



## Sensitivity of Marker Set and Knee Joint Centre on Knee Angles during Cutting Movement

방향 전환 달리기 동작시 마커 정의에 따른 슬관절각 비교

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### 국문초록

박상균, 이중숙, 방향 전환 달리기 동작시 마커 정의에 따른 슬관절각 비교. 한국운동역학회지, 2006, 제16권 3호, pp. 19-31, 2006. 이 연구의 목적은 각 분절의 마커세트와 무릎관절 중심 정의가 3차원 무릎 관절각을 산출하는데 얼마나 민감하게 영향을 미치는지를 연구하였다. 자료수집은 1명을 실험대상자로 하여 두 가지 형태의 각기 다른 분절의 정의와 무릎관절의 중심을 나타내는 반사마커들을 동시에 오른쪽 하지에 부착시켜 실험을 실시하였다. 실험대상자의 달리기동작 중 좌측으로 45도 방향 전환동작의 지지기를 분석하였다. 이를 위해서 8대의 고속카메라들을 이용하였고 달리기속도는  $4\text{m/sec} \pm (10\%)$ 로 통제하였다.

하지분절의 발분절에는 하나의 마커세트를, 정강이와 대퇴분절에는 두 가지의 다른 마커세트들을 부착시켰다. 발분절에는 3개의 마커를 신발의 뒷부분에 부착하였고 정강이분절을 정의하기 위하여 첫 번째 마커세트는 경골을 중심으로 3개의 마커들을 두 번째 마커세트는 비골을 중심으로 3개의 마커를 부착하였다. 대퇴분절의 마커세트를 정의하기 위하여 첫 번째 마커세트에는 대퇴골을 중심으로 3개의 마커를 두 번째 마커세트에는 대퇴근육을 중심으로 3개의 마커들을 부착하였다.

무릎관절중심을 정의하는데 두 가지 다른 정의가 적용되었다. 첫 번째 무릎중심을 무릎의 내측과 외측의 마커들을 통해 두 마커의 중심을 무릎관절의 중심으로 정의하였다. 두 번째 무릎중심정의를 무릎의 외측부분과 슬개골의 중심에 부착된 마커들로부터의 교차점을 무릎관절중심으로 산출하였다. 무릎관절의 각도를 산출하기 위해서 JCS(Joint Coordinate System)의 정의가 적용되었고 연구의 결과는 다음과 같았다.

두 가지의 다른 분절마커세트 사이에서 무릎의 신전(extension)과 굴곡(flexion)은 유사한 형태를 나타냈으며 최대 무릎굴곡(peak knee flexion)각에서  $4.746^\circ$ 의 차이를 나타냈다. 다른 분절마커세트 사이의 회전(rotation)각과 내전(adduction)/외전(abduction)에서는 서로 다른 형태를 나타내었고, 두 마커세트간 최대무릎외측회전(peak knee external rotation)각도에서는  $15.628^\circ$ 의 차이를 나타냈다. 또한, 각 분절마커세트 내에서 두 가지의 다른 무릎관절 중심의 정의가 얼마나 무릎각도 산출에 영향을 미치는지를 비교했을 때 무릎의 최대외측회전(peak external rotation)각에서 차이를 나타내었다.

첫 번째 분절마커세트의 무릎관절중심정의를 형태변화에 따라 최대외측회전각은  $0.549^\circ$ 의 차이를 나타냈고, 두 번째 분절마커세트에서 무릎관절중심정의를 형태변화에 따라 최대외측회전각은  $0.309^\circ$ 의 차이를 나타냈다.

이와 같이 분절을 나타내는 마커세트와 무릎관절중심정의를 형태변화에 따라 무릎각을 계산하는데 있어서 결과가 다르게 산출되었다. 즉, 관절각의 계산이 분절에 부착되는 마커의 정의 혹은 위치에 매우 민감하게 영향을 받았다. 따라서 연구자가 여러 실험대상자들을 대상으로 실험시 마커세트 혹은 마커들을 동일한 위치에 가깝게 부착하는 것이 마커부착으로부터 발생하는 실험오차를 줄일 수 있을 것이다.

