Quantification of Human Knee Kinematics Using the 3DM-GX1 Sensor

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INTRODUCTION

Measuring the kinematics of the knee during gait or other activities is an important component of many biomechanical studies. There are a limited number of tools available with which to perform such measurements. These include video based tracking systems (Vicon Motion Systems, Peak Performance Tech.), electromagnetic tracking systems (Ascension Tech., Polhemus Inc.), spatial linkages (Acufex, Enduratec), and radiographic techniques (not commercialized). With the possible exception of spatial linkages, all of these tracking systems require a substantial and costly infrastructure which limits their use to relatively small spaces in laboratory-like settings. There is a need then, for an in-expensive, easily portable tracking system which can be used in a wide variety of settings.

Many of the sophisticated tracking systems mentioned above are capable of making measurements in fully six degrees of freedom (three displacements and three rotations). Often times, however, only joint angles are of interest (three degrees of freedom). In these instances, the 3DM-GX1 orientation sensor may be capable of performing satisfactorily to capture kinematics of human gait and other activities.

The purpose of this study was to evaluate the performance of the 3DM-GX1 orientation sensor for use in human motion capture applications. Specifically, its performance was compared to the Knee Signature System spatial linkage originally manufactured by Acufex Inc.

BACKGROUND

3DM-GX1 The 3DM-GX1 (MicroStrain Inc., Williston VT) is a three-degree-of-freedom orientation sensor (Figure 1). It comprises a sensor cluster, analog to digital converter, and a microcontroller. The sensor cluster includes a tri-axial angular rate sensor (rate gyroscope), tri-axial magnetometer, and tri-axial accelerometer. The sensor outputs are continuously sampled at a rate of between 50 and 150 Hz. The microcontroller computes the time integral of the rate sensor outputs to provide an estimate of orientation.

If the rate sensors were perfect, the time integral alone would be sufficient for estimating orientation (following an appropriate initialization step). Due to the tendency of rate sensors to drift over time, however, it is necessary to continuously apply corrections. These corrections are derived from the accelerometers and magnetometers which provide absolute references. The basic assumption is made that the long term average of the measured acceleration vector is equal to the gravity vector. This is equivalent to the statement that any linear acceleration will be offset within a relatively short time period by an equal and opposite acceleration. This is generally a valid assumption for biomechanics applications. The term “short time period” here is dependent on the 3DM-GX1’s system time constant which the user has some control over. Practical values for most applications are in the range of 5 to 20 seconds.

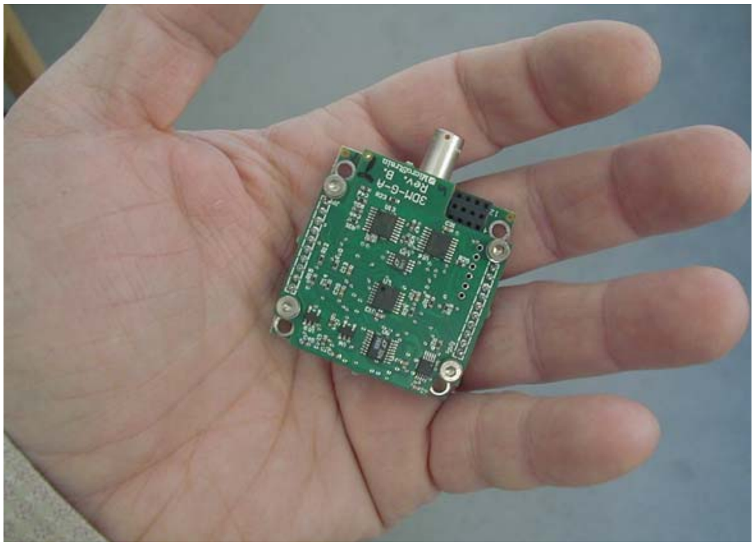


Figure 1. 3DM-GX1 Three axis orientation sensor. (Shown without enclosure.)

Similarly, the assumption is made that the long term average of the measure magnetic field vector is equal to Earth's Geomagnetic Field. The validity of this assumption depends mostly on the local environment in which the 3DM-GX1 is used. Ideally, there should be no magnetic interference caused by nearby sources of magnetic field (i.e., strong magnets) or large objects composed of ferrous materials (primarily steel, although the austenitic 300 series stainless steels generally do not cause interference).

The architecture of the filtering algorithm on-board the 3DM-GX1 has the characteristics of a complementary filter. Its high frequency response is dominated by the time integrated outputs of the angular rate sensors. Its low frequency response is dominated by the measured acceleration and magnetic field vectors. The cross-over frequency is user adjustable to some extent, but for most applications has a useful range of 0.2 to 0.05 Hz. The 3DM-GX1 will work well under conditions where the disturbances to the acceleration or magnetic field occur at a higher frequency that the cross-over frequency. When the disturbance occurs at a lower frequency (e.g., a linear acceleration is maintained in one direction for longer than 5 to 20 seconds) then artifacts due to these disturbances will begin to propagate into the 3DM-GX1's output. These generally cannot be distinguished from real rotations.

