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Three-Dimensional Kinematic Analysis Using the Xbox Kinect

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Human Three-Dimensional Kinematic Analysis Using the Microsoft Xbox Kinect™

R. Matthew Wham
Chancellor's Honors Program Senior Thesis
Presented May, 2012

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Abstract

The field of biomechanics and motion analysis is a far-reaching one that has implications in medicine, sports, motion pictures, and many other areas. There currently exist several different methods and tools for analyzing the movement of the human body in three dimensions. Though the effectiveness of these methods has been shown in the past, they are also expensive and lack portability, making them difficult to use in situations such as fieldwork. The functionality and 3D vision of the Microsoft Xbox Kinect may be leveraged to perform these tasks. At a much lower price and much improved portability, it may help to alleviate some of the disadvantages of using existing software. A new method for performing three-dimensional motion analysis is proposed that takes advantage of the Xbox Kinect's 3D vision to track the movement of the human body. A cursory analysis of the accuracy of this new software is analyzed and future work is proposed that may improve on the system and guide new investigators toward a useful biomechanical analysis tool utilizing the Xbox Kinect.

Introduction.

The study of biomechanics plays a central role in the field of biomedical engineering. Through its study, we can gain insight in to the movement of biological organisms and the evolution of this very movement. (Winter 1990) Indeed, day-to-day activities from the brisk jaunt from car to work in the morning to the meandering stroll after a large meal are all governed by the principles studied in biomechanics. Although in contrast to a century ago, much of society now remains sedentary, the study of biomechanics can yield understanding to the injuries incurred during leisure time or to the more esoteric such as the mobility of tyrannosaurus rex. (Nigg et al. 2000, Hutchinson et al. 2011) Through this scientific exploration, attempts can be made to correct underlying pathologies of movement or possibly study the progression of specific disorders involving the decline of mobility. (Nigg et al. 2000, Winter 1990) In the case of cerebral palsy, the study of biomechanics has allowed surgeons and biomedical engineers to predict the prognosis after tendon transfer surgery and also examine new surgeries that may assist in the treatment of the disease. (Joseph et al. 2010, Lieber 1992)

Biomechanics involves the synthesis of many scientific disciplines. Aspects from the study of work and energy in physics, forces and moments in mechanical engineering, and neuromuscular connections from biology must all be integrated, among other specialties, in order to fully understand human movement. (Griffiths 2006, Nigg et al. 2000) Because of the number of interacting disciplines and the large number of variables involved, this makes data collection and analysis in biomechanics very difficult. Nonetheless, data regarding the mechanics of human movement using motion analysis is a hallmark of the field and integral to the study of motor control and biomechanics. (Griffiths 2006)

There are a number of ways to collect biomechanical data both in two dimensions (2D) and three (3D). In 2D analysis, digital video cameras or other convenient methods of motion picture acquisition are used to collect a sequence of still images of the subject. The process of digitization then analyzes these images for information about the human anatomy (i.e. the locations of hip, knee, etc.). Finally, calculations can be performed on this digitization that yield useful biomechanical results – such as a knee angle. (Griffiths 2006) In 3D analysis and motion capture, numerous cameras are used to take images. After raw, two-dimensional information has been captured from each camera, often a technique known as direct linear transform is used to convert the 2D camera data to 3D coordinates for a point in space, typically on the anatomy. In both methods, reflective markers are used as “landmarks” that the cameras can use to orient themselves. (Griffiths 2006)

Another field that takes advantage of 3D scene reconstruction is that of robotic vision, thus it provides some insight into how 3D analysis can be performed in the field of biomechanics. (Florczyk 2005) Indeed, entire nationwide competitions have been devoted to using three-dimensional robotic vision reconstruction to perform a useful task such as autonomously driving a motor vehicle. (DARPA, 2005) In order to suit the needs of the field, a number of cameras have been developed that allow the robotic systems to reconstruct a given scene three-dimensionally. (Florczyk 2005) Two methods are generally achieved to achieve this goal: active and passive vision systems. (Morris 2006) Active vision systems interact with the scene by emitting a beam that interacts with an object and returns to the system. Passive systems typically use two cameras placed close to each other that then are triangulated in order to establish three-dimensional information about a scene, similar to human eyes. (Morris 2006)

The Microsoft Xbox Kinect (Microsoft Corp., Redmond, WA, USA) is an active vision system that attempts to recreate the scene in front of it using an infrared (IR) laser point cloud. (Khoshelham 2012). The method of determining 3D position for a given object in the scene is described by the Kinect's inventors as a triangulation process. (Freedman 2010) Essentially, a single infrared beam is split by refraction after exiting a carefully developed lens. This refraction creates a point cloud on an object that is then transmitted back to a receiver on the assembly. Using complex built-in firmware, the Kinect can determine the three-dimensional position of objects in its line-of-sight by this process. (Freedman 2010) The advantage of this assembly (shown below in Figure 1) is that it allows 3D registration without a complex set-up of multiple cameras and at a much lower cost than traditional motion labs and robotic vision apparatuses.

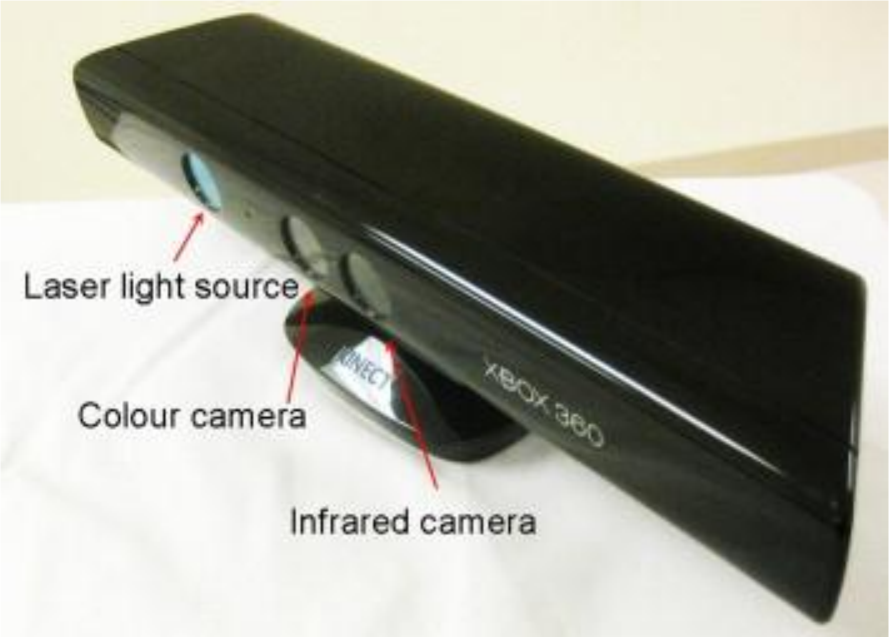


Figure 1. Image of the Kinect with arrows indicating the identity of the cameras. (Dutta 2011)