**주제어:** 마커세트, 관절중심, JCS(Joint Coordinate System), 무릎각도, 실험오차

## Introduction

Motion analysis has been widely used for clinical applications in human movement studies. Advancements in recent technologies allow for extremely accurate measurements. Thus, it is speculated that we are able to find small differences in kinematics between the control and experimental conditions.

However, there are two main error sources when calculating variables through Motion Analysis system: (1) system error and (2) measurement error. System error refers to an error which originates at the interface between measurement instrument and the substrate, which is the object of the measurement. These errors result from improper camera calibration and they influence the data. The most critical source of measurement error comes from skin movement artifact (Cappozzo A., Catank F., Leardini A., Benedetti M.G., and Della Croce U.D., 1996).

The human body in biomechanics is assumed to be rigid, but in reality it is not. Since reflective markers are attached to the skin, they can not estimate the actual bone movement. We are unsure of the effect of various marker placements on kinetics and kinematics. In clinical studies, as biomechanical experiment is often conducted over an extended period of time, it is difficult to place markers in the exact same positions.

In addition, more skin movement may occur at a certain location, which causes error in recording the actual orientation of each segment. It is important to optimize and standardize marker placements and marker set to obtain reliable variables. Thus, understanding to what degree different marker placements will alter the results is essential for accurate and reliable data collection

In the current study, one healthy male subject was recruited and he was asked to perform 5 trials of the cutting movement. The cutting movement was

performed by running straight forward, then planting the right foot in the middle of capture volume and cutting 45 degrees to the left. Cutting movement was controlled at 4 m/s (5%). Neutral court shoes(Adidas Supernova, US size 9) were used for this study.

Two different marker sets and two different applications of knee joint centers(JC) were applied to calculate three dimensional knee angles during the cutting movement. In order to describe the movement between two adjacent segments, the joint coordinate system(JCS) and Cardan angles are available. Even though the calculations used for the JCS and Cardan angle are different, they essentially produce the same results(Cole G., Nigg B., Ronsky J., and Yendon M., 1993). Since the JCS method represents an actual orientation of a specific joint, this method is applied to describe the relative orientation of two segments.

When two different marker sets(marker set 1, marker set 2) are defined to describe knee angles it was speculated some differences in kinematic variables will occur between the two marker set due to the difference in skin movement. In addition, two different knee joint centers(knee jc1, knee jc2) were applied in calculation of the knee angles. However, it was speculated that these two knee joint centers will not significantly affect the calculation of knee joint angles.

This current study investigated two main causes of error in kinematics data collection : 1. Accuracy of camera set up was evaluated with a calibration process. 2. The sensitivity of marker set and knee joint center was investigated in the results. Also, the JCS method was validated with a standing trial(a neutral trial).

It is expected that desirable marker placement and knee joint center will provide accurate information that will be sensitive enough to show small changes between different conditions when studying human movement.

## Purpose

The purpose of this project was to investigate the sensitivity of different marker sets and positions on the knee joint center during three dimensional analysis of a cutting movement.

## Method

### Experimental set up

Data collection was performed in the Human Performance Laboratory, Faculty of Kinesiology, at the University of C. Eight high speed cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) were used to collect kinematic data. Camera placement is the most important aspect of setting up this experiment. The key to placing cameras around the capture area is to position them where they will yield the highest resolution without excluding any part of the adjacent capture volume. In this study, the volume size was set to height: 1.2m, length: 2.5m and width: 1.2m which covers one stance phase of the lower extremity during movement <Figure 1>.

If the tracking volume is increased, the quality and

accuracy of the tracking data will decrease. In addition, the cameras are positioned evenly around the capture area and, are set to look down, to prevent cameras from seeing the opposite cameras' ring light. The main consideration of camera setup in this study was to capture test subjects' 45 degree cutting angles. Each camera provides a two-dimensional picture of a three-dimensional image. The DLT (direct linear transformation) method was used to determine a three dimensional spatial coordinate from several images of two dimensional information. In most cases, more than two cameras are involved to determine the position.

