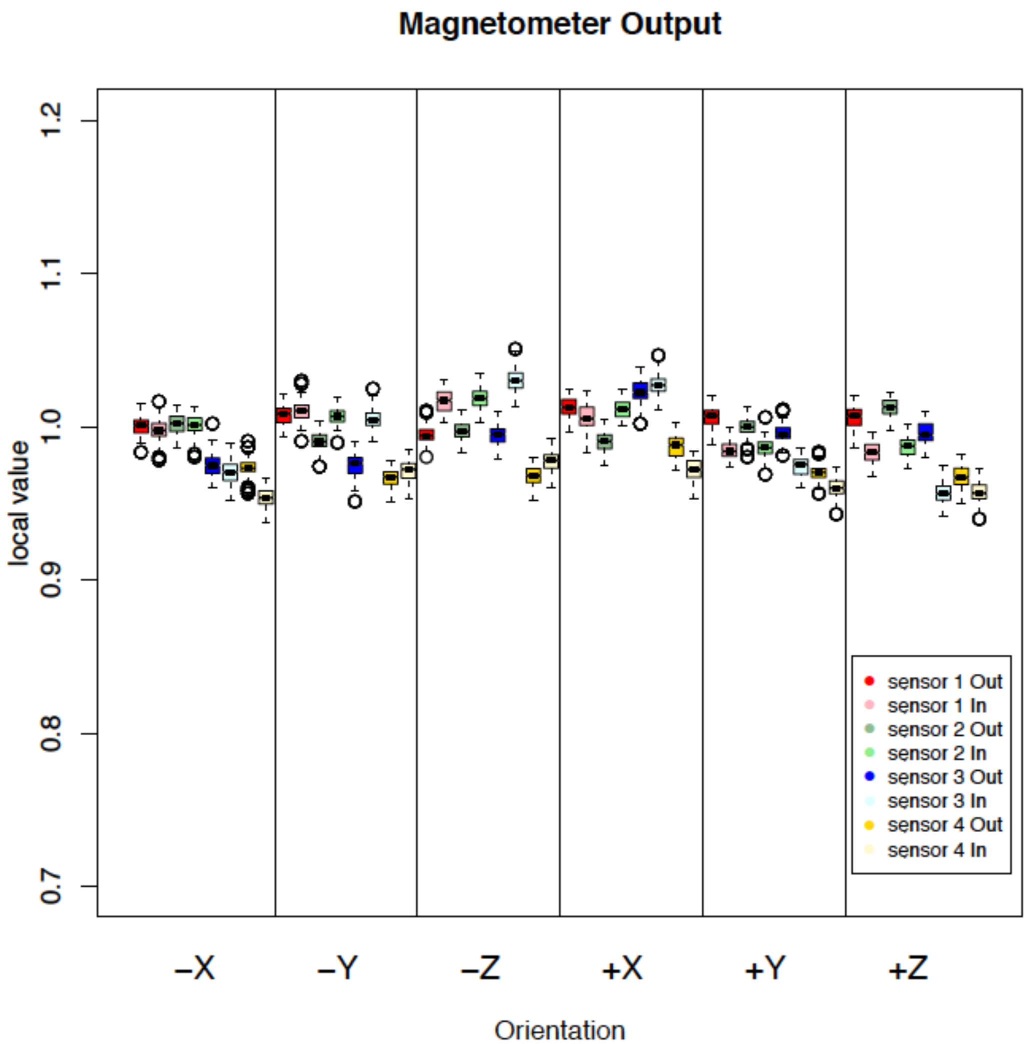

Figure 2.3. Realigned magnetometer outputs for all four sensors, six axis orientations and both locations (out and in the acrylic cube). The median is shown by the thick black horizontal line; the outer bounds of the boxes represent the interquartile range. The whiskers display the minimum and maximum values excluding the outliers that are represented by the circles.

Accelerometer and Magnetometer Precision: Q-Q plots of the realigned accelerometer and magnetometer data are shown in Figure 2.4 and reveal that there was rotational symmetry about the main direction. The accelerometer dispersions about the main direction out and in the cube were both 0.99989. The magnetometer dispersion values out and in the cube were both 0.99995. The direction of the data was very closely distributed around the main direction for both the accelerometer and magnetometer regardless of location. Since the values were close to 1.0000, further analysis was not completed.

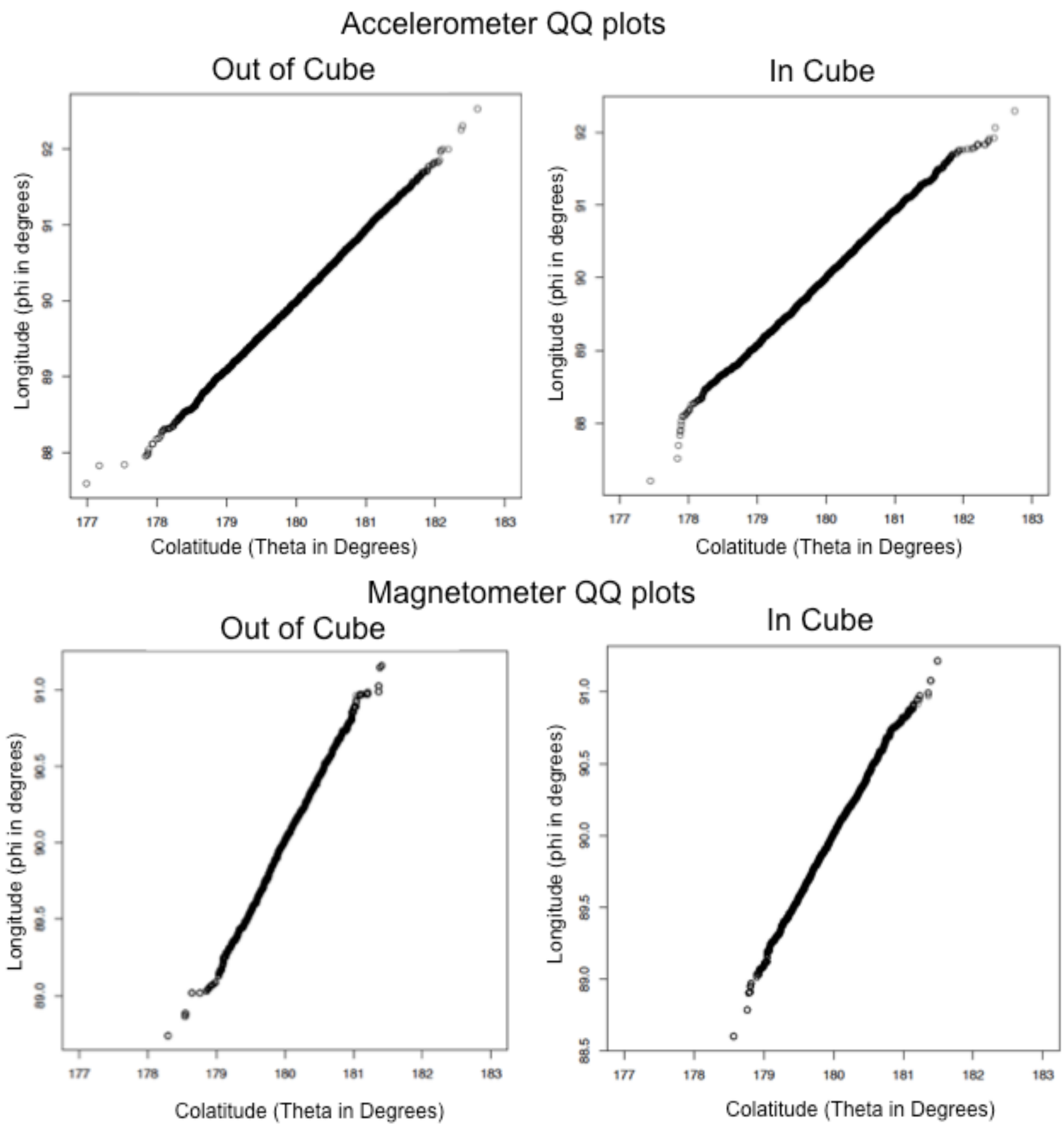

Figure 2.4. Accelerometer and magnetometer QQ plots out and in the acrylic cube. Outliers are represented by open circles.

2.5.2. Study III

Accelerometer Accuracy: Realigned accelerometer outputs at each height and location are illustrated in Figure 2.5.