A team of biomedical engineering seniors at the University of Tennessee has undertaken a project to use the Microsoft Xbox Kinect for biomechanical research. The task was to take advantage of the Microsoft Xbox Kinect's new Software Development Kit in order to take advantage of the functionality of the Kinect for use as a biomechanics analysis tool. Other tools currently in use for this purpose include the Dartfish (Dartfish, Inc., Fribourg, Switzerland), software from Quintic Sports (Coventry, UK), software from SportsCAD (Berlin, MD, USA), and many others. All of these programs are very expensive, often costing in the high hundreds of dollars, if not more. It is the goal of the Kinect biomechanics project to reduce this cost while maintaining -- if not improving -- ease of use and retaining as much accuracy as is possible.

In order to achieve this task, several goals have been undertaken. Constant practice and progress has been made in learning new aspects of the C++ programming language, a language they have not previously had any experience with, as well as hone their design skills and constantly test the product in order to ensure that it meets their expectations. The final deliverable this endeavor is software that takes advantage of the functionality of the Xbox Kinect in order to assess a person's biomechanics during a deep knee bend. This design project will provide a strong head start for those who may use it in the future in order to develop it into a more robust and efficacious software package.

Previous Work: Motion Analysis.

The analysis of gait and human movement has been conducted for quite some time. It has been used to study effectiveness of total knee replacement (Jolles et al 2012), Parkinsonian gait (Crémers et al 2012), cartilage degeneration in runners (Beckett et al 2012), and many more biomechanical phenomena. There are generally two components of motion analysis that engineers concern themselves with: kinematics and kinetics. The study of kinematics surrounds the actual motions themselves and associated properties such as velocity, angular acceleration, etc. Kinetics is concerned with Newtonian forces experience by the body and the load experience by various anatomical bodies. These two fields are driven by the use of motion capture systems that provide the tools necessary to estimate relevant properties pertinent to the investigation of the motion in question. (Griffiths 2006)

Three-dimensional kinematic analysis allows the measurement of displacements, velocities, and accelerations in terms of their components along the three axes of a three-dimensional coordinate system. It also allows the measurement of body rotation angles such as the flexion/extension of the knee. Measurement of the knee angle is an acceptable starting point to analyze the efficacy of a biomechanical analysis project due to its relative ease and applicability to a wide range of scenarios from general gait cycles to post-operative surgical evaluation. (Griffiths 2006, Iorio et al 2012) Indeed, measurement of three-dimensional knee kinematics is a very common experimental procedure in the field of biomedical engineering, though methods of tracking such kinematics differ somewhat. One study, performed to analyze the differences in kinematics between anterior cruciate ligament (ACL)-deficient knees and ACL-reconstructed knees, leveraged the power of an optical motion tracking system manufactured by Motion Analysis Corporation in Santa Rosa, CA. (Gao et al., 2012) Before data collection, the subject was required to maintain a pre-defined, static pose in order to calibrate the system. In order to perform the analysis, many 10mm reflective markers were placed at bony landmarks over the entire leg. In addition, more markers than are typically required were placed in order to attempt to minimize soft tissue artifact. Poses were calculated throughout the movements using a well-known optimization algorithm and the motion was subsequently analyzed with a complex MATLAB program. By testing their custom-built software, Gao et al. established their root-mean-square (RMS) error to be less than 2° in all three metrics: flexion/extension, varus/valgus, and internal/external rotation. (Gao et al. 2012) This study demonstrates the current "gold standard" in three-dimensional kinematic analysis and yields insight into what accuracy is currently expected in the body of research.

It can be seen that the motivation for three-dimensional lower-limb analysis is certainly very real, given the high importance of therapeutic treatment comparisons and even sports injury prevention. Given this, and the fact that many optical kinematic analysis packages are immobile and cost-prohibitive, some researchers are attempting to perform accurate analysis without the need for visual analysis programs. (Liu et al. 2012) This has been attempted in the past (O'Donovan 2007, Cooper et al. 2009), but has met with mixed results and has yet to be able to offer a method for determining limb position. Therefore, in an attempt to make lower-limb kinematic analysis more mobile and less expensive, Liu et al. use accelerometers and a method incorporating a physical sensor difference-based algorithm to calculate the acceleration of various points on the femur and tibia. Their method was compared to the results obtained using a NAC Hi-Dcam II digital high-speed camera systems (NAC Image Technology, Tokyo, Japan). Results were acceptable and correlated well with the camera's results, however the prototype for their device remains bulky. (Liu et al. 2012) Further work in reducing the costs of kinematic analysis must include other options if progress is to be made.

Previous Work: Xbox Kinect

Perhaps due to the commercial popularity of the Kinect, many amateur studies have been conducted regarding its efficacy in applications as wide-ranging as robotic vision to surveillance. Though published literature is still sparse, some studies yield insight into the promise of the Kinect for three-dimensional motion analysis. One of the most important aspects of studying the Kinect's efficacy in biomechanics is the analysis of the range camera's accuracy. Indeed, it has proven so critical that many research teams have addressed this issue. In a study by Khoshelham et al., the accuracy of the Kinect's depth images was evaluated. First, a camera calibration was performed using a checkerboard setup and parameter bundle adjustment. Next, the Kinect's infrared point cloud was compared with that of a "high-end" laser scanner, the FARO LS 880. In this instance, the mean and median discrepancies between the two were very nearly zero. (Khoshelham et al. 2012) The results are shown below in Figure 1.