Thus, a least squares fit technique (Veldpaus F., Woltering H., and Dortmans L., 1988) was used for the over determined system of linear equations.

Calibrating the system is a two step process: first, the seed calibration was done by employing the calibration squares. A 'L' shape metal frame was used to determine the laboratory coordinate system (LCS). LCS was set to x (posterior to anterior), y (lateral to medial) and z (down to up) axis with the right hand rule. Secondly, a wand calibration was performed. Wand calibration ensures that a direct measurement of an object of a known size (500mm) has been made by all cameras throughout the entire capture volume. A wand with markers was waved around throughout the

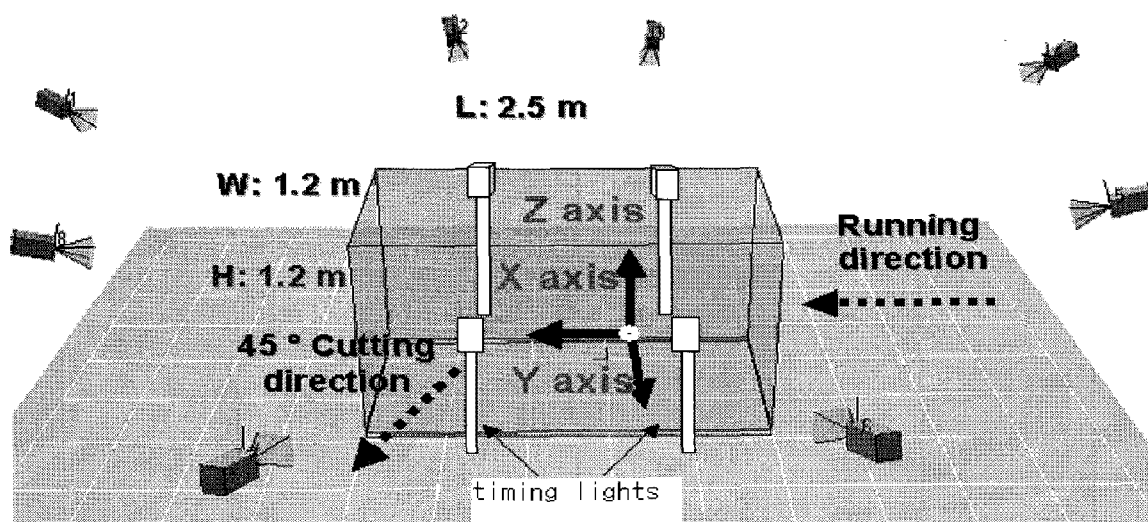


Figure 1. Capture area

capture volume for 60 seconds. This process located the exact positions of the cameras and accounts for any geometric distortion the camera lenses may have, as well as accurately measuring the camera lens focal-lengths.

The pre-determined criterion for tolerable error in space calibration was set at 0.06 % (i.e., 0.6 mm maximum error for a 1m<sup>3</sup> volume). This process is important and it should be followed until good calibration occurs. Once the calibration process was completed, a static trial was collected for further comparison with respected to a neutral position.

#### Different marker sets for the segments

For the purpose of this study, two different marker sets and two different definitions of knee joint centers were applied. Three reflective markers were attached to the anatomical structure on each segment (foot, shank, and thigh). Three markers were placed on the lower back, upper back and the lateral side of the shoe. These three markers for the foot were applied for both

marker sets. In the first marker set, three markers were placed on the proximal and distal sides of the tibia and the middle of lateral side of the shank. For the thigh, three markers were placed on the quadriceps tendon, the middle of iliotibial band, and the greater trochanter. In the second marker set, three markers were placed on the proximal and distal sides of the fibula and the middle of the tibia. For the thigh, the muscle belly of the quadriceps was chosen for marker placement. Two markers were attached on the lateral side of thigh (vastus lateralis) and one in the middle of the rectus femoris.

Two markers on the medial and lateral malleoli were used to determine the ankle joint center. Two different marker sets were applied to define the knee joint center. First, two markers on the lateral and medial femoral epicondyles were used to determine the knee joint center. Secondly, two markers were placed on the lateral femoral epicondyle and the center of patella. Hip joint center was calculated from the marker on the greater trochanter.