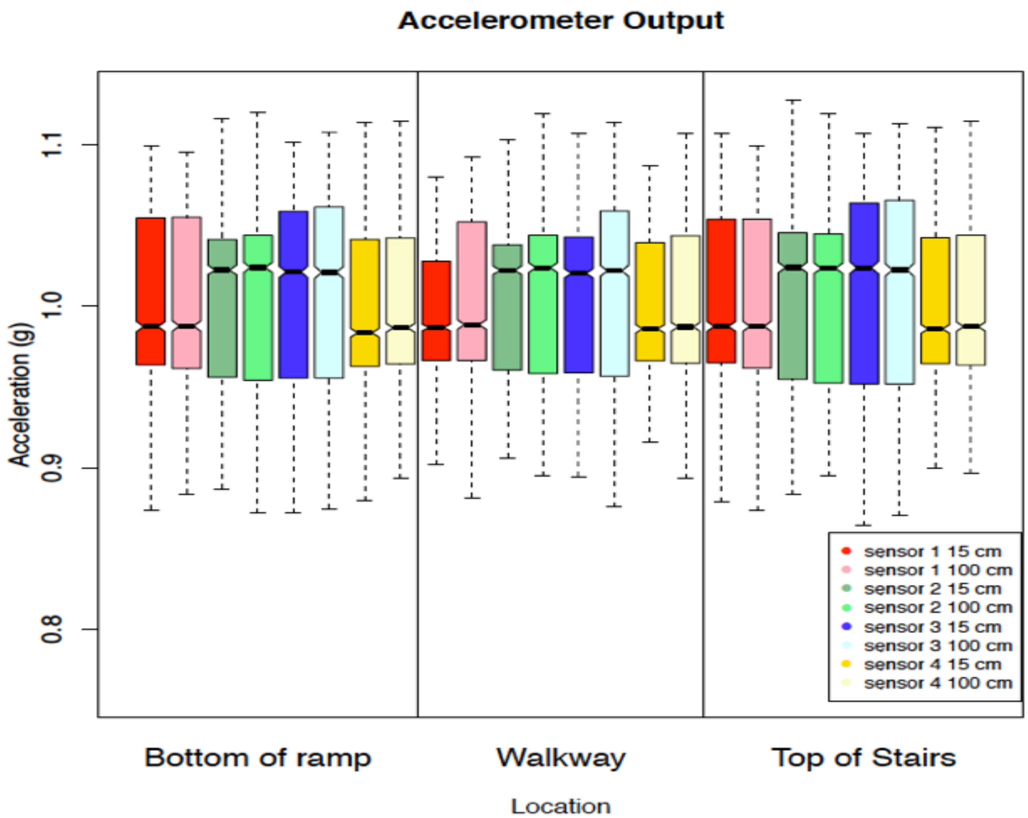

Figure 2.5. Boxplots of realigned accelerometer output for each sensor at each height grouped according to location in the clinical environment. The median is shown by the thick black horizontal line; the outer bounds of the boxes represent the interquartile range. The whiskers display the minimum and maximum values with any outliers represented by circles.

Accelerometer means across location and height are summarized in Table 2.3.

Table 2.3. Mean realigned accelerometer output means at each location and height in the clinical environment.

Accelerometer Means (g)

	Height	
Location	**0.15 m**	**1.00 m**
Ramp	1.00166	1.00247
Walkway	1.00038	1.00269
Top of stairs	1.00287	1.00263
All locations	1.00164	1.00260

Although a significant difference of the sensor height on accelerometer output ($t_{(25199)} = -9.0352$, $p < 0.001$) was determined, all realigned accelerometer output means were within the ± 1 % acceptable tolerance value set *a priori*. Four-way ANOVA determined that there were main effects for sensor ($F_{(3,50388)} = 569.76$, $MSE = 0.57$, $p < 0.001$), orientation ($F_{(5,50388)} = 19504.00$, $MSE = 19.37$, $p < 0.001$), location ($F_{(2,50388)} = 6.2975$, $MSE = 0.01$, $p < 0.05$) and height ($F_{(1,50388)} = 11.7473$, $MSE = 0.01$, $p < 0.001$). Tukey post hoc analysis identified that the main effect due to location, reflected the difference in values acquired at the top of the stairs and the walkway.

Magnetometer Accuracy: Realigned magnetometer outputs or each sensor as a function of height and location are illustrated in Figure 2.6.

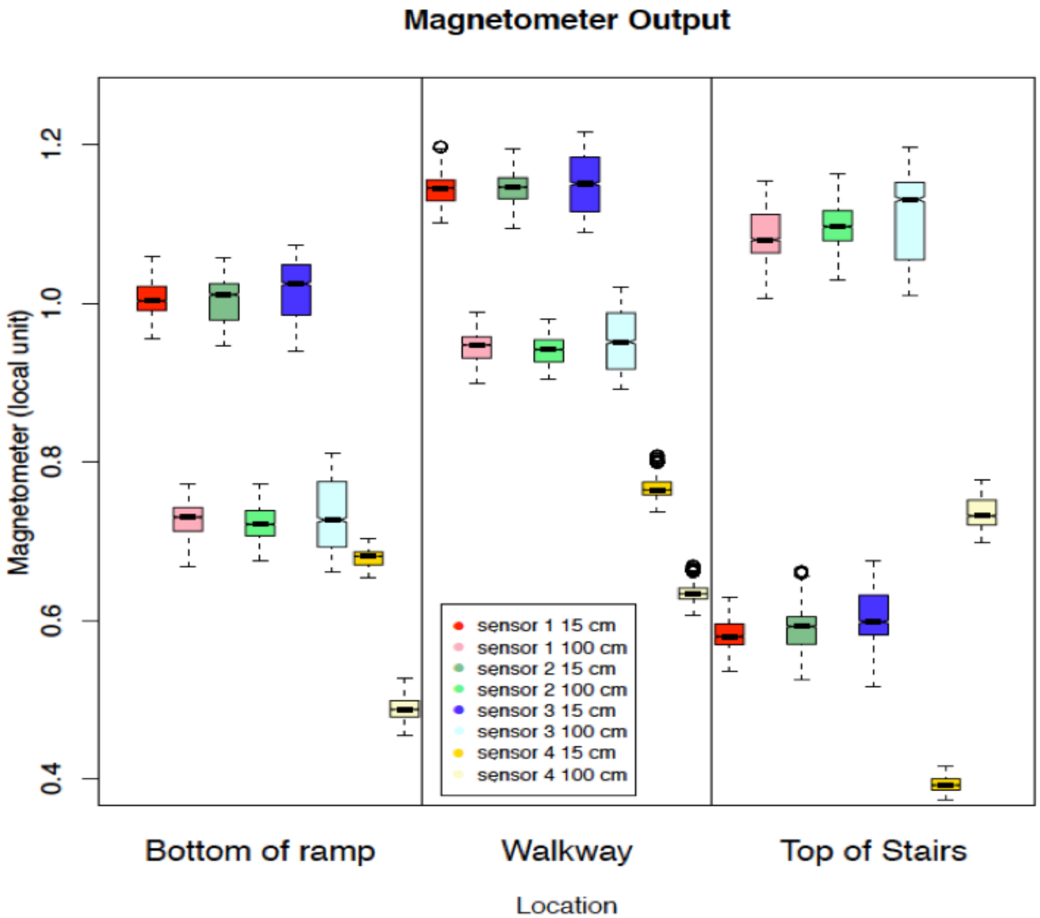

Figure 2.6. Boxplots of individual sensor magnetometer outputs at each height are grouped according to location in the clinical environment. The median is shown by the black horizontal line; the outer bounds of the boxes represent the interquartile range. The whiskers display the minimum

and maximum values excluding the outliers that are represented by the circles.

Table 2.4 displays the grand mean of the realigned magnetometer output when the sensors were placed at each of the three locations and two heights. A t-test determined that there was a significant difference in magnetometer output depending on the height ($t_{(25199)} = -3.9702$, $p < 0.001$). Four-way ANOVA determined that there were main effects for sensors ($F_{(3,50388)} = 10394.126$, $MSE = 289.52$, $p < 0.001$), orientation ($F_{(5,50388)} = 36.899$, $MSE = 1.03$, $p < 0.001$), location ($F_{(2,50388)} = 6145.572$, $MSE = 171.18$, $p < 0.05$) and height ($F_{(1,50388)} = 30.8$, $MSE = 0.858$, $p < 0.001$). Tukey post hoc analysis indicated that main effects due to the factors height, all locations and all sensors (except for sensors 1 and 2) interacted. Post hoc analysis of orientation indicated some pairwise differences although there was no clear pattern.

Table 2.4. Realigned magnetometer output means for all four sensors according to height and location in the clinical environment.

Magnetometer Means (local units)		
	Height	
Location	**0.15 m**	**1.00 m**
ramp	0.92608	0.66812
walkway	1.05119	0.86807
top stairs	0.54174	1.00757

Accelerometer and Magnetometer Precision: The dispersion of the accelerometer was between 0.99988 and 0.99989 while the magnetometer dispersion ranged from 0.99969 to 0.99992. The accelerometer and magnetometer grand mean dispersion values at the three locations and two heights are displayed in Table 2.5. The direction of the data was very closely distributed around the main direction for both the accelerometer and magnetometer regardless of height or location. Since the values were close to 1.0000, further analysis was not completed.

Table 2.5. Grand mean dispersion values for the accelerometer and magnetometer outputs at two heights (0.15 m and 1.00 m from the floor) in three locations within the clinical environment.