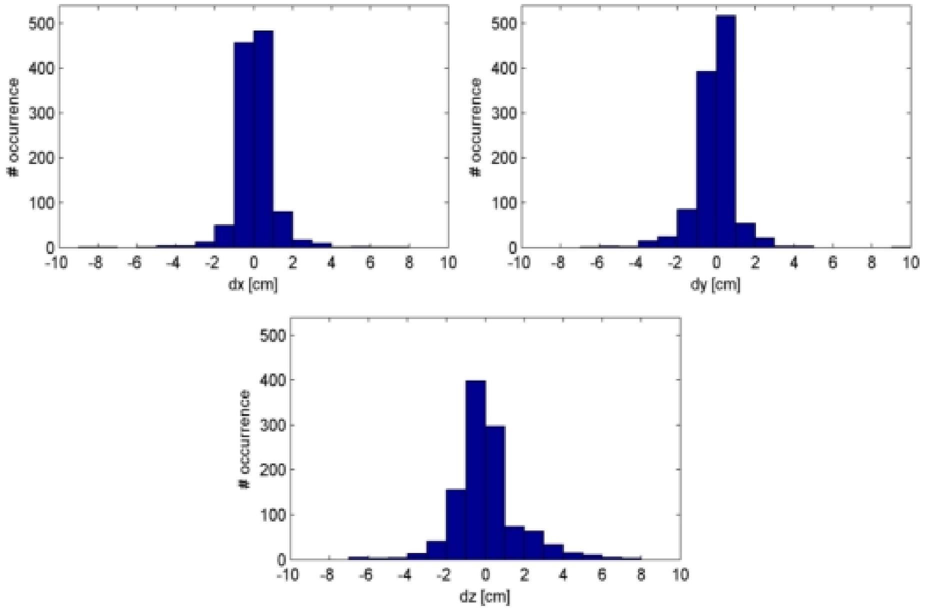


Figure 2. Discrepancies between the Kinect and commercial laser scanner's point clouds. Results are plotted as histograms indicating the discrepancy length versus number of occurrences. (Khoshelham et al. 2012)

An investigation into the Kinect's ability to scan human bodies in three-dimensions has also been performed. (Tong et al. 2012) This particular study used three Kinect's to measure the top, middle, and lower parts of a person as he spun around on a turntable. Subsequent reconstruction was necessary in order to fuse the data and register many frames of noisy data in order to create a 3D model. The resulting model is shown below in Figure 2. It should be noted that the mean error was approximately 2.5 cm and varied among body segments. (Tong et al.) This study further demonstrates the power and efficacy of the Kinect in replacing expensive three-dimensional analysis tools for applications when the additional accuracy isn't necessary.

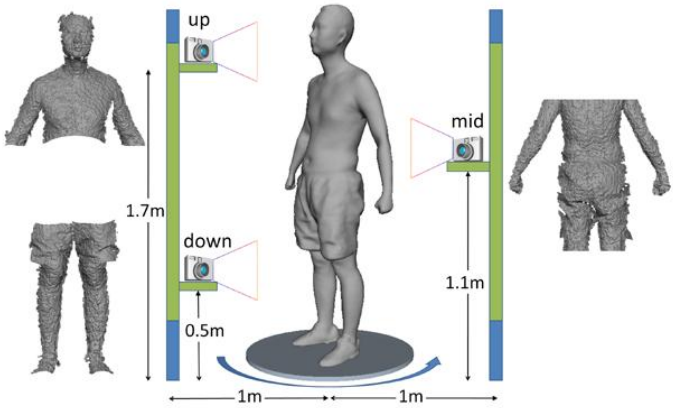


Figure 3. Resulting 3D model from the study by Tong et al. The set-up used to attain the model is also displayed. (Tong et al. 2012)

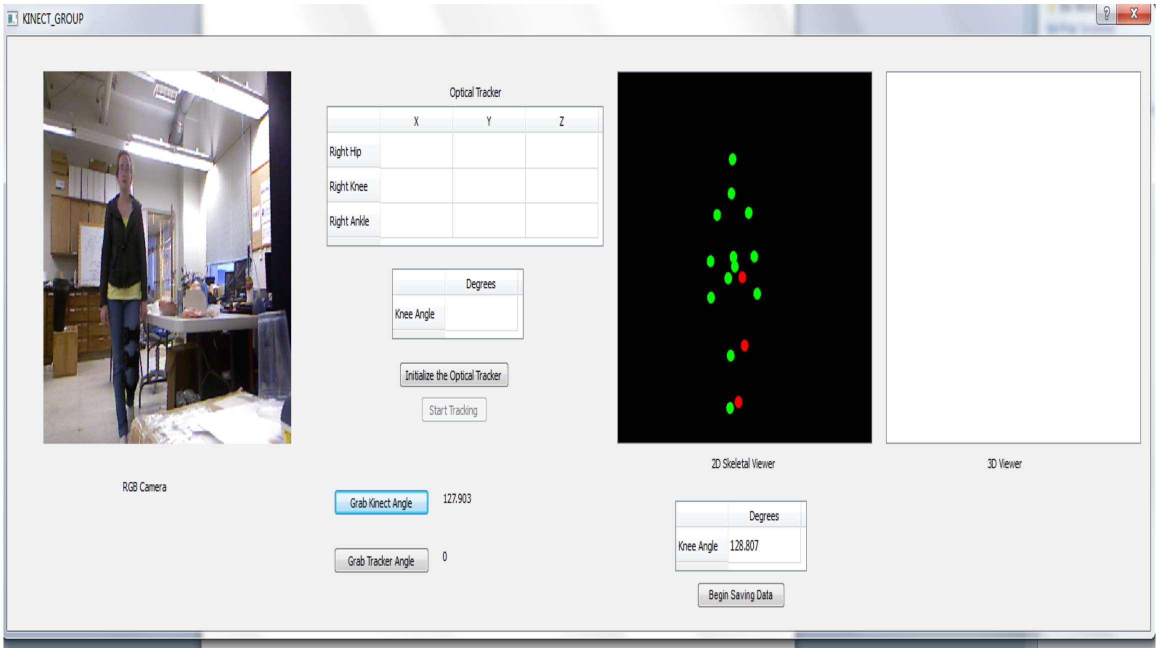
Beyond simple laser scanning and scene reconstruction, there is a small precedent for the use of the Kinect in biomechanical studies. In a study by Stone and Skubic, two Kinects were used to track the variances in gait associated with elderly patients exhibiting declining mobility. (2011) In this analysis, the Kinects were used to gather three-dimensional point cloud data and gait parameters were extracted from a time series of a correlation coefficient computed from normalized ground-plane projections. In each three-dimensional point cloud, all points below a height of 20 inches were projected onto the ground plane and then normalized by subtracting the mean. Measurements were taken of individual strides and inter-stride variance. The results of the Kinects were then compared to a Vicon motion capture system (Peak Performance Technologies, Inc., CO, USA). The Kinects' accuracy was comparable to that of the camera, though it is interesting to note that the Kinect placed perpendicular to the direction of motion showed quite a bit more accuracy than the Kinect facing the subject directly. (Stone & Skubic 2011)