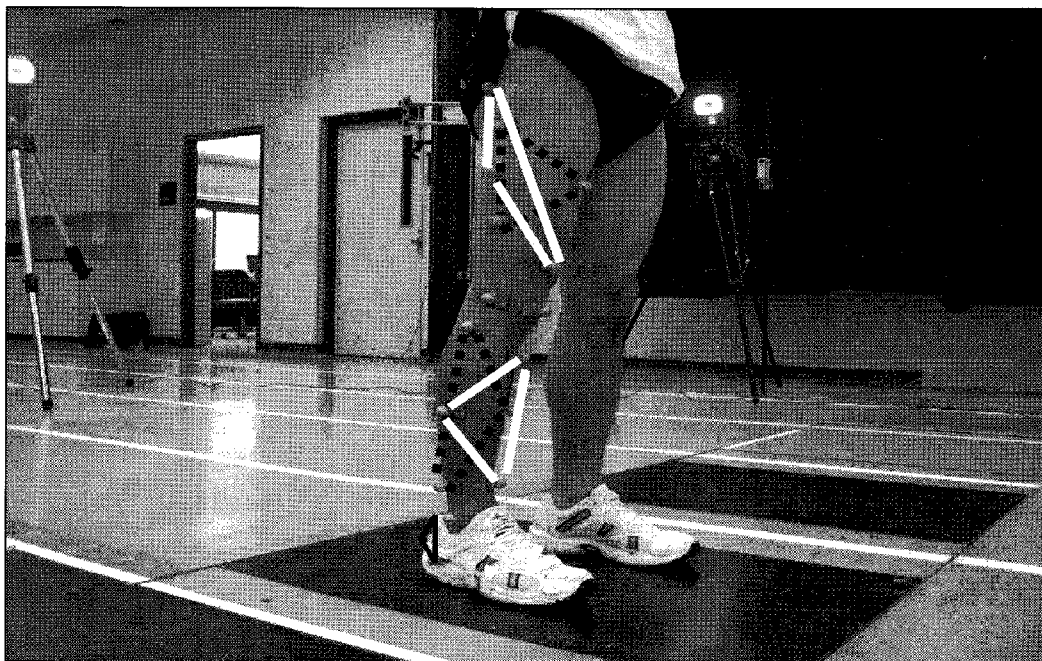


Figure 2. Marker set 1 (white & solid line) and Marker set 2 (black & dotted line) (markers for joint center (gray), marker for the foot (black))

## Data collection

One healthy male subject (age: 33yrs, weight: 67kg, height: 172cm) was recruited for this study. The subject was asked to perform 5 trials of the cutting movement. The cutting movement was performed by running straight forward, then planting the right foot on the force platform and cutting 45 degrees to the left. Cutting was performed at 4 m/s and the running speed of the subjects was monitored with photocells placed just before and after the force plate. Trials were rejected if they were not within 5% of the defined running speed. Neutral

Court shoes (Adidas Supernova, US size 9) were used for this study. Three-dimensional marker traces at a sampling rate of 240 Hz were reconstructed using Expert Vision Three-Dimensional Analysis software (Motion Analysis Corporation, Santa Rosa, CA, USA). Each marker was digitized for the entire collection period that includes the stride before and after the stance phase in the capture volume. Kinematic data was filtered using a low-pass Butter worth filter, with a cut-off frequency of 10Hz.

## Calculation of variables

### Neutral trial

Before starting data collection, the subject stands in the middle of the capture volume where he later will be expected to perform the cutting movement. Through this neutral trial, the marker positions in the lab coordinate system were calculated. However, marker positions were not the same during 1 second data collection even though the subject tried to stand perfectly still. Thus, mean values of each position were calculated as the neutral position of each marker.