	Dispersion			
	Accelerometer		Magnetometer	
	0.15 m	1.00 m	0.15 m	1.00 m
ramp	0.99989	0.99989	0.99989	0.99981
walkway	0.99989	0.99989	0.99992	0.99988
top stairs	0.99988	0.99989	0.99969	0.99991

2.6. Discussion

The use of an acrylic cube was a feasible method of simultaneously collecting data from four MEMS' in rural and clinical environments. All four MEMS' accelerometers and three of the four MEMS magnetometers examined in this study produced data that were of sufficient accuracy, in both the home and clinical environment, for use in clinical studies of gait. Precision of the MEMS was satisfactory in both the rural or clinical environments

A paired t-test performed on the realigned accelerometer output, in the rural home environment, revealed that there was a significant difference in means when sensors were assessed out and in the acrylic cube. Further z-test analysis determined that the realigned accelerometer output values in the cube were not significantly different than the calibrated known gravitational value of 1.00000 g while values obtained when the sensors were out of the cube were significantly different. When the axis of the accelerometer is not parallel to gravity, the raw data points are more likely to be distributed among the three axes causing the eigenvector to be less accurate. Out of the cube the sensors had to balance on all six sides potentially increasing the variation as sides of the sensors may have a light emitting diode (LED), a port for charging or seams in the sensor construction making it difficult to balance on a level surface. The sensors within the acrylic cube were securely held in place using ethafoam. It is possible that the in cube results were more accurate than out of cube because the cube held the sensors securely and provided an external enclosure that aligned the axes parallel to gravity as checked using a spirit level more easily.

Although in the rural home environment there was no significant difference in realigned accelerometer output means in the cube compared to gravity, three-way ANOVA results showed significant main effects for sensor, orientation and location. However, all four sensor and six orientation means were within 1 % of 1.00000 g. Axial and tangential accelerations expected in gait of individuals with a transtibial amputation are 2.0 - 5.1 and 1.0 - 4.1 g respectively (Van Jaarsveld et al., 1990) therefore it was determined that these main effects were a function of the size of the dataset and were not clinically relevant and that it was acceptable to test the sensors in the acrylic cube at the clinical environment site.

Although architectural specifications describing the building materials in the clinical environment were not available, it is expected that there would be more ferrous material in the flooring and stairwell, compared to a home environment, which may affect the sensor output. A significant difference in realigned accelerometer outputs of the sensors was found between the two heights. Although this would imply that the environment affected the accelerometer, the difference in output values acquired at 0.15 m and 1.00 m were within 0.00231 g of each other (1.00038 g and 1.00269 g, respectively). This difference is minimal compared to the normal variability of human gait and is not deemed clinically significant with respect to the future research applications of these sensors.

The initial experiments were performed in a rural home environment to determine if there was a difference in magnetometer output means where the environment minimized any influence from metal and/or ferromagnetic building structures. Although a t-test determined there was a significant difference in magnetometer outputs out or in the cube and z-test revealed that outputs out and in the cube were significantly different that the known local value, the outputs (except for sensor four) were all within 1 % of the known local value of 1.00000. Since the differences were relatively small, it was assumed that the acrylic cube was not interfering with the magnetometer outputs. A recalibration of sensor four will be required to help identify whether there is a problem with the sensor.

The raw magnetometer outputs would be affected if the acrylic cube is rotated in a transverse plane, affecting the heading direction of the magnetometer. There was no attempt to align the X, Y and Z axes parallel to the Earth's magnetic north axis. As a result the raw magnetometer output may be dispersed among all three axes of the sensor reducing the magnitude of the eigenvalue. It is possible that this is the primary source of error in magnetometer outputs.

In the clinical environment, the realigned magnetometer outputs were less consistent than the accelerometer outputs. As in study I and study II, sensor four appeared to underestimate the magnetometer output compared to the other three sensors (Figure 2.6). A significant difference in magnetometer output was found as a function of height of the sensors. The magnetometer output was less 1.00 m above the floor (compared to 0.15 m) at the ramp and walkway locations while the findings at the top of the stairs were opposite. This implies that the building environment did have an effect on the magnetometer output.

Q-Q plots confirmed rotational symmetry about a main direction for both the accelerometer and magnetometer outputs in study I and study II. The accelerometer and magnetometer dispersion values were very close to 1.00000 (0.99989 and 0.99995, respectively) regardless of location, indicating that the direction of the data was closely distributed around the main direction and the acrylic cube did not have an effect on the dispersion.

In the clinical environment, the dispersion values of the accelerometer were consistent with studies I and II therefore it is safe to say that the clinical environment did not affect the precision of the accelerometer outputs. The dispersion of the magnetometer outputs are not as consistent in the clinical environment as in studies I and II implying that the clinical environment did affect the magnetometer precision. The location that affected the precision of the magnetometer output the most was placement of the sensor 0.15 m above the floor at the top of the stairs (0.99969). It is likely that there was a high ferrous content in the staircase affecting the sensor when it was closer to the floor. The building structure did have an influence on the dispersion of the magnetometer output.

In this study, the building environment did have an effect on the accelerometer output although it is deemed to be clinically insignificant. The materials in the building have a greater effect on the magnetometer output and the precision of their output as compared to the accelerometer output. It is also noted in this study that the magnetometer in sensor four underestimated magnetic north. Therefore it is advisable to investigate the effects of the environment on the sensor outputs where they are to be used, as well as the individual sensors themselves.

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2.9 Appendix

Appendix A. Characteristics of the Shimmer 2r wireless platform with kinematic module.[1]

Dimensions	53mm x 32mm x 19mm
Weight	27 g
Battery	450 mAh rechargeable Li-ion battery
Microcontroller	8 mHz, 16 Bit
Bluetooth	RN-42, 802.15.4
Radio	TI CC2420

Accelerometer (Freescale MMA7361)

Accel Range	±1.5 - 6 g

Magnetometer (Honeywell HMC5843)

Description	3 axis Digital Compass IC
Conversion Rate	0.5 - 50Hz
Gain	390 - 1620 counts/milligauss
Input Field Range	± 0.7 - 4.5 Ga
Resolution	12 bit signed*also says ±7 gauss
Cross Axis Sensitivity	
Cross field	0.5 gauss
Happlied	± 3 gauss
Typical	± 0.2% gauss

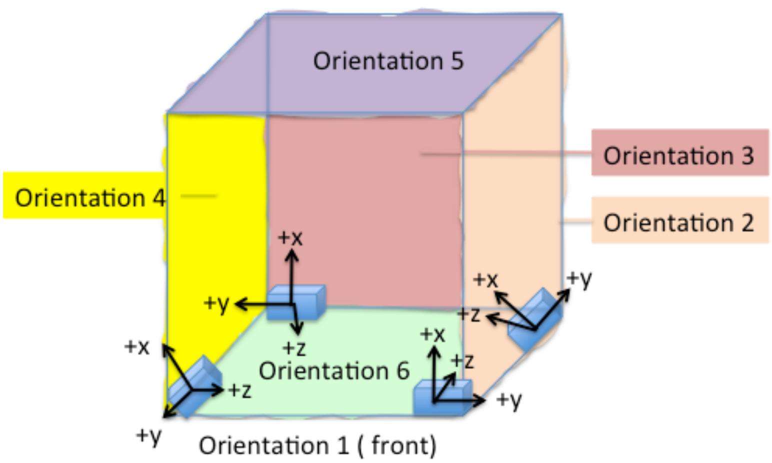
Gyro (Invensense 500 series MEMS Gyros)

Full Scale Range	± 500 deg/sec
Sensitivity	2 mV/(deg/sec)

[1] "Shimmer 2r Spec Sheet". Shimmer Sensing, www.Shimmer-Research.com (Accessed May 2, 2012)

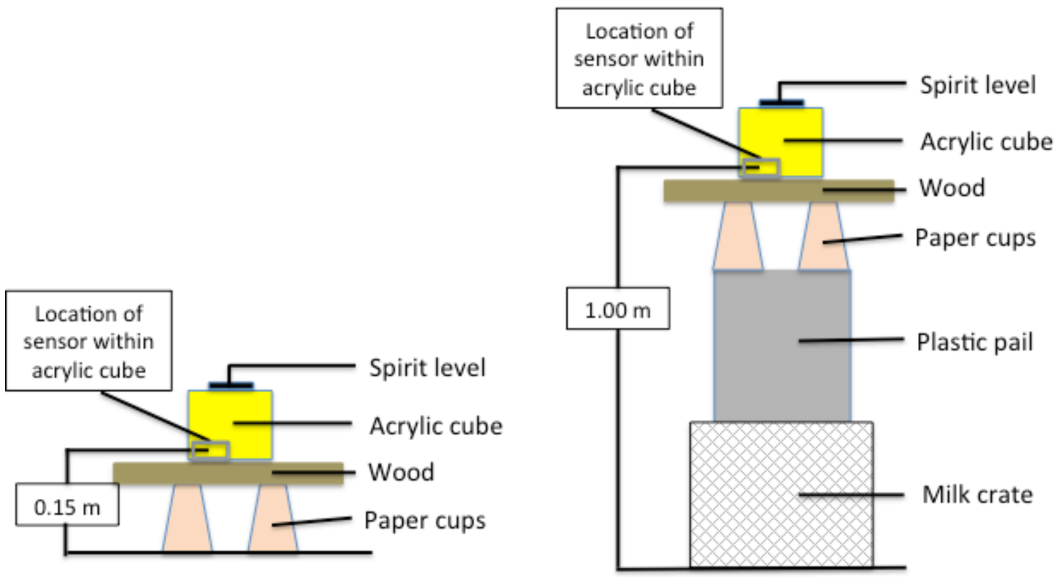
Appendix B

Study I: Six orientations of the acrylic box used during data collection to align the positive and negative axes of each X, Y and Z axes of all four sensors with gravity.