The output of the 3DM-GX1 is a measure of its orientation with respect to a reference frame fixed to the earth. In order to measure the kinematics of the knee, two sensors are needed, one fixed to the thigh and one fixed to the shank. The outputs of these two devices are then differenced to produce the desired measure of knee joint angular motion.

KSS spatial linkage The Knee Signature System (KSS, Acufex Inc.) is a simple spatial linkage capable of measuring knee flexion/extension (*FE*) and internal/external (*IE*) rotations (Figures 2a &2b). It consists of two light weight frames that can be easily strapped to the thigh and shank respectively. A compound parallelogram linkage interconnects the two frames. This allows for relative translation and rotation between the two frames in all directions. The design of the linkage isolates these motions such that *FE* motion of the knee results in rotation about only one hinge axis of the linkage. Likewise, *IE* rotation of the knee is isolated to rotation about a second hinge axis of the linkage. Two potentiometers integrated into these axes are used to measure the *FE* and *IE* rotations of the knee.

The configuration of the KSS device lends itself to use in this study where the main purpose was to compare the measurements of the 3DMG –GX1 with a reference system. The two frames of the KSS provide convenient points to which the two 3DM-GX1's can be mounted. This ensures that they both undergo the same motion profile, and therefore, their outputs should be directly comparable.

METHODS

Equipment Setup Two 3DM-GX1 sensors were rigidly clamped to the KSS device, one each on the proximal and distal frames. They were carefully aligned such that the X axis of the proximal 3DM-GX1 was parallel to the rotation axis of the KSS's *FE* sensing potentiometer, and the Y axis of the distal 3DM-GX1 was parallel to the KSS's *IE* sensing potentiometer. This alignment was verified by performing uniaxial rotations about those axes and observing the expected correspondence between the KSS and 3DM-GX1 outputs.

The potentiometers of the KSS device were powered by a medical grade +/-10V DC power supply. The output of each potentiometer was calibrated by rotating them through 90 degrees, and monitoring the output change.

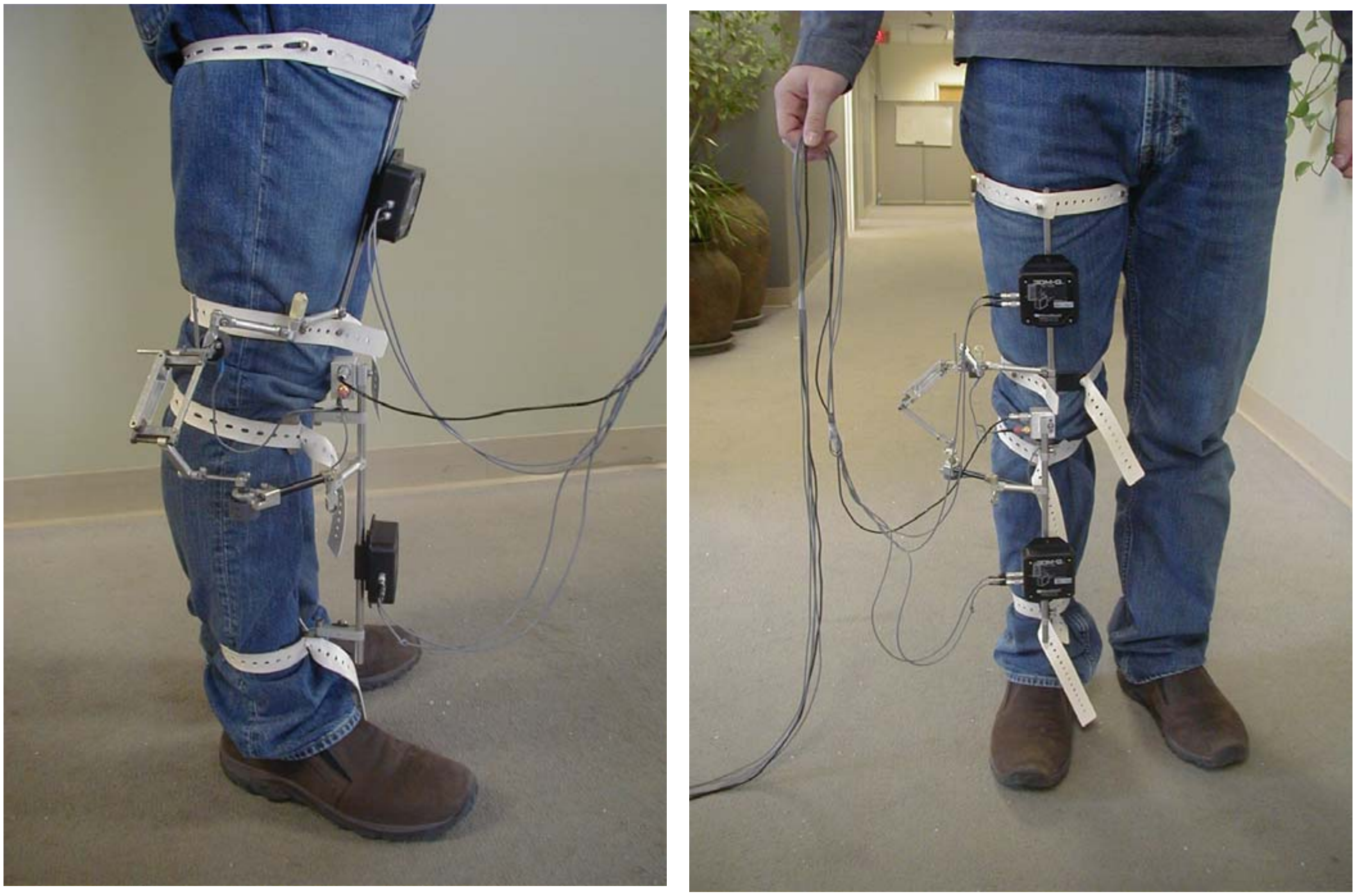
Application of Sensors to Human Subjects The KSS device (with attached 3DM-GX1's) was strapped to the right leg of each subject. The proximal frame was positioned such that the rotation axis of the *FE* sensing potentiometer was approximately aligned with the transepicondylar axis, the approximate rotation axis of the knee. The distal frame was positioned such that the parallelogram linkage did not bind at any point during normal knee motion.