Efficacy of the Kinect has also been investigated for studying ergonomics in the workplace. (Dutta 2011) As previously stated, because of the bulk of traditional motion capture setups a more portable system is desired, and Dutta studied the possibility of using the Kinect as such. After calibration, the Kinect was used to take a 3D image of a scene containing cubes at varying distances. The results were compared with the cubes' known coordinates in the world coordinate system and with data extracted from a Vicon camera. RMS errors in this investigation were reported to be 0.0169 m, 0.0348 m and 0.0141 m in the x, y and z directions, respectively. More than simply depth camera accuracy, however, Dutta points out that object detection (important in skeletal tracking) is dependent on surface reflectivity: the Kinect demonstrated difficulty in detecting dark surfaces that tend to absorb light and shiny surfaces that reflect too much light. Note that the latter has been observed by this author as well. It is concluded that the Kinect would likely mean sacrificing some accuracy in motion analysis, but the increase in portability may be attractive to some users. (Dutta 2011)

Software Design.

Thus, it was the aim of this investigation to begin devising a method of using the Xbox Kinect for biomechanical analysis. Such a design may yield results with lower accuracy than more expensive equipment such as the Vicon Motion Capture system, but the decrease in cost and increase in portability may make it more attractive for applications such as home healthcare or fieldwork in sports or ergonomics. Such a design would need to include functionality for analyzing the three-dimensional kinematics of a subject and reporting the kinematic data to the user. Finally, some data visualization tools were implemented in order to facilitate both ease of use and visual appeal.

A graphical user interface (GUI) has been designed for the software and is shown below in Figure 4. Open source software known as QT from Nokia has been used to accomplish this task. (Nokia, Inc., Finland) It is a plugin to Microsoft Visual Studio 2010 that allows the user to simply "drag and drop" tools into a window that then becomes the GUI. This tool writes code for the user that not only governs the GUI window but also places this code into a thread that allows for interaction between the GUI and the underlying program architecture so that the program does not become unresponsive while the user is interacting with it. The task for the developer simply becomes connecting the GUI with "black box" code that handles the hardware and manipulates the data into a useful form.



	X	Y	Z
Right Hip			
Right Knee			
Right Ankle			

	Degrees
Knee Angle	

Grab Kinect Angle 127.903

Grab Tracker Angle 0

	Degrees
Knee Angle	128.807

Figure 4. Interactive GUI. From left to right: RGB camera view, optical tracker data table, 2D graphics with accompanying knee angle calculation, viewer window for 3D tibia/femur scene.

In addition to the graphical user interface, code has been written in C++ to connect the tools in the interface with the underlying code that controls the Kinect. Additionally, the group has written multiple classes that divide the program into sensible and manageable pieces. One C++ class is used to display image frames that the Kinect delivers to the computer. Another, threading class has been written to emit signals that the display class can use to render the images. This threading class retrieves data from the Kinect approximately 30 times per second. Finally, a dialog class has been written specifically to provide functionality and connections to the user interface. The dialog class also functions as a Kinect "controller," initializing and directing the Kinect throughout the lifecycle of the program.

There are unique challenges involved in displaying the data that the Kinect delivers to the workstation. One of the most interesting is how the developer chooses to visually display the depth frame data that the Kinect contains. Each frame of depth data is structured in such a way that each pixel in the frame is tagged with its distance from the Kinect sensor. (IProgrammer 2011, MSDN 2011) There is no explicit image contained within the depth data frame structure. Therefore, it is the province of the developer to devise an algorithm with which to use this information to create a visual display. There are two popular methods of performing this task: one uses a grayscale color scheme in which pixels further from the camera are lighter and pixels closer to the camera are darker. The second popular method is to use a color scheme similar to a heat map in which objects closer to the Kinect are displayed with "hotter" colors, and objects further away are cooler colors. (MSDN 2011) This particular project uses the grayscale method of coloring the depth scene. The grayscale method allows visualization without the complex computation and algorithms required to produce color.

Furthermore, the data output from the skeletal tracking engine is structured in such a way as to give quite a bit of flexibility in how the developer chooses to display it. Skeletal position information is delivered in a large data structure containing Boolean tracking states (for each tracked point), a Boolean tracking state for the skeleton itself, and 3D position vectors for each of 20 different points on the human skeleton. (IProgrammer 2011, MSDN 2011) The author chose to display this information to the user by using ellipses and "tagging" them to the X and Y positions of several points on the body. The position retriever for this class has been placed in a thread so that the skeletal ellipses are rendered in real time and follow the movement of the subject. This information is displayed in a QGraphicsView widget that renders a 2D graphics view of our subject's skeleton positions.

In addition to the 2D graphics view housed within the GUI, the group has undertaken a project to include within the project a 3D viewing window that displays three-dimensional models of the human tibia and femur. These models are currently rendered using a toolbox known as OpenInventor (Silicon Graphics International Corp., Fremont, CA, USA) and appear upon program initiation. As of the time of this writing, the tibia and femur are rendered upon opening the program, but an engine has not yet been built to rotate and translate them in accordance with the subject's movement.

At the heart of this design project is the structure of the underlying calculations that are being performed on the skeleton joint positions. The program's architecture samples the NUI API's skeleton data approximately 30 times per second and uses information gleaned therein to calculate a knee angle. It does this by first retrieving vectors for the positions of the right hip, right knee, and right ankle (joints typically tracked in knee angle calculations). It then finds two relative vectors, one vector from the right knee to the right angle and one vector from the right knee to the right hip. Finally, these vectors are normalized to have a magnitude of one. Using the equation:

$$A \cdot B = |A||B|cos\theta$$

a function within the dialog class calculates θ and displays it in the GUI with the heading "Right Knee Angle". This calculation has also been placed into a thread so that it is calculated in real time and displayed on the screen.