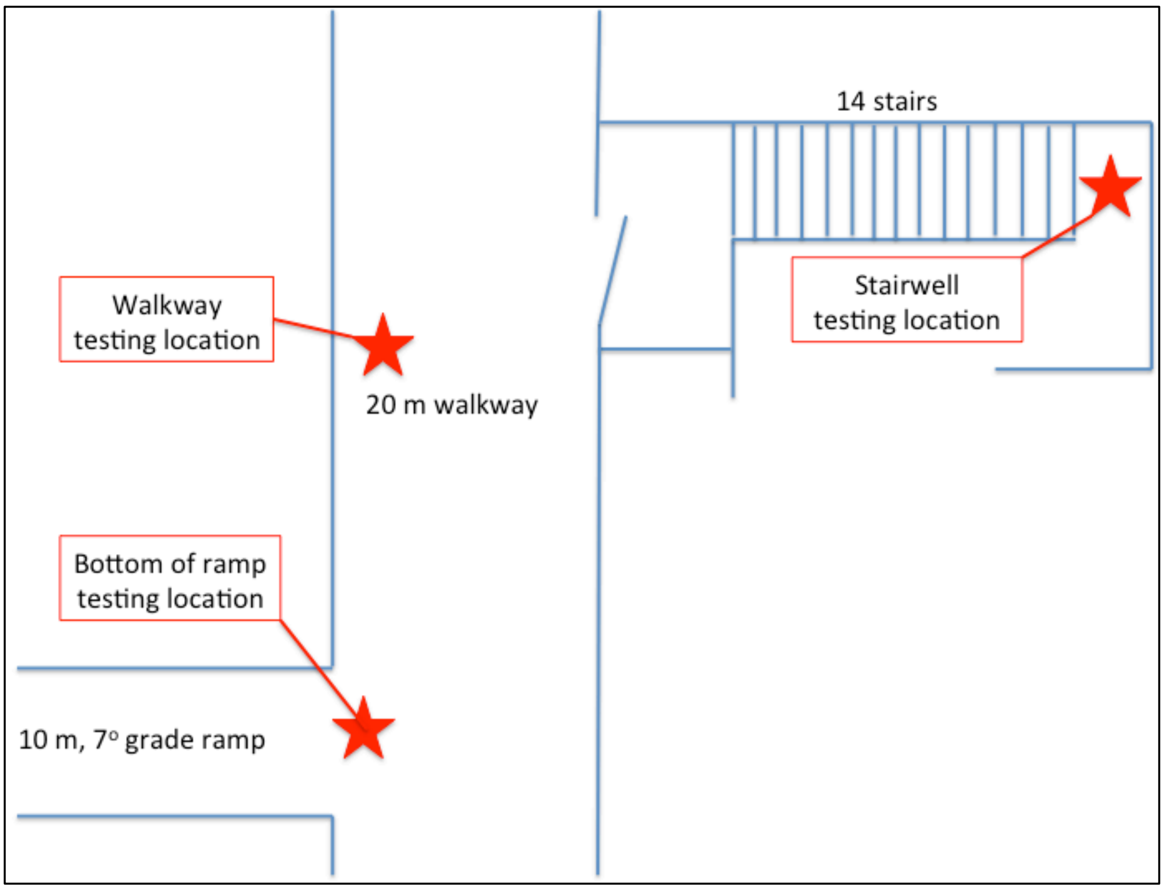
Appendix C

Study III: Placement of the acrylic cube on non-ferrous materials to obtain 0.15 m and 1.00 m heights of the sensors. A spirit level was used to assess levelness of the acrylic cube.



Appendix D

Study III: Layout of clinical area showing the three sensor testing locations. Sensors were statically positioned 0.15 m and 1.00 m above the floor in all three locations.



Chapter 3

Utilizing a Turntable to Simultaneously Assess the Accuracy and Precision of Four Shimmer 2r MEMS Accelerometer and Gyroscope Outputs in a Dynamic Condition.

Abstract

A turntable was used in a rural environment to dynamically assess the accuracy and precision of four Shimmer 2r Microelectronic Measuring Systems (MEMS) prior to their use in clinical research. Utilizing the turntable allowed assessment of the triaxial gyroscope and accelerometer at two turntable speeds (33.33 revolutions per minute (rpm) and 45 rpm) and two radii (0.05 m and 0.10 m). Initially the gyroscope output was spectral decomposed using Fast Fourier Transform (FFT) to identify the harmonic consistent with the electrical mains. The effect of the electrical mains was determined to be 1% of the signal and was deemed to be insignificant. Results indicated that the gyroscope output along one of the axes was less accurate at both turntable speeds and radii although this may have been due to the precarious positioning of the sensor. Z-tests of the individual sensor gyroscope outputs revealed that sensor four was significantly different along one of the axes for all turntable speeds and radii indicating that it may require recalibration or possible exclusion from future research. The radial and tangential accelerations were spectral decomposed and reconstructed using the harmonic that contained the largest part of the signal. Results indicate that there were no significant differences between the experimental radial and tangential accelerations and their expected values. Gyroscope and accelerometer standard error of the mean (SEM) values were relatively minimal and consistent across all sensor orientations. It is advisable to dynamically assess individual sensors for accuracy and precision to inform the researcher of optimal sensor orientation and identify MEMS that may require recalibration or exclusion prior to their use in research.

Key Words: Microelectronic measurement system, accelerometer, gyroscope, accuracy, precision.

3.1 Introduction

Microelectronic Measuring Systems (MEMS) are a classification of electronic devices that include triaxial accelerometers, gyroscopes and magnetometers within one sensor. MEMS will capture kinematic data when placed on a human body segment. Benefits of using MEMS to collect gait data are their low cost (relative to an Optical Motion Capture System (OMCS)), small size (allowing for unencumbered walking) and ability to capture real-time data over a larger number of strides in most real-world environments (Hanlon & Anderson, 2009; Kavanagh & Menz, 2008). Direct accelerometer data collected with MEMS reduces the noise amplification that results from differentiating displacement data to acceleration data as is required in OMCS (Esser et al., 2009; Kavanagh & Menz, 2008). These characteristics make MEMS useful and practical for capturing gait data in a real-world environment, where there is the potential that a subject may forget they are being monitored (Samà et al., 2011).

MEMS outputs that are inaccurate and imprecise may lead to distorted results and erroneous conclusions; therefore assessing accuracy and precision prior to use in a study is necessary. Accuracy refers to how close a measure is to a real or known value (Gavin, 1996; Streiner & Norman, 2006). Accuracy of gyroscope and accelerometer outputs of MEMS can be established because the outputs can be compared to known values. Precision refers to the repeatability of a measure under the same conditions on repeated occasions (Gavin, 1996; Streiner & Norman, 2006). Evaluation of the MEMS outputs under replicate conditions over a time period can provide repeatability data in order to assess precision. Manufacturer datasheets should not be explicitly trusted (Brodie et al., 2008a; Büsching et al., 2012). Individual assessment of the MEMS should be completed in order to exclude MEMS prior to data collection (Deluzio et al., 1993; Picerno et al., 2011). Assessing the accuracy and precision of MEMS in a similar application and environment in which they will ultimately be used for data collection, prior to their use in clinical studies, will increase confidence in the results of the study (Brodie et al., 2008a; De Pasquale & Somà, 2010; Picerno et al., 2011).

The MEMS in this study must be accurate and precise during dynamic (motion) states such as human walking as they will eventually be utilized to characterize daily activities in human gait. To assess the dynamic state of walking, studies have compared MEMS to the gold standard of an OMCS (Esser et al., 2009; Mayagoitia et al., 2002). As mentioned previously, any noise and errors present in the displacement data are multiplied during the differentiation process (Esser et al., 2009; Kavanagh et al., 2006); therefore it would be ideal to assess the MEMS in a dynamic situation that would allow direct comparison of raw acceleration data. During human gait, angular motion of some segments is similar to a pendulum (Brodie et al., 2008a) and will utilize the gyroscope (angular velocity) and accelerometer (tangential and radial (centripetal)) MEMS outputs (Esser et al., 2009; Mayagoitia et al., 2002).

Custom pendulums have been constructed to test the accuracy and precision of MEMS in a dynamic state (Brodie et al., 2008a; Godwin, Agnew, & Stevenson, 2009). These studies compared the MEMS data with data collected from camera systems and report errors varying from 30^{o} (Brodie et al., 2008a) to 9.4^{o} (Godwin et al., 2009). Others have customized a turntable as an inexpensive and convenient way to assess the precision of accelerometers. Measured accelerometer values of six accelerometers were found to be lower than their expected values during higher accelerations (Büsching et al., 2012). Large measurement errors were also detected at accelerometer values below 2 m/s^2 (Büsching et al., 2012). These findings underline the need to assess each MEMS used in a study to ensure accuracy and precision.