### Joint center calculation

For joint center calculation, several anatomical marker placements were used. First, ankle joint center is assumed to be in the middle of two markers on the medial and lateral malleoli (Figure 3. Ankle center). Secondly, there were two different knee joint definitions (knee joint center1, knee joint center2) applied for the purpose of this study. The knee joint center (knee joint center1) is assumed to be in the middle of the medial femoral epicondyle and the lateral femoral epicondyle. The second of knee joint center (knee joint center2) was calculated with one marker on the lateral femoral epicondyle and one marker on the center of patella. The intersection of the line from the lateral femoral epicondyle to the medial direction (positive y axis in the LCS) and the line from the patella to the posterior direction (negative x axis in the LCS) was assumed to be a knee joint center. Two knee joint centers, from different applications, were not expected to be the same.

Thirdly, the hip joint center (Figure 3. Hip center) was calculated with the marker on the greater trochanter. The horizontal distance between the greater trochanter and anterior superior iliac spine (ASIS) in the frontal plane plus 14% of the distance between the markers placed on each ASIS and 30 % of the distance between right ASIS and left ASIS were applied for the subject. Once joint centers were defined, joint centers are assumed to be the same during data collection.

### Segment coordinate system (SCS)

The segment coordinate system (SCS) was defined with a neutral trial. Posterior to anterior direction is defined as the x axis, distal to proximal (down to up) direction is defined as the y axis and medial to lateral direction is defined as the z axis in each joint center (Figure 4). The SCS was anatomically aligned in order