Test activities Nine healthy subjects (eight men, one woman) with normal gait were enrolled for the study. Their ages ranged from 22 to 49 years. The right leg of each subject was tested.

The subjects were asked to perform three test activities. The first was normal walking. The subject started at one end of a straight hallway, and once the data collection system was running, took three normal strides at their normal walking pace. They paused following the last stride for approximately 3 seconds until the data collection was halted. The same procedure was then repeated for a second time, appending the data to the first run.

For the second activity, the subjects were asked to perform a set of five jumping-jacks. These were slightly non-standard in that the subjects were asked not to move their upper extremities in the normal manner. This was done primarily because the subject was required to hold the data collection lead wires in their right hand to prevent them from tangling around the protruding parts of the KSS linkage. The motion of the lower extremities, however, was judged to be similar to normal jumping-jacks.

The third activity consisted of rising from a chair to a standing position. The subject started in a standing position in front of a conventional desk chair. Once the data collection was initiated the subject sat down, paused for several seconds, and the rose again to a standing position. This was repeated for three complete cycles.



Figures 2a &2b : Photographs showing KSS device with 3DM-GX1's applied to human subject.

Data Collection   The KSS device inherently produces an analog voltage output. This must be digitized to allow for subsequent data analysis.   We used a NI 6030E, 16-bit, NIST-traceable data acquisition system (National Instruments, Austin TX) in combination with a PC computer.

Each of the 3DM-GX1 devices was set up to output its orientation estimate in Euler Angle form on its analog output channels. Note that the 3DM-GX1 primarily operates in the digital domain. That is, once the raw sensor signals are digitized, all further processing is done by the microcontroller running a C language firmware program. The preferred method of communicating the results is via an RS-232 or RS-485 communications link to a host computer. As an option, however, the 3DM-GX1 can be configured to write its final orientation estimate to an on-board digital-to-analog converter (DAC). This provides the user with the means to acquire the system's orientation estimate as a set of analog output voltages. The analog voltages derived in this manner are entirely analogous to the digital results. No additional information is available in the analog output form. If fact, the digital to analog conversion should be viewed as a source of potential data degradation due to the introduction of some amount of noise, and imperfect behavior of the DAC.

Although it is generally recommended that the digital output of the 3DM-GX1 be used whenever possible, there are applications where the analog output is preferred. The current experiment is one such case. Since the primary objective was to compare the performance of the 3DM-GX1 with the KSS device it was important to guarantee synchronization of the data collection. That is, the data from the KSS must be accurately aligned in the time with the data from the 3DM-GX1. One way to ensure this is to collect both sets of data simultaneously using the same multi-channel analog data acquisition system.   This was done.

The analog outputs of both the KSS and the two 3DM-GX1's were collected at 250 Hz. The inter channel time delay was 10 microseconds which was considered negligible.

The 3DM-GX1 operates with a fixed 19.66msec cycle period (50.86 Hz). At the beginning of each cycle, the on-board sensors are sampled. The computations required for estimating orientation are then carried out, consuming the majority of the cycle time. Lastly, the final results are output, either over the digital communications line, or to the digital to analog converter. The analog output is therefore only updated every 19.66 milliseconds. Between updates, the voltage simply remains steady. This gives rise to a characteristic "stair-case" appearance in the outputs. To smooth this out, it is usual to apply a low-pass filter to the outputs. This was done in post processing by applying a two pole low-pass Butterworth filter with a cutoff frequency of 20 Hz. Note that this is analogous to receiving digital data at regular sampling intervals. Between samples, no information is available. The signal is simply assumed to transition smoothly between discrete samples (so long as the Nyquist criteria is satisfied).

In addition to smoothing the 3DM-GX1 outputs, we also shifted them in time (to the left) by 19.66 milliseconds. This accounts for the dime delay between the actual sampling of the sensors (the true sampling time), and the appearance of the corresponding updating of the analog voltage. The KSS potentiometers were assumed to have instantaneous response.