The purpose of this paper was to assess the accuracy and precision of the triaxial gyroscope and triaxial accelerometer (tangential and radial) outputs in four Shimmer 2r MEMS in a dynamic state. The MEMS will be utilized in a future study to assess seven dynamic activities of daily living (including level walking, ramp walking and stairs) performed by individuals wearing a transtibial prosthesis. This study will determine if the MEMS are accurate and precise in a dynamic state.

3.2 Materials

3.2.1 MEMS Initialization

Data collection was performed using four Shimmer 2r sensors each with integrated 9DoF (Shimmer, Dublin, Ireland). Initial calibration of the sensors was accomplished in the data collection environment using the manufacturer's recommended protocol and the Shimmer 9DoF Calibration software application (Shimmer, Dublin, Ireland). Configuration and synchronization of the four MEMS during data collection were achieved utilizing the Multi Shimmer Sync for Windows application (Shimmer, Dublin, Ireland). Ultimately these sensors will be utilized to asses human gait therefore data were collected at 102.4 Hz, which greatly exceeds the Nyquist sampling theorem requirements of doubling the highest frequency expected during gait (Hamill et al., 1996). The accelerometer range was set at the maximum setting of ± 6 g as this exceeds the tangential and radial accelerometer range expected during gait activities with individuals wearing a prosthesis (Van Jaarsveld et al., 1990). The sensors were turned on and remained static for a minimum of 15 minutes prior to data collection to establish the sensors orientation to the global frame (Picerno et al., 2011). Data from all experiments were analyzed starting one second after sampling commenced to ensure that start up transients were minimized.

3.2.2 Turntable

A belt-driven turntable (Technics SL-B200) using a direct current (DC) motor capable of operating at speeds of 33.33 and 45 revolutions per minute (rpm) was used.

3.3 Methods

Data were collected in a rural home environment where building structures would have minimal effect on the various sensor outputs. Additional potential sources of error in this experiment include: electrical mains (60 Hz frequency), turntable motor influence as well as turntable stability. To minimize environmental effects from the motor in the turntable, all four MEMS were placed on top of a 0.15 m piece of ethafoam (Vitacare, Canada) that had been cut to the same diameter as the turntable. Data collection was initiated 10 seconds after the turntable had started rotating to minimize the possibility that the turntable was accelerating while reaching its target speed.

Terminology:

Expected values: Values that are expected. For example, the speed of the turntable is expected to be 33.33 or 45 rpm. Specific formulas and calculations used for expected values are located in the Statistical Methods section.

Experimental values: Accelerometer and gyroscope outputs collected using the sensors. It was assumed that the accelerometer axes were parallel to the sensor casing. The radial accelerometer axis was aligned so that it would pass as close as possible to the center of the turntable and that the center of the sensor to the center of the turntable reflected the expected radii measurement.

Estimated values: Values that are calculated using expected and experimental values. For instance, the formula $a=\omega^2 r$ is used to calculate an estimated value for acceleration (a) using the experimental value from the gyroscope (ω) and the expected radius (r).

Triangulation provides insight into data by using several sources (experimental and estimated values) to verify and validate the data (Thurmond, 2001). For the triangulation calculations, the expected radii values were used in the formula $a=\omega^2 r$ with the experimental gyroscope (or accelerometer) values to calculate an estimated acceleration (or angular velocity) for each turntable speed and radii (only expected radii values were used as there is no experimental radius value). To determine if the gyroscope or accelerometer experimental values were more accurate in predicting the expected, the difference was expressed as a percentage.

To test the gyroscope outputs of each axis (X, Y and Z), each respective axis (of each sensor) was placed on top of the ethafoam so that the positive direction of the axis being collected was directed into the turntable and rotating clockwise. While collecting the gyroscope output, accelerometer outputs were simultaneously captured to analyze the radial and tangential accelerations in the positive and negative directions of the other two axes. All 4 sensors were placed on the turntable in the same orientation in order to collect data simultaneously. Appendix A illustrates sensor placement for simultaneous data collection of the positive Z gyroscope, positive X radial acceleration and positive Y tangential acceleration.

To analyze the influence of the electrical mains, five trials of data were collected at 204.8 Hz for 10 seconds. Sampling frequencies of the sensors are preset at 102.4 or 204.8 Hz. The later was chosen as it is the sampling frequency offered that fulfilled the Nyquist sampling theorem of doubling and adding 1 to the electrical mains frequency of 60 Hz.

Once the influence of the electrical mains was analyzed and determined negligible, the remaining data were collected for all sensor orientations for 10 seconds at 102.4 Hz. This sampling duration was chosen to ensure that 5 complete revolutions were captured at 33.33 rpm, the slowest rpm tested. These data were collected with the MEMS placed in 2 radius locations (0.05 m and 0.10 m from the center of turntable) and at 2 turntable speeds (33.33 and 45 rpm). Each gyroscope axis output was captured at each radii location and turntable speed along with the accelerometer outputs from the remaining 2 axes.

3.4 Statistical Methods

All statistical analyses were performed using R (version 0.97.248, R Core Team, 2012). Values were truncated after analysis to 5 decimal places in order to display an adequate level of accuracy and precision. The level of significance was set at $p \leq 0.05$.

3.4.1 Identifying the Effect of Electrical Mains

To identify the electrical mains power source, a Fast Fourier Transform (FFT) was used on the gyroscope output collected at 204.8 Hz to identify the amplitude of the signal at the 60 Hz frequency.

3.4.2 Accuracy of Gyroscopes

The accuracy of each gyroscope axis was determined by comparing the corresponding measured mean experimental value to the expected value of the turntable velocity. The expected turntable angular velocities were calculated as 33.33 rpm = (33.33 / 60) * 2 π = 3.4903 radians/s (rad/s) and 45 rpm = (45 / 60) *2π = 4.7124 rad/s. A z-test was used to determine if the experimental means were different from the expected means.

3.4.3 Accuracy of Accelerometers

Expected radial acceleration was calculated using the following formula $a = \omega^2 r$ where ω = expected angular velocity (3.4903 rad/s or 4.7124 rad/s) and r = expected radius (0.05 m or 0.10 m). Expected tangential acceleration will equal 0 during uniform circular motion at a constant angular velocity. To determine the accuracy of the experimental tangential acceleration, an expected value of 0 was used since the accelerometers should be moving at a constant angular velocity.

The experimental radial and tangential accelerations were spectral decomposed and reconstructed using the FFT harmonic that contained the largest part of the signal, thereby removing noise. This signal was then used to calculate experimental acceleration using the bias, amplitude and frequency. A z-test determined if the expected radial and tangential accelerations were different than the experimental accelerometer output. A three-way ANOVA was used to determine if there was a main effect due to sensor, orientation or axis on mean z values.

3.4.4 Precision of Gyroscopes and Accelerometers

Standard error of mean (SEM) was used as a measure of precision. The SEM takes into account the standard deviation or variance of the experimental values as well as the sample size using the formula: $SEM = sd/\sqrt{N}$. The SEM units are the same as the original experimental value.

3.5 Results

3.5.1 Identifying the Effect of Electrical Mains

The location of the 60 Hz signal was found at the 270th harmonic. The amplitude of the signal at this frequency was 0.00954, which contributed 1/100 (1%) to the original signal.

3.5.2 Accuracy and Precision of Gyroscopes

Results of the z-tests are summarized in Table 3.1 and reveal that the original experimental outputs from the X and Z gyroscope axes were not significantly different from their expected angular velocities; in contrast, the Y-axis experimental outputs are significantly different at both turntable speeds.

Table 3.1. Gyroscope z score and standard error of the mean (SEM) for both turntable speeds. The z scores were compared to the expected z score of 1.96 using a z test.

	X		Y		Z	
	z score	**SEM**	**z score**	**SEM**	**z score**	**SEM**
33 rpm	0.99812	0.00014	2.43656**	0.00017	1.61461	0.00014
45 rpm	1.08636	0.00021	2.79741**	0.00025	1.65797	0.00024

**significant ($p \leq 0.05$)

Table 3.2. Expected and experimental gyroscope output means and standard deviations (sd) for each sensor axis, turntable speed and location.

	Expected Gyroscope Value (radians/s)	**Experimental X**		**Experimental Y**		**Experimental Z**	
		mean	sd	mean	sd	mean	sd
33rpm 0.05 m radius	3.4903	3.51450	0.02308	3.55923	0.03007	3.54585	0.04425
33rpm 0.10 m radius	3.4903	3.51534	0.02606	3.56265	0.02761	3.54896	0.04511
45rpm 0.05 m radius	4.7124	4.75792	0.03695	4.82290	0.04241	4.80420	0.06413
45rpm 0.10 m radius	4.7124	4.74519	0.03385	4.84412	0.04156	4.79983	0.06280

Although the z scores in the Z-axis of the gyroscope were not significantly different, the experimental angular velocities were higher compared to those acquired for the X-axis. Experimental gyroscope means and standard deviations shown in Table 3.2 indicate that the Z-axis not only had elevated means but also greater standard deviations.