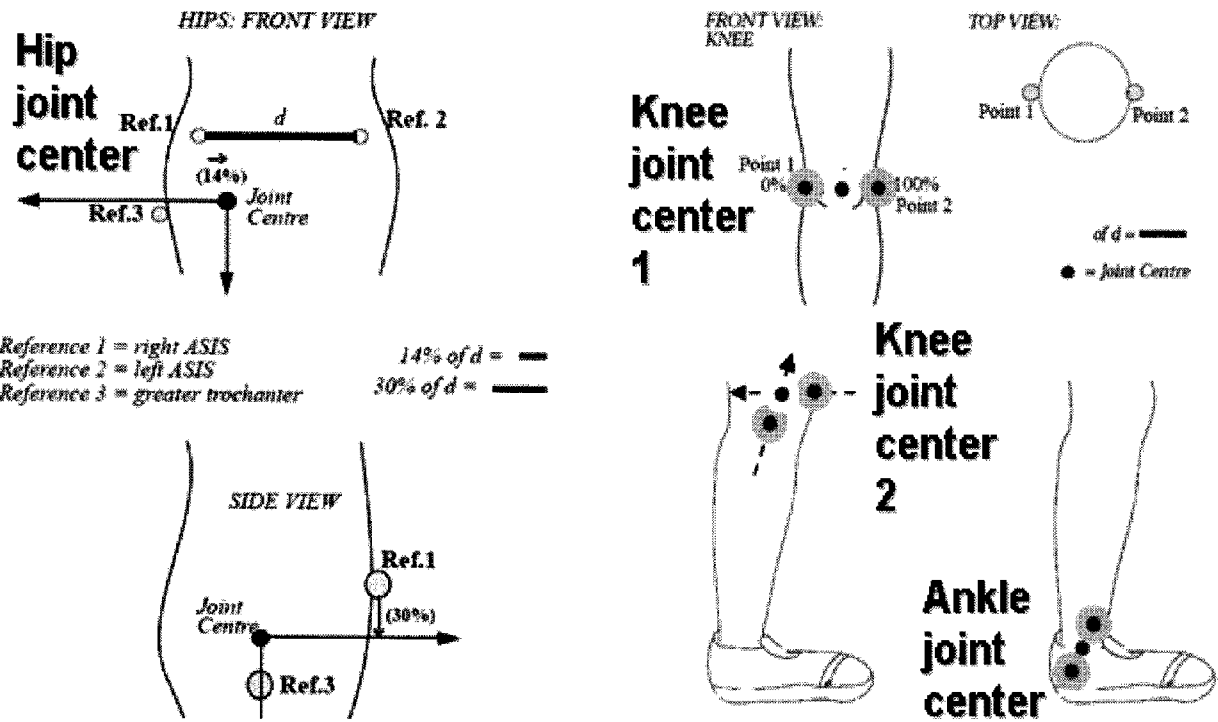


Figure 3. Definitions of joint centers

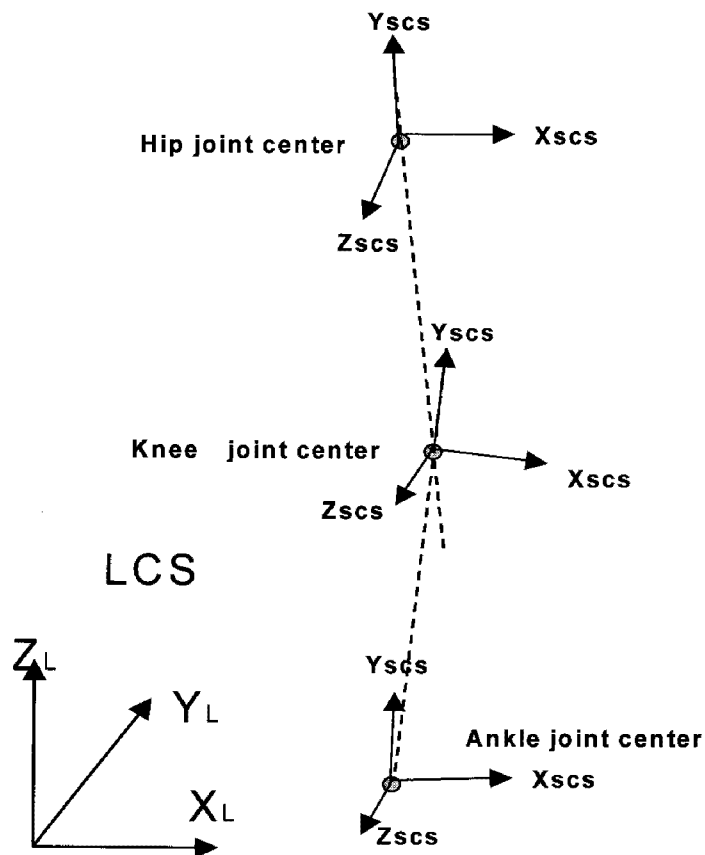


Figure 4. Segment Coordinate System (SCS) in the sagittal plane

to analyze data for meaningful application. This is useful whenever the neutral position does not provide adequate alignment between the LCS and the SCS. Results obtained from aligned segments are more clinically relevant.

For the thigh segment, first, the longitudinal axis was defined from the knee joint center to the hip joint center. The hinge axis was calculated with the positions of the hip joint center and the greater trochanter.

Thus, the cross product of longitudinal axis and hinge axis defined the anterior and posterior axis at the hip joint center. The cross product of this anterior and posterior axis and the longitudinal axis defined the medial and lateral axis at the hip. This process can be applied to define the axis for the shank segment.

However, no alignment is applied for the foot segment since there is no distal segment. At the knee joint center, flexion and extension occur at the hinge axis, internal and external axis occur at the longitudinal axis, and adduction and abduction occur at the anterior and posterior axis for further analysis.

Calculation of transformation matrix for each segment in neutral position

When the segment coordinate systems were anatomically aligned, the unit vector can be defined in each joint center. The rotation matrix from LCS to SCS at each joint center was calculated with unit vectors and the rotation matrix becomes a 3x3 matrix combined with unit vectors (equation 1).

$$\begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \times \begin{bmatrix} X_L \\ Y_L \\ Z_L \end{bmatrix} \quad (1)$$

$X_S$ ,  $Y_S$ , and  $Z_S$  are the coordinates for SCS

$X_L$ ,  $Y_L$ , and  $Z_L$  are the coordinates for LSC

$a$ ,  $b$ ,  $c$ ,  $d$ ,  $e$ ,  $f$ ,  $g$ ,  $h$ , and  $i$  are the coefficients of unit vectors

$[a \ b \ c]$ ,  $[d \ e \ f]$ ,  $[g \ h \ i]$  are unit vectors in SCS.