A table within the GUI has provided for analysis via an optical tracker. The table is populated with real-time, 3D coordinates of three optical tracker probes and it outputs a calculation of knee angle for comparison with the Kinect. This data streaming is made possible through another thread in the program that regularly pings the optical tracker for position information. In order to perform the knee angle calculation using two optical tracker probes, a systematic method using transformation matrices was devised. The transformation matrix for the tibial coordinate system is:

$$ {}^{Lab}T^{Tibia} = \begin{bmatrix} & {}^{Lab}R^{Tibia} & & P^{Tibia} \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

where ${}^{Lab}T^{Tibia}$ is the transformation matrix from the lab coordinate system to the tibial coordinate system, ${}^{Lab}R^{Tibia}$ is the 3x3 rotation matrix from the lab to tibial coordinate system, and P^{Tibia} is a three-dimensional vector from the origin in the lab coordinate system to the origin of the tibial coordinate system. Similarly, the transformation matrix for the femoral coordinate system is:

$$ {}^{Lab}T^{Femur} = \begin{bmatrix} & {}^{Lab}R^{Femur} & & P^{Femur} \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

where ${}^{Lab}T^{Femur}$ is the transformation matrix from the lab coordinate system to the femoral, ${}^{Lab}R^{Femur}$ is the 3x3 rotation matrix from the lab to femoral coordinate system, and P^{Femur} is a three-dimensional vector from the origin in the lab coordinate system to the origin of the tibial coordinate system. Both position vectors are given by the optical tracker system, while the equation:

$${}^{A}R^{B} = \left[\left[b_x\right]_A \quad \left[b_y\right]_A \quad \left[b_z\right]_A \right]$$

can be used to calculate the relevant rotation matrices. B_x, b_y, and b_z are unit vectors establishing the coordinate system of interest and are values also given by the optical tracker. Once the transformation matrices have been established, the equation:

$${}^{Femur}T^{Tibia} = \left({}^{Lab}T^{Femur}\right)^{-1} * {}^{Lab}T^{Tibia}$$

is used to establish a transformation matrix between the two anatomical coordinate systems. These equations now yield information about the knee angle in terms of three Euler angles describing flexion/extension, abduction/adduction, and internal/external rotation. (Griffiths 2006) Because this investigation is primarily concerned with knee flexion/extension, the rotation about the medial-lateral axis of the femur must be extracted and used to calculate the knee angle with an atan2 function. (Griffiths 2006, Reinbolt 2012)

In addition to the software code, several schematics of Kinect placement for gait analysis have been created. It has been determined by the group that for purposes of active, full skeleton tracking, the Kinect has a horizontal viewing window of about 30° on either side. In addition, it seems that a subject position of 6 feet away from the Kinect works best for tracking a skeleton most accurately. Both of these measurements were taken into account when drawing the schematics that follow. Initial schematics are shown below in Figure 5.

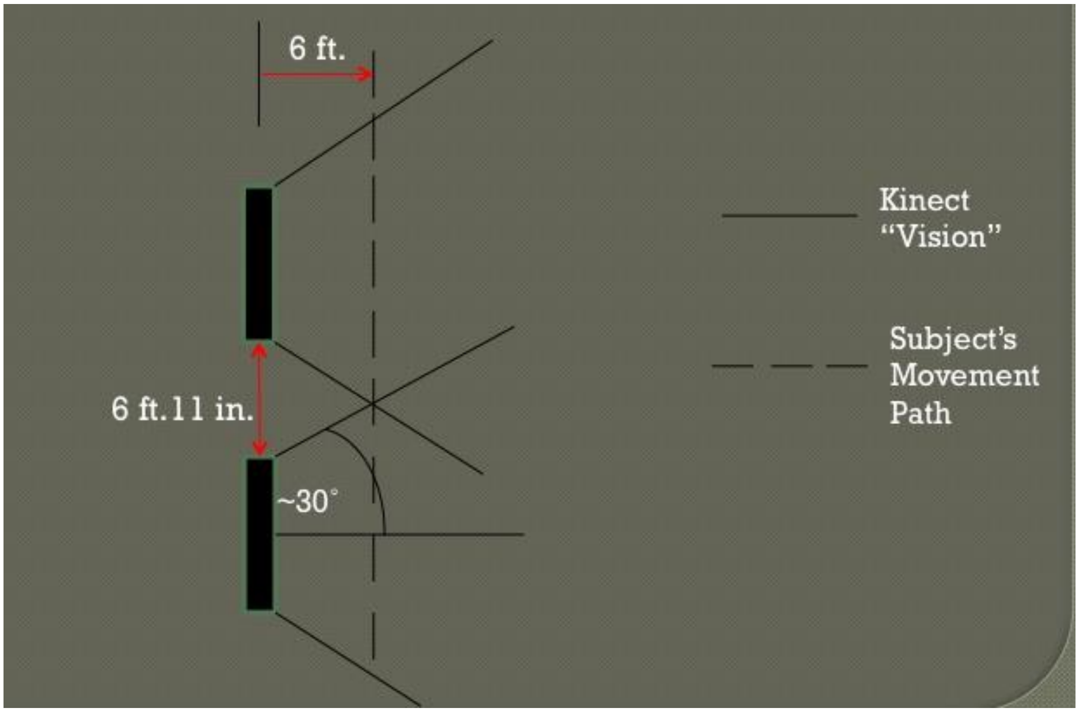


Figure 5. Schematics of a gait cycle analysis system that analyzes subject movement perpendicularly.

Figure 6 shows the schematics of a gait analysis system that analyzes the subject from a perpendicular viewpoint. This is one of many options, but one that should be tested in order to assess which setup may work best. An alternative to this particular schematic is shown below that allows for a 45° viewing angle.