Variability in the means of the gyroscope angular velocity output between sensors is displayed in Figure 3.1. Consistently sensor 4 appeared to have a higher median yet similar variability in values especially in the Z-axis. Sensor four may be the primary contributor to the elevated values in the Z-axis.

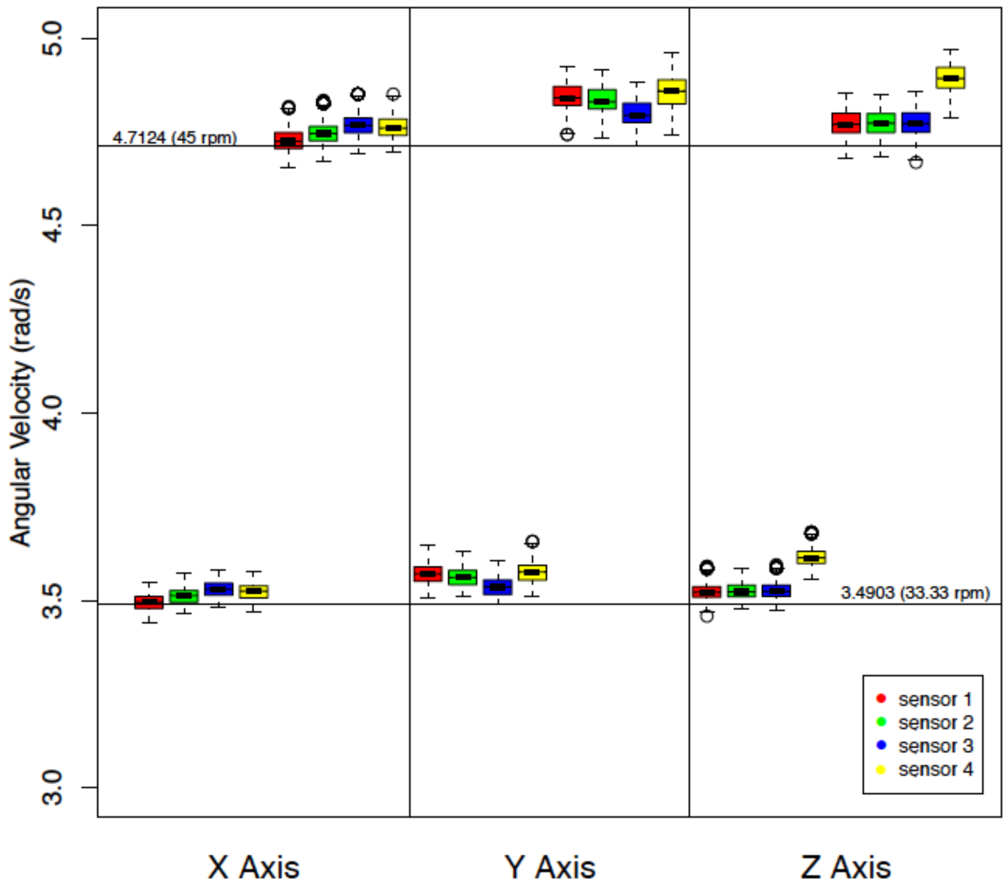


Figure 3.1. The boxplots display experimental gyroscope output for each sensor as a function of axis (x-axis) and turntable speed (y-axis). The median is shown by the thick black line; the outer bounds of the boxes represent the interquartile range. The whiskers display the minimum and maximum values excluding the outliers that are represented by the circles.

Z-tests of the individual sensors at both turntable speeds and sensor locations, summarized in Table 3.3, confirmed that sensor 4 was significantly different in the Z-axis at both turntable speeds and locations as was sensor 3 at the 33.33 rpm and 0.05 m location.

The SEM of the experimental gyroscope outputs of each axis at the two turntable speeds are found in Table 3.1 while the SEM of individual sensor experimental gyroscope outputs are displayed in Table 3.3.

Table 3.3. Z scores and SEM of the gyroscope outputs for each axis, sensor, turntable speed and radius.

Z-TEST

		X axis		Y axis		Z axis	
	Sensor	z score	SEM	z score	SEM	z score	SEM
33 rpm 0.05 m radii	1	0.19358	0.00031	3.14305*	0.00042	1.59935	0.00033
	2	1.10513	0.00030	2.7861*	0.00041	1.68476	0.00032
	3	2.10743*	0.00031	1.7821	0.00041	1.68191	0.00033
	4	1.77349	0.00031	2.73289*	0.00049	6.11395*	0.00033
33 rpm 0.10 m radii	1	0.21068	0.00037	3.41570*	0.00039	1.48096	0.00038
	2	0.99365	0.00036	3.47191*	0.00035	1.65904	0.00036
	3	1.76569	0.00037	2.24349*	0.00034	1.66329	0.00037
	4	1.49739	0.00037	3.52040*	0.00041	5.3804*	0.00039
45 rpm 0.05 m radii	1	0.64813	0.00056	3.28452*	0.00061	1.68136	0.00061
	2	1.24561	0.00054	3.17977*	0.00058	1.69646	0.00059
	3	1.81115	0.00057	2.25968*	0.00057	1.65963	0.00061
	4	1.76266	0.00053	3.00663*	0.00071	4.60988*	0.00065
45 rpm 0.10 m radii	1	0.30926	0.00049	4.08129*	0.00057	1.61409	0.00056
	2	0.91768	0.00051	4.01632*	0.00054	1.61723	0.00059
	3	1.62683	0.00050	2.89270*	0.00054	1.70345	0.00057
	4	1.50083	0.00049	4.29534*	0.00061	5.06676*	0.00058

*significant ($p \leq 0.05$) without Bonferroni correction

3.5.3 Accuracy and Precision of Accelerometers

Z-tests shown in Table 3.4 reveal that the experimental accelerometer outputs in the radial direction were not significantly different than the expected accelerations for each turntable speed and sensor location. The SEM of all sensors at both turntable speeds and locations in the radial direction were between 0.06874 and 0.09809 m/s^2.

The tangential accelerations were expected to be 0. Although they were not significant, the mean experimental tangential accelerations summarized in Table 3.5 varied from 0.35526 to 0.39251 m/s^2 indicating that the turntable was not rotating at a constant velocity. The experimental acceleration and angular velocity will be affected by the lack of constant velocity in the turntable. Triangulation was used to determine if one of the above errors had a greater influence on the estimated values.

Table 3.4. Expected radial turntable accelerations and experimental mean, standard deviation, z-test value and SEM for each turntable speed and radii.

Radial Turntable Accelerations (m/s^2)					
	Expected value	**Experimental mean**	**Experimental sd**	**z-score**	**SEM**
33 rpm (0.05 m radius)	0.60911	0.66674	0.47293	0.12102	0.06874
33 rpm (0.10 m radius)	1.21822	1.22088	0.67958	0.24339	0.08054
45 rpm (0.05 m radius)	1.11034	1.24615	0.55800	0.00391	0.09809
45 rpm (0.10 m radius)	2.22067	2.29770	0.56588	0.13612	0.08168

Table 3.5. Expected tangential turntable accelerations and experimental mean, standard deviation, z-test value and SEM for each turntable speed and radii.

Tangential Turntable Accelerations (m/s^2)					
	Expected value	**Experimental mean**	**Experimental sd**	**z-score**	**SEM**
33 rpm (0.05 m radius)	0.00000	0.38732	0.36032	1.07492	0.05201
33 rpm (0.10 m radius)	0.00000	0.39251	0.36003	1.09020	0.05197
45 rpm (0.05 m radius)	0.00000	0.35526	0.38323	0.92700	0.05531
45 rpm (0.10 m radius)	0.00000	0.36357	0.38336	0.94836	0.05533

3.5.4 Triangulation

The experimental gyroscope (or accelerometer) outputs were used with the expected radii to calculate estimated accelerometer (or angular velocity) values at both turntable speeds and locations. The experimental gyroscope output in the X-axis was more accurate at estimating acceleration (69% of the time) compared to the Y and Z-axis (31% and 38%, respectively). The experimental accelerometer output in the Y and Z-axes were more accurate (both 63%) than the X-axis (31%) at estimating angular velocity.

3.6 Discussion

Dynamically assessing the accuracy and precision of the triaxial gyroscope and accelerometer outputs within MEMS is an initial process in preparation for future research involving the assessment of various activities of human movement. Utilizing a turntable, with a belt driven motor, provided a convenient, inexpensive way to assess four MEMS sensors simultaneously. The electrical mains required to operate the alternating current motor represented 1/100 of the amplitude of the gyroscope output signal. It was determined that potential noise from electrical mains did not have a major influence on the output signals obtained during this experiment.