Although the analog output of the KSS was inherently continuous and relatively noise-free, it was also low-pass filtered in the digital domain using a two pole Butterworth filter with a cutoff frequency of 20 Hz. This was considered necessary since the low pass filtering operation employed introduced a time delay on the order of 10 milliseconds. By filtering all data in the same manner, the effect of this delay was negated.

Data Analysis The analog outputs of the KSS linkage provide *FE* and *IE* rotations directly. Little post processing was necessary. The raw voltages were simply scaled by the conversion factor of 35 degrees/volt that was determined in a simple calibration procedure.

Each of the 3DM-GX1 devices computes an estimate of its orientation with respect to a stationary inertial reference frame. Specifically, an earth-fixed reference frame is assumed with its X coordinate pointing North, its Y coordinate pointing East, and its Z coordinate pointing down. Each 3DM-G has a local, or body-fixed, coordinate system attached to it with its axes nominally aligned with the square edges of its enclosure. The primary orientation measure computed by the 3DM-G is in the form of a coordinate transformation matrix (orientation matrix), M, which gives the orientation of the body fixed coordinate system with respect to the earth fixed system.

If requested, the 3DM-GX1 can convert the orientation matrix into the form of "ZYX" convention Euler Angles, or quaternions prior to output. These are simply alternative forms of quantifying orientation. When using digital communications, the orientation matrix output form is generally recommended unless the application dictates otherwise. When using the analog output option of the 3DM-GX1, however, it is not possible to use the matrix form. The reason is that the matrix contains nine individual components, whereas only four analog output channels are available. Therefore, when using analog output, either the Euler Angle (three components), or the quaternion (four components) output form must be used. For this work, we obtained the orientation output in the form of Euler Angles.

In this manner, the orientation of each 3DM-GX1 with respect to earth was obtained at each instant in time in the form of ZYX convention Euler Angles. These were converted back to the orientation matrix form using the standard formulation (see appendix). This resulted in an orientation matrix giving the orientation of the thigh, *Mt*, and the shank, *Ms*, with respect to the earth at each instant in time.

A modified form of each orientation matrix was computed by multiplying each by a constant,

$$Mt^{*} = A * Mt$$

$$Ms^{*} = A * Ms$$

where $A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix}$

This essentially swapped the local Y and Z axes. Each 3DM-GX1 had been mounted to the leg such that when the subject was standing upright, its local X axis was in the frontal plane pointing to the subject's right, its Y axis was pointing up, and its Z axis pointed backwards. For compatibility with the analysis technique of Grood and Suntay,(1) it was desirable to swap the Z and Y axes such that the local Z axis pointed up, and the local Y axis pointed forwards. This could have been done simply by remounting the 3DM-GX1's in a different manner, but was considered easier to do mathematically in postprocessing. This allowed for the most favorable mounting of the 3DM-GX1's from a mechanical setup point of view.

A differencing operation was then carried out to identify the orientation of the thigh with respect to the shank, *Mr*.

$Mr = Mt^{*} * (Ms^{*})^{T}$ where the superscript T indicates a matrix transpose operation.

Finally, the orientation matrix, *Mr*, was converted to a form which was directly comparable to the *FE* and *IE* angles measured by the KSS system. This was done using the technique of Grood and Suntay.(1) They proposed a formulation whereby the three clinically relevant rotations (flexion/extension, internal/external, abduction/adduction) could be calculated from the corresponding orientation matrix. This formulation shares some similarities with the conventional Euler angles, but is distinct in a number of ways. One important difference is that the three angles are independent of one-another. This is not true of Euler angles. Importantly, the mechanical linkage system of the KSS inherently identifies the *FE* and *IE* angles in a manner which corresponds to Grood and Suntay's formulation.

For the right leg, Grood and Suntay's formulation for the *FE* angle is:

$$F/E = A\cos\left(ER1 \bullet \left[C3 \times E1\right]\right)$$
$$I/E = A\cos(C2 \bullet \left[C3 \times E1\right])$$

where $ER1 = [0,1,0]^T$
$E1 = [1,0,0]^T$
$C2$ = Vector consisting of the second column of *Mr*
$C3$ = Vector consisting of the third column of *Mr*

The signs of the results are subsequently adjusted according to the following tests:

If the third element of $\left[C3 \times E1\right]$ is greater than zero, *FE* is negated.
If Acos($\left[C3 \times E1\right] \bullet C1$) is greater than $\pi/2$, IE is negated.
Where $C1$ is the vector consisting of the first column of *Mr*

Statistics The data analysis produced estimates of the *FE* angle, and the *IE* angle made independently by the KSS device, and the 3DM-GX1. A comparison was made to evaluate the agreement between the two.