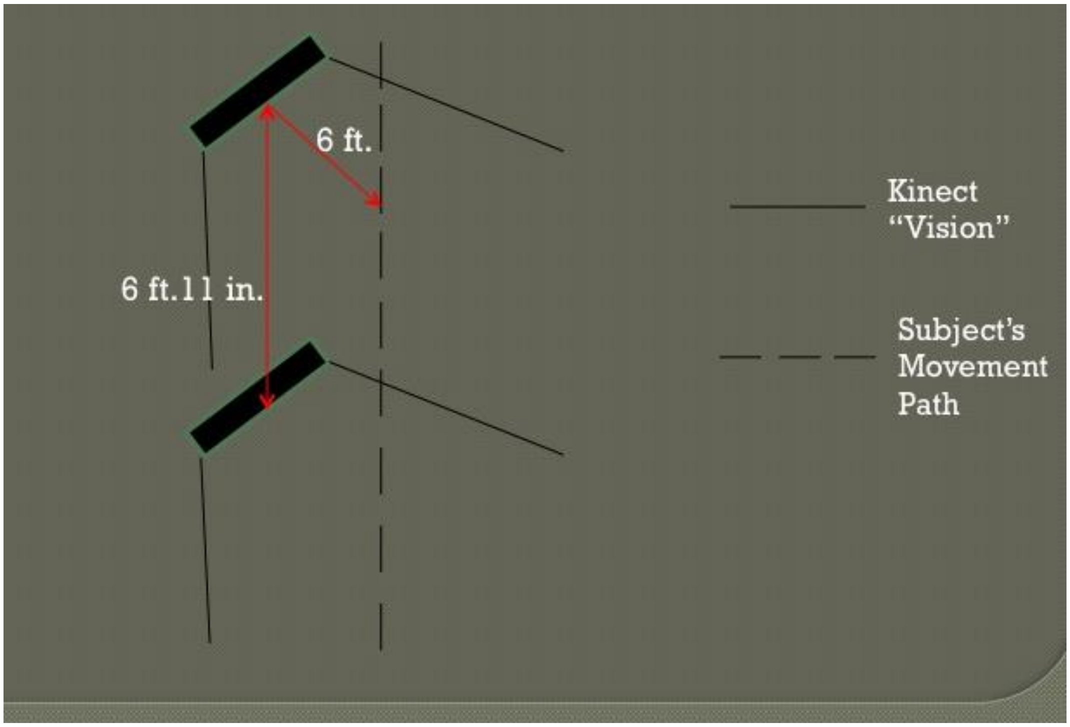


Figure 6. Schematic of Kinect gait analysis setup showing a 45° viewing angle.

Finally, it is suggested that analysis be performed with a subject on a treadmill, and a schematic for this analysis is provided as well in Figure 7.

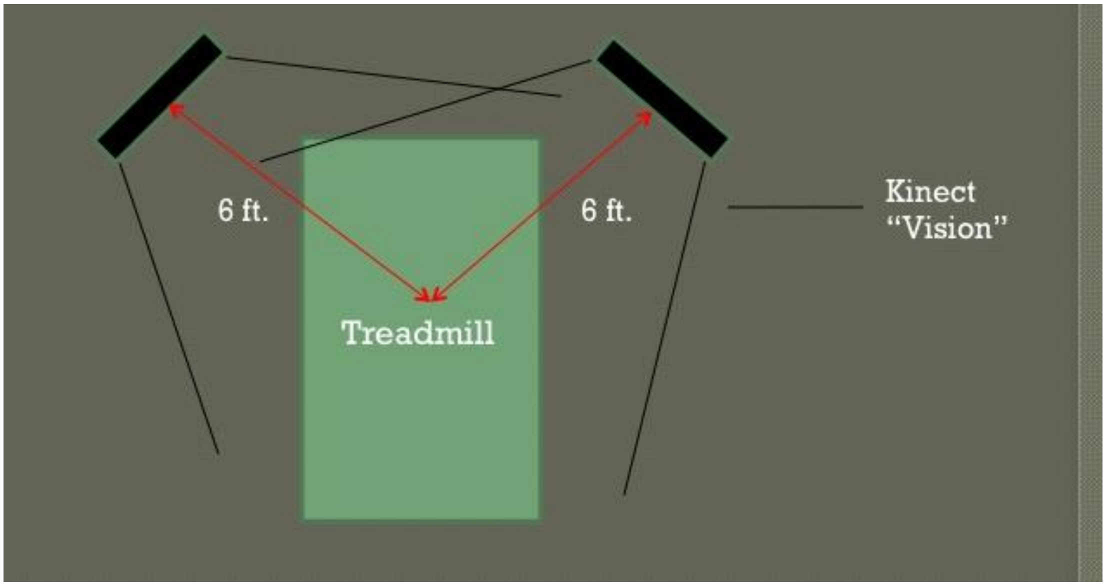


Figure 7. Kinect analysis schematic utilizing a treadmill for gait analysis.

Feasibility Analysis.

In order to test the output of this system two standards were selected by the group: a Northern Digital, Inc. optical tracker and an orthopedic knee brace that restricts the movement of a patient's knee. In this way, accuracy verification could be performed in order to assess the efficacy of the Kinect in performing biomechanical analyses. A useful feature within the program is the ability to save knee angle data to a text file on the computer's hard drive. In this way, spreadsheets and graphs can be used to compare the two sources of data and analyze the accuracy of the Xbox Kinect. It is possible that in the future MATLAB may also be used to analyze the data.

Several tests have been performed to investigate the Kinect's comparability to other methods of knee angle measurement. One of the most primitive was with the use of an orthopedic knee brace from Tennessee Orthopaedic Clinics (Knoxville, TN, USA). In order to leverage this knee brace for studying the accuracy of the Kinect, a small experiment was performed in order to do just that and to assess the change in accuracy as the subject's angle relative to the Kinect changed. In order to perform the experiment, the first subject stood in front of the Kinect with the knee brace on. He faced it directly and without flexion of the knee. As the subject stood facing the Kinect with a straight leg, a reading was taken of the calculated knee angle of the Xbox Kinect. A reading was then taken from the knee brace. Next, the subject stood at approximately a 45° angle to the Kinect, and the two readings were again taken. Finally, he stood at a 90° angle to the Kinect, and readings were again taken from the Kinect and the knee brace. This process was repeated for knee angles of twenty degrees, forty degrees, and sixty degrees, each at relative subject angles of zero, 45° and 90° to the Kinect. It was again repeated with a new subject in order to obtain data for differing body types. The experimental method is pictured below in Figure 5.