A turntable is optimally designed for sound quality. A belt-driven turntable tends to be less accurate for speed compared to a direct drive and may have had an effect on turntable speed (http://thelimitedpress.com/turntable-basics-belt-drive-vs-direct-drive/). Although the z-tests on the data obtained for the three gyroscope output axes revealed that two out of the three axes were not significantly different than the expected gyroscope values, all three axes were biased slightly higher, suggesting that the turntable was rotating faster than expected. Although not significant, the experimental radial accelerometer outputs were also higher than expected for all turntable speeds and sensor locations. Busching et al. (2012) found that their radial experimental accelerations were lower than expected at higher accelerations; they were using a customized turntable with a radius of 0.30 m and speeds of up to 8.1675 rad/s compared to our maximum speed of 4.7124 rad/s (Büsching et al., 2012). The presence of tangential accelerations at both turntable speeds and locations could be due to a systematic instrument error in the MEMS, the turntable or both.

The experimental Y-axis gyroscope output was significantly different than expected. To collect data about the positive Y-axis gyroscope, the positive Y-axis had to be oriented downward into the turntable, which meant that the sensor was placed on the narrowest side with the longest side vertical (see Appendix B). Once the turntable was up to speed, the sensors had a tendency to fall over, especially at 45 rpm, therefore plasticine (Harbutts, Canada) was used to stabilize the sensors. This particular sensor orientation was the least stable therefore the lack of accuracy may have more to do with misalignment of the sensor than actual accuracy of the Y-axis gyroscope. Embedding the sensors into the ethafoam may have provided a more stable positioning.

The turntable may have had a nutation, or wobble, thereby resulting in some movement of the sensors as the turntable was rotating. The experimental radial and tangential accelerations were calculated using FFT to identify the harmonic that contained the largest part of the signal, thereby minimizing the effect of nutation and noise, but not misalignment of the sensor. Positioning of the MEMS was attained using the researchers eye (with levelness verified using a spirit level) and it is possible that axis alignment was inconsistent. The SEM for the gyroscope outputs at both turntable speeds were < 0.00071 rad/s and the accelerometer outputs at both turntable speeds and locations were $<$ $0.09809\ m/s^2$ indicating that the effect of any movement was minimal and consistent among the sensor orientations.

Assumptions were made in the calculations of expected angular velocity, radius and acceleration values. The expected angular velocity calculation was based on a turntable rotating at a constant velocity, but the experimental results showed that this was likely not the case. The center of the sensor was used as the expected radii, however the true locations of the accelerometer or gyroscope within the sensor were unknown. The expected acceleration was calculated using the expected angular velocity and expected radii, both of which may be erroneous. Triangulation was used to provide insight into the data and determine if the experimental gyroscope (or accelerometer) values would calculate an estimated acceleration (or angular velocity) value closer to the expected while keeping the radius constant. Not surprisingly, the experimental value that was closest to the expected value was more accurate at calculating the estimated value. Ideally, having the exact location of the accelerometer and gyroscope within the sensor would have provided more accurate calculations.

When assessing accuracy and precision of a device, the intended end use of the device must be kept in mind to give perspective on the level of accuracy and precision required. Utilizing a turntable to assess gyroscope and accelerometer accuracy and precision may not be as robust as custom fabrication of a testing device; it is convenient, relatively inexpensive and available. Using a turntable we were able to assess that the triaxial accelerometer (radial and tangential) outputs along with the X and Z-axis gyroscope outputs were not significantly different than what was expected. We were also able to determine that one of the MEMS gyroscope outputs was different than the other three along one of its axes providing insight into its optimal orientation during future research and possible exclusion if more stringent accuracy and precision boundaries are required. The gyroscope and accelerometer SEMs of the four MEMS tested in this study were relatively small when compared to motor variability in human gait. We concluded that each MEMS had sufficient accuracy and precision for the intended end use of the sensors, which is to assess seven activities of daily living performed by individuals wearing a transtibial prosthesis.

3.7 References

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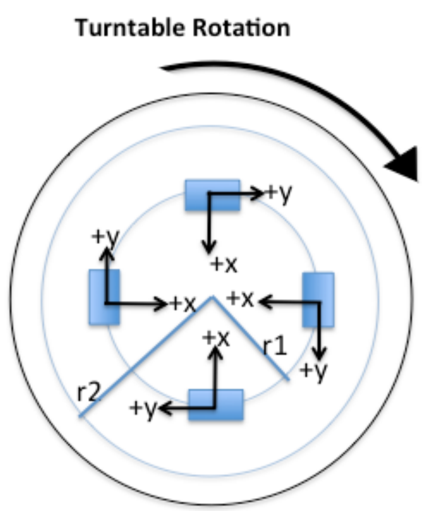
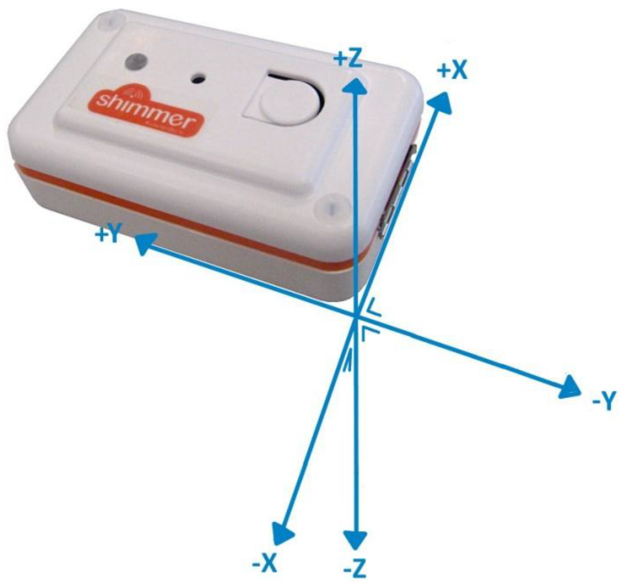
3.8 Appendices

Appendix A: Axial view of the turntable showing placement of the four sensors at the r1 (0.05 m) radius. The positive Z-axis is pointing down into the turntable in order to collect gyroscope data. Tangential and radial accelerations are being collected along the positive Y and positive X axes respectively



Appendix B: Orientation of Shimmer 2r axes



Chapter 4: DISCUSSION

4.1 Thesis Overview

The overall objective of this thesis was to determine if the output of the triaxial accelerometer, gyroscope and magnetometer within four Shimmer 2r microelectronic measuring systems (MEMS) produced data that were accurate and precise in static and dynamic conditions. This knowledge is required prior to their use in a future study to assess seven activities of daily living (including level walking, ramp walking and stairs) performed by individuals with a unilateral transtibial amputation in a clinical environment. The environment can have an effect on MEMS outputs (de Vries et al., 2009; Haverinen & Kemppainen, 2009; Roetenberg et al., 2005). The MEMS were assessed in a rural environment to reduce the effect of building materials, as well as the clinical environment where they will eventually be used for research.

MEMS outputs are often compared to values obtained using optical motion capture systems (OMCS). Noise or errors present in the OMCS displacement data are multiplied during the differentiation process (Esser et al., 2009; Kavanagh et al., 2006) therefore comparing MEMS outputs to known values is preferred. Initially data collection was performed while the MEMS were static so that the accelerometer output could be compared to a known acceleration (gravity) and the magnetometer output could settle on the Earth’s magnetic north.

Simultaneous sampling from all four sensors is more time-efficient than sampling one sensor at a time and reduces the potential for systematic errors between conditions. The four sensors were placed in an acrylic cube and held in place using ethafoam (Vitacare, Ontario). One sensor was placed along each of the four sides of the acrylic cube so that the cube could be statically positioned to align the MEMS axes parallel to the Earth’s gravitational field.

The MEMS were subsequently tested in a dynamic condition similar to Busching et al. (2012) who used a turntable to assess gyroscope and accelerometer (radial and tangential) outputs (Büsching et al., 2012). The turntable provided an expected angular velocity (ω) that was used with an expected radius (r) of 0.05 m or 0.10 m to calculate an estimated radial acceleration using the formula $a=\omega^2 r$. Uniform circular motion provided by the turntable provided an expected tangential acceleration value of 0 m/s^2. The turntable required the use of electrical mains therefore the contribution of the electrical mains to the original signal was determined.

Prior to their use in research, assessing the accuracy and precision of MEMS in the same environment and conditions they are to be used provides insight on their optimal orientation or possible exclusion (Picerno et al., 2011). The intended purpose of the MEMS should be kept in mind so that a practical level of accuracy is set in order to minimize the chance that MEMS are excluded unnecessarily from future research. For this study, an *a priori* acceptable tolerance of 1% was set based on manufacturer datasheets as well as literature assessing force platforms (Ballaz et al., 2013; Gill & O'Connor, 1997) and normal variability in human gait (Kavanagh et al., 2006). Ultimately these MEMS will be utilized in a future study to assess gait during daily living, as well as within a clinical environment. The MEMS outputs, if inaccurate and imprecise, could provide misleading results and conclusions.