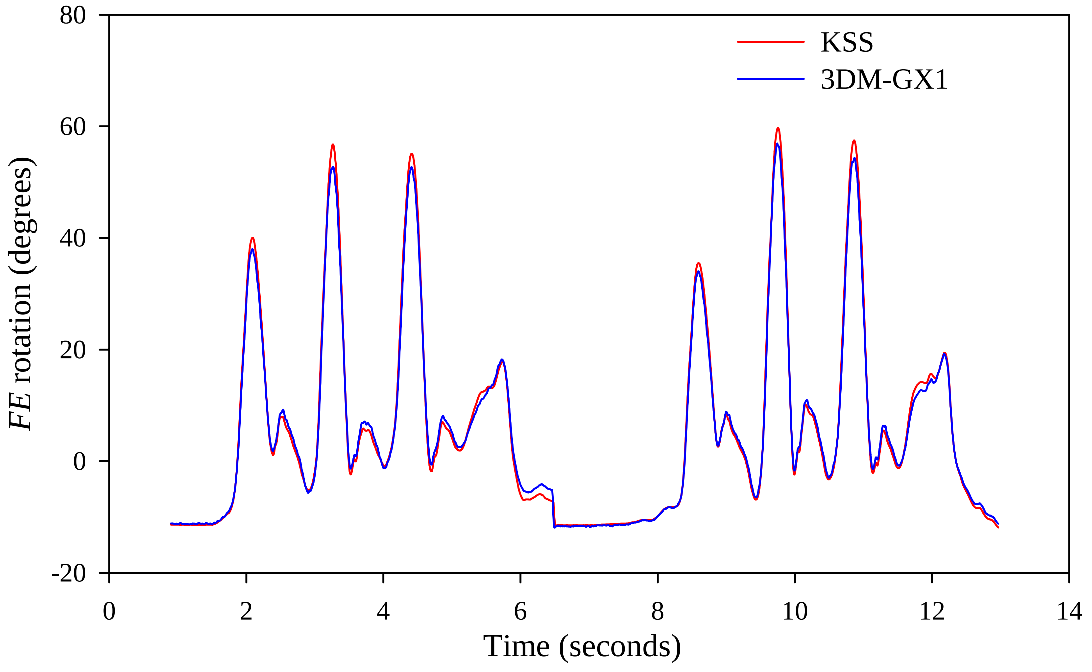
The *FE* and *IE* angle estimates were treated independently. For each data set, (representing one subject carrying out one activity), the difference between the KSS angle estimate and the 3DM-GX1 angle estimate was calculated at each time point. The root mean squared (RMS) of these differences over the whole dataset was calculated. Also, the Peak instantaneous difference was identified.

Finally, for each activity, a mean (across subjects) value was computed for the RMS difference, and Peak difference between the KSS and the 3DM-GX1.

RESULTS

The KSS frames were successfully applied to all subjects with little difficulty. For two subjects, the parallelogram linkage appeared to bind when the knee was flexed to approximately 90 degrees or greater. This was believed to primarily affect the accuracy of the KSS reported *IE* angle during the sitting activity. Because this could not be confirmed, the data was still included in the analysis (subjects 5 and 6). The KSS system includes a number of adjustable links which would normally have been used to alleviate this problem. Because of the necessity to maintain a uniform alignment of the 3DM-GX1 devices with their respective KSS potentiometers, no adjustments were made.

Typical results for the walking, jumping, and sitting activities are shown in figures 3 through 5 respectively. These demonstrate qualitatively that there was good agreement between the KSS and the 3DM-GX1. Note that the 3DM-GX1 was also able to calculate the Abduction/Adduction angle as shown on the plots. No corresponding measurement was available from the KSS system.