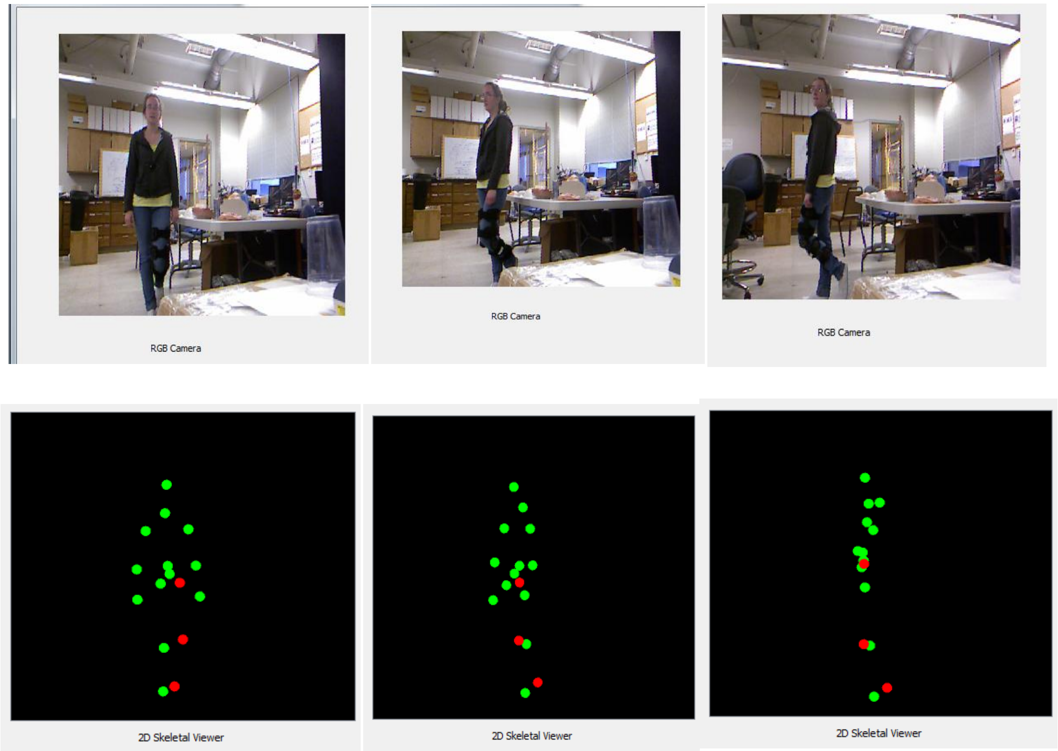


Figure 8. Experimental method for testing of the Kinect compared to the knee brace. From left to right: testing a 0 degree angle, 45 degree angle, and 90 degree angle of the subject relative to the Kinect. Above are the RGB images with their associated 2D rendering directly below.

The results of this study yielded some insight into the Kinect's accuracy (results below in Figure 6). It does not appear that any one particular angle of the subject relative to the Kinect seems to improve accuracy. It is not surprising, however, to note that on the whole, accuracy at a 90° angle to the Kinect proved to be poor. This stems from the way that the Kinect determines where a human is in a frame. Because of the way it was trained using machine learning, it "expects" to see the person facing it straight on and therefore must make many assumptions if it doesn't see both sides of the subject. (Freedman 2010) These assumptions may have led to the decreased accuracy at a 90° subject angle. Furthermore, when the subject is facing the Kinect directly and the knee is at an angle that occludes the ankle (i.e. a small angle), the Kinect must make inferences about the location of the ankle that also negatively affect the accuracy.

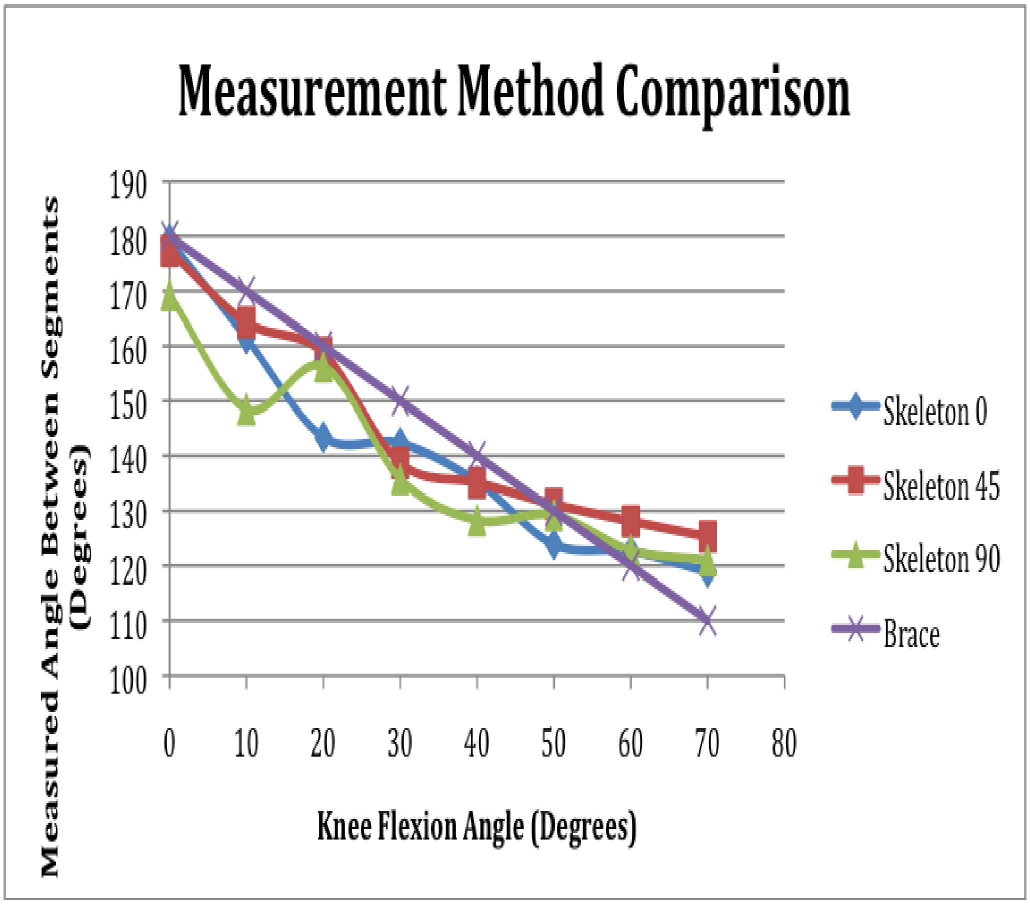


Figure 9. Kinect's measured knee angle as a function of the brace's reading of the knee flexion angle. Note that for the bottom axes, the knee flexion angle = 180 - brace reading.

Results of the study were very similar between subjects.

Furthermore, many assumptions were made in this experiment and various errors could contribute to the results. Because the purpose of this experiment was to compare the Kinect to a knee brace, an assumption was made that the angle given on the knee brace was “correct.” This may not be the case, as human error may play a factor in how the subject is bending his or her knee, leading to invalid conclusions regarding the Kinect’s accuracy. Further error could be caused by the noise in the Kinect’s calculations. Skeleton positions may vary frame-to-frame, and depending on when the conductors of the experiment pressed the button to grab a frame of data and calculate a knee angle, the Kinect’s results could vary as much as a few degrees. This would further affect the results of the experiment.

Overall, this was an interesting experiment to take a cursory look at how the Kinect compared to a standard knee brace, but further work must be done in order to get a better idea about the accuracy of the Kinect's calculations. It will be interesting to compare the Kinect to an optical tracker and see how the results of a deep knee bend compare among the two. Furthermore, future work should include a study of the noise in the Kinect's calculations and attempts made to smooth out the data it produces. A calibration may also provide a way to obtain more accurate results.