4.2 Summary and discussion of results

The assessment of accuracy and precision of the accelerometers and magnetometers within the MEMS in the static condition was enhanced using spectral decomposition to minimize the impact of alignment errors including the following: non-orthogonal axes of the accelerometer or magnetometer inside sensor, alignment of accelerometer or magnetometer inside the sensor and cube, non-orthogonal surfaces of sensor casing or cube as well as a non-level surface. Chapter two determined that an acrylic cube could be used to simultaneously collect data in the static conditions without interfering with the MEMS outputs.

Studies have used non-ferrous materials to secure one or more MEMS in order to obtain data from each axis but have not compared secured to unsecured MEMS outputs (Brodie, Walmsley, & Page, 2008b; Picerno et al., 2011). The realigned accelerometer output values in the cube were not significantly different than the expected known gravitational value of 1.00000 g. The z-tests revealed that the accelerometer values inside the cube were actually more accurate than outside the cube. This may be due to the fact that the cube held the sensors securely and provided an external enclosure that aligned the axes more parallel to gravity as checked using a spirit level.

The realigned magnetometer output values inside and outside of the cube were both significantly different than the expected local value of 1.00000. This is possibly due to the fact that the placement of the sensor was focused on aligning the axes with gravity and not magnetic north. As a result, the signal may have been distributed amongst the three axes and a mean direction was not obvious during spectral decomposition resulting in uncertainty in realignment of the vector.

Regardless of whether the MEMS were in or out of the acrylic cube, realigned accelerometer and magnetometer (excluding sensor four) outputs were within the predetermined 1% acceptable tolerance of their respective expected values in the rural environment. The acrylic cube did not have an effect on the realigned accelerometer or magnetometer output precision. As a result, it was determined that the acrylic cube did not affect the accelerometer and magnetometer outputs and was a viable option to simultaneously collect data from the four MEMS in the clinical environment and reduce error due to positioning across replicate experiments..

Once calibrated in the clinical environment, the four MEMS were placed in the acrylic cube and were assessed at two heights (0.15 m and 1.0 m up from floor) in three locations (ramp, walkway and stairs) where data collection will occur in a future study. Although there was a significant effect of sensor height on the realigned accelerometer outputs, they were within the 1% acceptable tolerance set *a prior* indicating that the clinical environment had a minimal effect on the accuracy of the accelerometer within the MEMS. The clinical environment did not have an effect on the precision of the realigned accelerometer outputs.

The realigned magnetometer output was significantly less 1.00 m above the floor (compared to 0.15 m) at the ramp and walkway locations while the findings at the top of the stairs were opposite, implying that the building environment did affect the accuracy of the magnetometer. The building structure also had an effect on the precision of the realigned magnetometer output. The location that affected the precision of the realigned magnetometer output the most was placement of the sensor 0.15 m above the floor at the top of the stairs. It is likely that there was a high ferrous content in the staircase affecting the sensor when it was closer to the floor.

A turntable was used for dynamic testing in the rural environment. The influence of the electrical mains was found to contribute 1% to the gyroscope output and was therefore deemed insignificant. Experimental accelerometer outputs in the radial and tangential direction were not significantly different than the expected accelerations for each turntable speed and sensor location. Although there was no significant difference between the expected and experimental tangential accelerometer outputs, they were not 0 m/s^2 indicating that the turntable was not rotating at a constant velocity. Utilizing a turntable, Busching et al (2012) had similar radial acceleration results, however tangential acceleration was not assessed (Büsching et al., 2012). During uniform circular motion, there is no change in velocity over time therefore tangential acceleration is equal to 0 m/s^2. The effects of this were minimal since there were no significant differences between the expected and experimental radial acceleration outputs despite the observation that they were slightly elevated for all turntable speeds and sensor locations. The standard errors of the mean

(SEM) values were minimal therefore the accelerometers were found to have sufficient precision for their intended purpose.

The gyroscope outputs for all three axes were biased slightly higher indicating that the turntable was rotating faster than expected. Busching et al. (2012) also discovered their turntable deviated from the expected speed (Büsching et al., 2012). The experimental gyroscope output along the Y-axis was found to be significantly different than the expected gyroscope value. This was not surprising. To collect data about the positive Y-axis the sensor had to be placed on its narrowest side with the longest dimension positioned vertical. This particular sensor orientation is the least stable therefore the lack of accuracy may have more to do with misalignment and precarious positioning of the sensor than actual accuracy of the Y-axis gyroscope. Embedding the sensors into the ethafoam may have provided a more stable setting. Busching et al. mechanically attached their MEMS to a rigid extension built onto the turntable in order to extend the radii options (Büsching et al., 2012). The use of Fast Fourier Transform (FFT) enabled identifying and eliminating the nuisance effects associated with nutation (wobble) but not misalignment of sensors.

The Z-axis experimental gyroscope output was not significantly different but was elevated. Further investigation using z-tests of individual sensors revealed that there were significant differences for sensor four in the Z-axis for all turntable speeds and radii as well as sensor three in the X-axis at 33.33 revolutions per minute (rpm) and 0.05 m radius. These issues with sensor three are possibly due to operator error in placement of the sensor or method error if the sensor moved once the turntable was turned on. Sensor four was different for all turntable speeds and radii indicating that there may be a systematic instrument error with the gyroscope within the sensor. Sensor four also underestimated the magnetometer output by more than the acceptable tolerance of 1% compared to the other three sensors during the static assessment in the rural environment. Picerno et al. (2011) compared nine MEMS from various companies and discovered that one of the MEMS behaved differently than the others (Picerno et al., 2011). Sensor four may need to be recalibrated or possibly excluded from future research. It is possible that if gyroscope data from all three axes are not essential in the research protocol, sensor four could be oriented so that data from the Z-axis gyroscope is not essential.

Overall, three of the four MEMS assessed were sufficiently precise to use for the intended purpose of the future study. The clinical environment affected the MEMS and, therefore, it is advisable to assess the accuracy and precision of MEMS in the conditions and environments in which they will be used during research studies. Utilizing methods such as Eigen analysis and FFT, as illustrated in this thesis, help to reduce the impact of systematic and random errors.

4.3 Limitations

Although the turntable proved to be a convenient and inexpensive device to dynamically assess the accuracy and precision of the MEMS, there are some limitations to its use. The turntable itself needs to be calibrated in order to determine that it rotates at a constant velocity with the weight of the ethafoam and sensors on top of the turntable (Büsching et al., 2012). The turntable is built for sound quality and has an inherent nutation or wobble. Due to the speed and nutation of the turntable, the sensors are prone to moving and falling over. Placing the MEMS in a more secure vessel that will securely hold and maintain them in a desired orientation in order to assess their internal components would be ideal. Such a vessel could be used statically and dynamically to help to minimize human error in MEMS placement and orientation. Ideally MEMS manufacturers would supply such a device in order to allow researchers to conveniently and consistently assess MEMS outputs statically and dynamically in various environments.

Although the building material specifications used to construct for the clinical environment were not available, it is expected that there would be increased ferrous material in the flooring and stairwell that may affect the sensor magnetometer output. Attention was placed on orienting the MEMS so the accelerometer axes were parallel to gravity. There was no attempt to align the magnetometer axes parallel to the Earths magnetic north axis. As a result the raw magnetometer output may be dispersed among all three axes of the sensor inhibiting the ability of spectral decomposition to identify the mean direction of the signal.

4.4 Recommendations for future research

To reduce systematic operator error, simultaneous assessment of MEMS in a vessel that will hold the MEMS securely in the appropriate orientation would reduce extraneous movement during both static and dynamic data collection. When assessing the MEMS in a static condition, care should also be taken to align the axes of the sensors parallel to gravity as well as magnetic north.

Dynamic assessment of the MEMS should encompass accelerations and angular velocities expected during the intended use conditions.

DePasquale et al. (2010) found that there was decreased precision among the X,Y and Z axes within the MEMS after dynamic excitation (De

Pasquale & Somà, 2010). This study compared the expected values during dynamic testing to assess the accuracy but did not assess the effect of the dynamic testing on the sensors pre and post dynamic condition. Future work should assess the effect of dynamic excitation on the MEMS outputs by analyzing static outputs pre and post dynamic state in the environment they are to be used.

4.5 Conclusion

The overall objectives of this thesis were to assess the accuracy and precision of four Shimmer 2r MEMS in static and dynamic conditions in the environment they will be utilized prior to their use in applied clinical research. The information attained provides insight on the optimal orientation or exclusion of MEMS. It proved to be advantageous to use an acrylic cube to simultaneously assess the four MEMS statically in both the rural and clinical environments. The stairwell in the clinic environment had the largest effect on the accuracy and precision of the magnetometer output. Although the clinic environment did have an effect on the accelerometer output, it was deemed to be clinically insignificant for the intended use of the MEMS.

Similar to Picerno et al. (2011) one of the MEMS was found to have outputs that were different from the other three being tested (Picerno et al., 2011). Although it was concluded that each MEMS was accurate and precise enough for the intended end use of the sensors, knowing that one sensor was different provides insight into its optimal orientation during future research and possible exclusion if more stringent accuracy and precision boundaries are required. Prior to using MEMS in research, it is advisable to investigate the effects of the environment on the sensor outputs in similar conditions to which the MEMS will be exposed

4.6 References

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