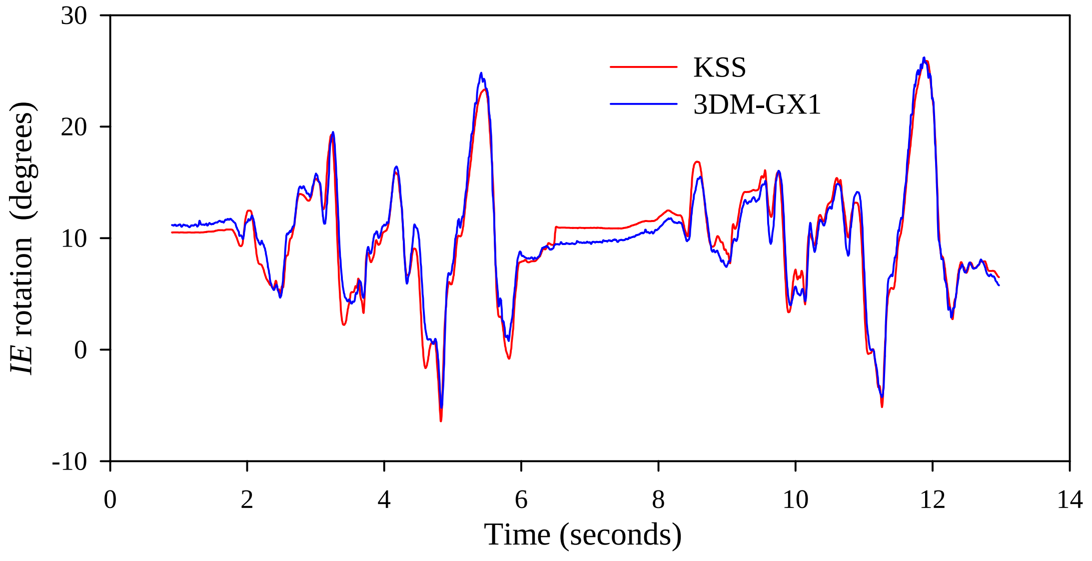
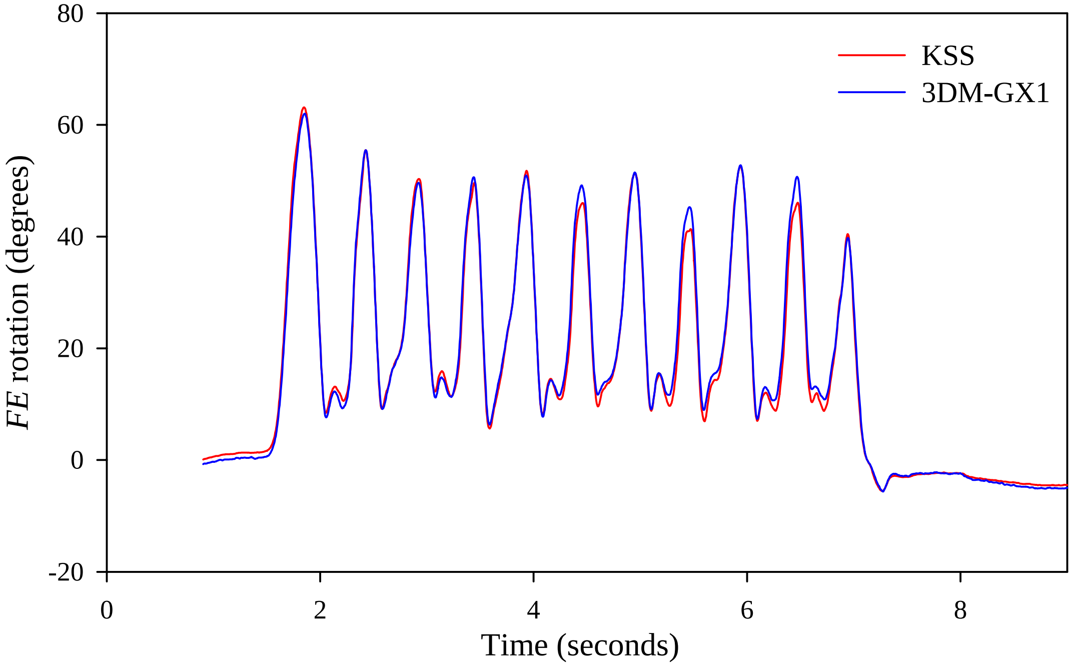


Figure 3 Typical *FE* and *IE* knee joint angles measured by KSS and 3DM-GX1 during **walking** activity. Data from subject #9 is illustrated. Subject took three strides at normal pace, paused, and repeated. Discontinuity at center of plot is due to data collection being temporarily stopped while subject repositioned between first and second pass.



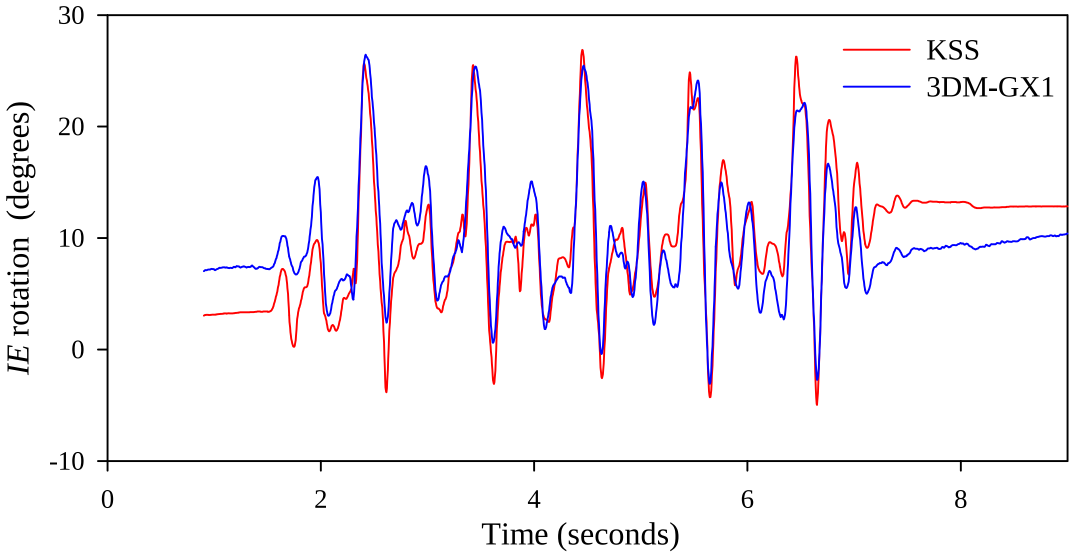


Figure 4 Typical *FE* and *IE* knee joint angles measured by KSS and 3DM-GX1 during **jumping** activity. Data from subject #9 is illustrated. Subject executed five jumping-jacks.