In order to improve accuracy and reduce noise, an original goal of this project was to utilize multiple Kinects and fuse the data they obtained. Unfortunately, skeletal tracking using multiple Kinects is not possible with the Microsoft Corporation software development kit at the time of this writing. Depth analysis can be performed with up to four Kinects at the same time, however. (MSDN 2012) Therefore, it is possible to use one Kinect for skeletal tracking and write an edge-detection algorithm to provide human body analysis for the other three, but that is beyond the scope of this project. Regardless, of some concern is the interference between multiple infrared speckle projections when more than one Kinect is viewing a subject at one time. In order to study this further, cursory analysis was performed in order to assess the difference in an image when one Kinect is viewing a subject versus two. This is shown in Figure 10.

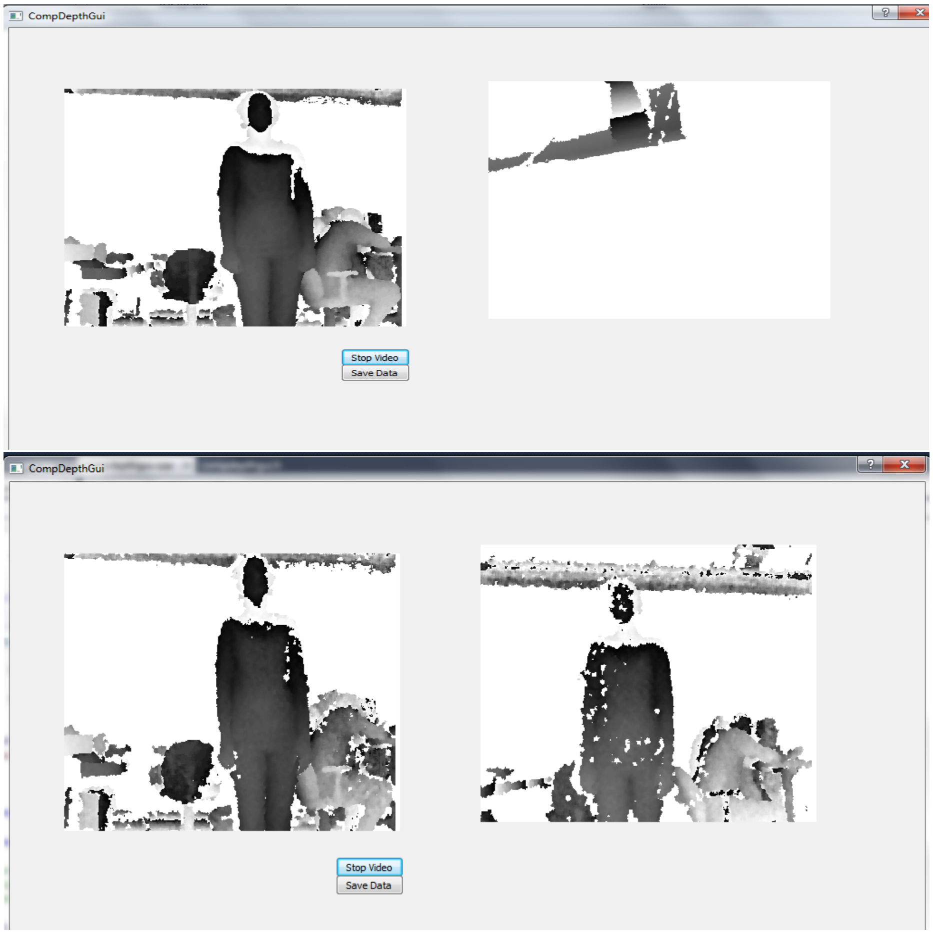


Figure 10. Above shows a depth image using a single Kinect. Below is the difference when two are used. Note the surprising lack of excess speckling in the left picture, but marked speckling on the right.

Based on the above cursory analysis it seems that viewing the subject with multiple Kinects will not significantly affect accuracy, especially given the potential for noise reduction. More work will need to be done, however, to confirm this and it will likely depend on the nature of the algorithm for body detection. Finally, the author suggests that placing the Kinects at 90° to each other will probably minimize any accuracy loss, but this too must be investigated further.

Conclusion and Future Work.

A method has been described for leveraging the capabilities of the Xbox Kinect for human, three-dimensional kinematic analysis. At present, a system has been designed that integrates the data feeds from the RGB camera, an optical tracker system, and the Kinect skeletal tracking streams in order to provide a visually pleasing, interactive GUI that gives the user data on the subject's knee angle in addition to a method of saving this data. This program also provides a viewing window for a 3D rendering of the human tibia and femur for further visualization of the anatomy in question.

The author suggests a few goals to include within the future work that may occur on this project. These were goals that were not necessarily accomplished within the constraints of this particular endeavor, but may help to continue the study of the efficacy of the Kinect in three-dimensional kinematic analysis. First, and perhaps most importantly, is the noted absence of tracking using multiple Kinects. This particular milestone was not achieved by this group due to the lack of support for this feature in the Microsoft SDK. Though skeletal tracking using more than one Kinect is not yet supported, these authors see two ways in which this may be overcome. The first is that Microsoft may soon provide access to this feature in their SDK, making this a trivial pursuit. Second, the use of an edge detection algorithm for use with the depth information may provide the functionality necessary to perform this task, provided the developers possess the technical knowledge required. As stated earlier, this was beyond the scope of this project due to the programming competency that was needed to complete it.

It is not yet known whether the accuracy of the Kinect in analyzing 3D kinematics will be sufficient for gait analysis or other applications, however, preliminary analysis is relatively positive. Though an accuracy decrease may be observed, the Kinect's price and portability certainly make it more attractive than other, more bulky setups. A thorough comparison of the Kinect's knee angle calculation was not complete within this investigation, and should be pursued in the future. Although the necessary matrix calculations have been determined on paper and begun to be coded into the software, the physical resources necessary to perform the comparison itself were not available. Due to lack of a sufficient number of optical tracker probes, verification was not performed. Because the calculations have already been determined, however, it should be a trivial task once the proper resources are acquired.

Ultimately, the Microsoft Xbox Kinect could prove to be a valuable tool in the biomechanist's arsenal. Utilizing its reduced cost and portability, it could one day see use in home health care scenarios, fieldwork for workplace ergonomics, or time on the basketball court analyzing ankle injuries. More work is needed, however, before this can become a reality. Above all, a comprehensive analysis should be performed in order to determine what accuracy loss, if any, will come from using the Kinect over a more conventional approach. Only then can the Kinect realize its full potential within the world of biomechanics.

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