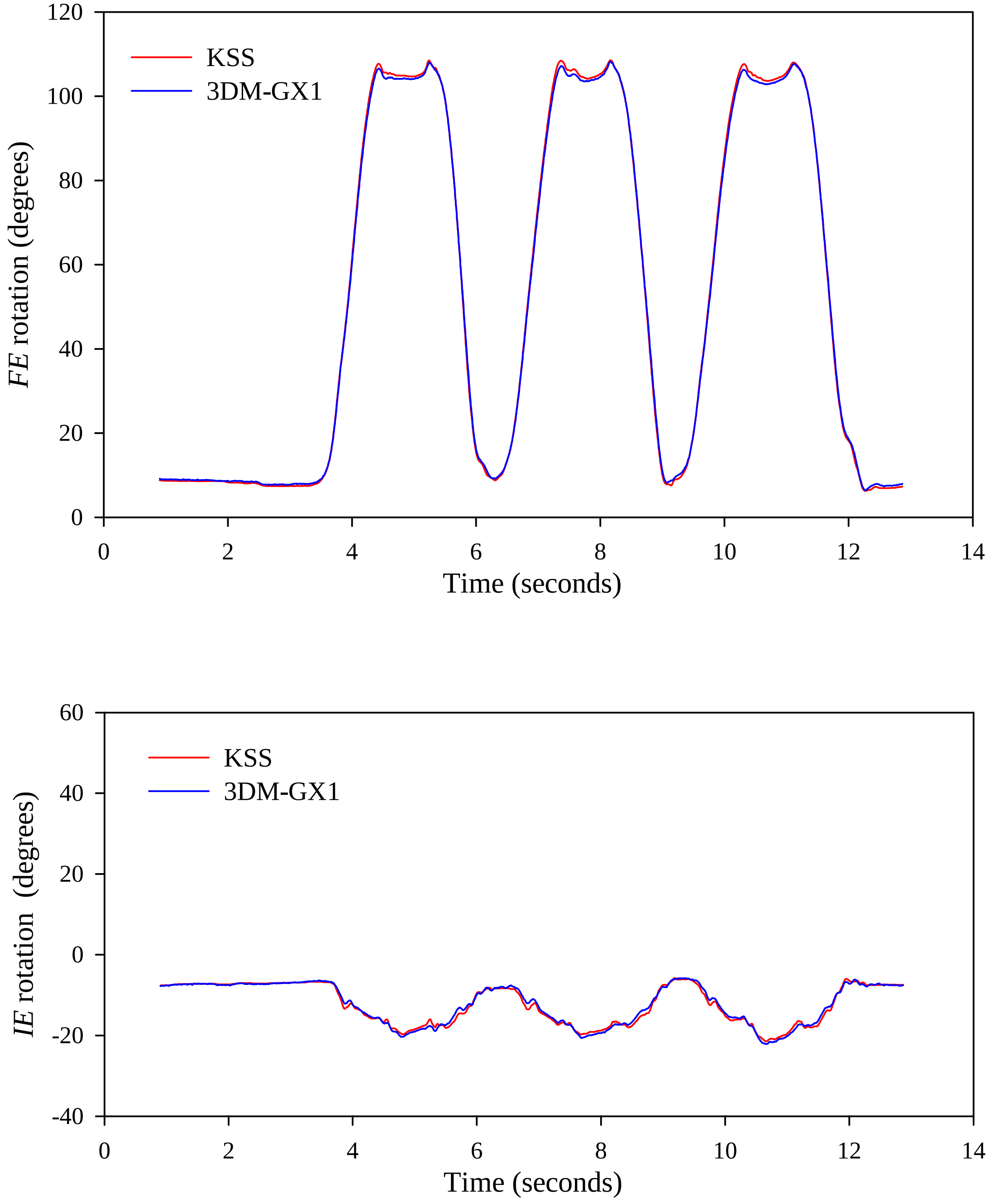


Figure 5   Typical *FE* and *IE* knee joint angles measured by KSS and 3DM-GX1 during **sitting** activity.   Data from subject #9 is illustrated.   Subject began in a standing position, sat in a chair, and then rose again. This was repeated three times.

The statistical results are summarized in Table 1. For the *FE* angle, the RMS differences between the KSS and 3DM-G ranged from a minimum of 0.6 degrees for the sitting activity, to 2.7 degrees for the jumping activity. The peak differences for *FE* angle ranged from 1.2 degrees to 10.3 degrees, again for sitting and jumping respectively.

For the *IE* angle, the RMS differences ranged from 0.5 to 3.8 degrees (if subjects 5 and 6 whose KSS derived *IE* data is suspected of being corrupted). The Peak difference ranged from 1.7 degrees to 10.4 degrees.

As expected, the best agreement was found for the sitting activity where the accelerations were the lowest. Conversely, the jumping activity, which had the largest accelerations, had the least agreement. This was true for both the RMS difference and the *Peak* difference outcome measures.

	FE Angle						*IE* Angle					
	Walking		Jumping		Sitting		Walking		Jumping		Sitting	
Subject	Peak	RMS	Peak	RMS	Peak	RMS	Peak	RMS	Peak	RMS	Peak	RMS
1	4.6	1.5	4.0	1.1	2.0	0.8	5.1	1.7	7.3	2.4	1.7	0.6
2	4.8	1.5	5.6	2.7	1.6	0.8	7.4	2.1	8.9	3.8	1.8	0.6
3	9.5	1.8	11.3	1.3	2.5	1.3	6.0	1.8	8.9	2.7	1.9	0.5
4	6.1	5.3	7.9	2.7	3.5	2.1	5.3	1.8	7.1	3.3	2.1	1.0
5	3.9	1.3	3.3	1.4	1.2	0.4	8.9	3.3	9.6	3.2	10.8	5.5
6	4.7	1.5	6.0	1.4	3.4	2.0	10.4	3.1	9.0	3.5	17.0	9.9
7	10.3	1.5	3.3	1.0	2.4	1.3	4.9	1.4	6.0	2.1	1.9	0.7
8	5.2	1.5	6.7	2.6	1.8	0.6	5.9	1.7	12.0	3.7	1.9	0.9
9	4.4	1.2	6.0	1.2	2.5	1.2	4.7	1.2	7.0	2.7	3.8	2.1
Group Mean	**5.9**	**1.9**	**6.0**	**1.7**	**2.3**	**1.2**	**6.5**	**2.0**	**8.4**	**3.0**	**4.8**	**2.4**

Table 1. Summary of Statistical Results. All quantities in degrees.

DISCUSSION

The results demonstrate a very close agreement between the KSS and the 3DM-GX1 derived joint angle measurements. The RMS differences between the two devices was better than 4 degrees for both the *FE* and *IE* angles for nearly all subjects and activities. The only exceptions were for two subjects (5 and 6) during the sitting activity in which the KSS derived *IE* angle was suspected of being faulty, and subject 4 during the walking activity. This level of agreement is within the accuracy range of both devices.

The usefulness of the KSS device in accurately measuring knee joint kinematics has been criticized for a number of reasons. First, it only measures two degrees of freedom (*FE* and *IE* rotations). Also, its means of fixation to the leg is such that passive soft tissue compliance, and active muscle contractions can lead to significant relative motion between the device and the underlying bone. These criticisms, however valid, were not of concern in the current study. The primary purpose here was to compare the 3DM-GX1's output with a reference device. This could be done accurately since the two devices were rigidly fixed to one-another.

Naturally, in any study where the primary objective is to accurately measure knee kinematics, the issue of soft tissue compliance must be considered. This problem, however, is present in essentially equal measures with all available tracking technologies (except radiographic techniques). Because of the objective of the current work, it was necessary to mount the 3DM-GX1's to the KSS frame. This would normally be the case, however. The researcher would normally have freedom the place the 3DM-GX1's in whatever position was deemed optimal.

In any application where the 3DM-GX1 system would be used as the primary angle measurement instrument, the preferred configuration would be for all units to communicate to the host computer using the digital RS-232 or RS-485 communications link. In the case of RS-232 communications, a separate serial port and cable is required for each sensor. An advantage of RS-485 communications is that a multi-drop network can be set up where each sensor comprises one node on the network. Up to 15 3DM-GX1;s can be run simultaneously on a single network. This minimizes the cabling required, and also minimizes the host computer's requirements. The disadvantage of RS-485 communications is that it can be mode difficult to ensure synchronization between individual sensors.

CONCLUSION

We found a very close agreement between the KSS and the 3DM-GX1 derived joint angle measurements. The RMS differences between the two devices were better than 4 degrees for both the *FE* and *IE* angles for nearly all subjects and activities. These results suggest that the 3DM-GX1 can be successfully used to accurately measure the kinematics of human gait. To achieve good results, several conditions must be met as follows:

1. The rotation rate must not exceed the measurement range of the 3DM-GX1. The standard range is +/- 300 degrees/second, although higher ranges are available.
2. Potential sources of magnetic interference should be minimized.
3. The non-gravitational accelerations that the devices is exposed to should not have frequency components below about 0.1 Hz which have large magnitude in comparison to 1G.

If these conditions are met (which they are in many biomechanics applications) favorable results should be expected.

REFERENCES

1. Grood ES, Suntay WY, "A Joint Coordinate System for the Clinical Description of Three-Dimensional Motions: Application to the Knee", *Journal of Biomedical Engineering*, **105**, May 1983, pp136

ACKNOWLEDGEMENT

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APPENDIX

The orientation matrix, *M*, corresponding to a given set of "ZYX" convention Euler angles is given by:

$$M = \begin{bmatrix} \cos(\psi)\cos(\theta) & \sin(\psi)\cos(\theta) & -\sin(\theta) \\ \cos(\psi)\sin(\theta)\sin(\phi)-\sin(\psi)\cos(\phi) & \sin(\psi)\sin(\theta)\sin(\phi)+\cos(\psi)\cos(\phi) & \cos(\theta)\sin(\phi) \\ \cos(\psi)\sin(\theta)\cos(\phi)+\sin(\psi)\sin(\phi) & \sin(\psi)\sin(\theta)\cos(\phi)-\cos(\psi)\sin(\phi) & \cos(\theta)\cos(\phi) \end{bmatrix}$$

where $Pitch = \theta, Roll = \phi, Yaw = \psi$