The translation matrix was defined from the cross product of the rotation matrix and position vectors in the LCS (equation 2).

$$\begin{bmatrix} T_X \\ T_Y \\ T_Z \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \times \begin{bmatrix} -P_X \\ -P_Y \\ -P_Z \end{bmatrix} \quad (2)$$

$[T_X \ T_Y \ T_Z]^T$  is the translation vector

$[P_X \ P_Y \ P_Z]^T$  is the position vector of joint center in LCS

Thus, a 3x3 rotation matrix, a 1x3 translation matrix, and a 4x1 scale factor becomes a 4x4 transformation matrix, which transforms position data from LCS to

SCS (equation 3). Thus, the position data of each marker during the neutral trial in LCS can be expressed in SCS with a transformation matrix.

$$[T] = \begin{bmatrix} a & b & c & P_X \\ d & e & f & P_Y \\ g & h & i & P_Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

Finally, the position data of each marker during movement in LCS can be transformed into SCS.

Each segment is assumed as a rigid body, but it is not perfectly rigid due to skin movement and measurement error. The least squares method, using the singular value decomposition (Soderkvist and Weiden, 1993) was used to calculate the rotation matrix from the three dimensional positions of markers before movement and the positions after the movement in SCS.

A Matlab program (6.5.1 version, Mathworks Inc.,

Massachusetts, USA) was used to calculate the transformation matrix. The transformation matrix for the segment at each sampling point was determined for further calculation of relative movement between two segments.

### Application of the joint coordinate system (JCS)

There are two ways of describing the relative movement between the shank and thigh. First, the Cardan angle method is used with two transformation matrices for each segment. The transformation matrix from the first segment to the second segment can be calculated from the cross product of the first transformation matrix and the inverse of the second transformation matrix.

This method is widely used in biomechanics, but as it is sequence dependent. In addition, in order to meet the anatomical application, the sequence of Cardan angles have to follow flexion/extension, internal/external rotation, and abduction/adduction. It is speculated that the range of motion of the knee joint is decreased in this order.

The second method for describing the relative movement is a "Joint Coordinate System" or JCS. This method was proposed by Grood and Suntay(1983) and standardized by Cole et al.(1993). In this system, one joint axis is fixed in the proximal segment, a second axis is fixed in the distal segment, and the intermediate or "floating" axis is normal to the two body fixed axes. In this study, the z axis of the thigh segment coordinate and y axis of the shank segment coordinate were chosen for the first unit vector ( $e_1$ ) and the second unit vector ( $e_2$ ). The calculation of the JCS (Cole et al., 1993) is showed in appendix A.

The advantages and disadvantages of the JCS for representing three-dimensional joint orientation are identical to those described for Cardan angles. The

major difference between the two methods is conceptual. For a given joint orientation, the sequential nature of the Cardan angle approach implies that a movement from the neutral position is occurring to obtain the joint orientation of interest, which is not necessarily the case. On the other hand, JCS is conceptually an actual representation of a specific joint orientation. Thus, the JCS approach is preferable. The angles were normalized to 100% during the stance phase in this study. The calculation of JCS was used with Matlab program.

Knee joint angles in three axes were compared between marker set 1 and marker set 2. Within each marker set, peak flexion and external rotation angles were compared between the first application of the knee joint center and the second application of the knee joint center.

## Statistical Analysis

Peak values of knee angles ( $^{\circ}$ ) between two different marker sets and knee joint centers were compared with a paired t-test with  $\alpha = 0.05$  using Stata 7.0(Stata Corp., Texas, USA).

## Results

After wand calibration, 3-D residuals were calculated as 0.5855 mm(deviation: 0.2803mm) which is low. This calibration can calculate very accurate wand length (original length: 500 mm, mean: 499.94 mm, deviation: 0.71 mm) when the wand was swayed for 60 seconds <Figure 5>.

In order to verify calculation of the JCS, a neutral trial for a second was applied to the calculation process. Three angles at the knee were expected to be zero degrees and the results were very close to zero angles <Figure 6>.



When the two marker sets are compared, the knee flexion angles from JCS showed similar patterns, but the rotation and abduction/adduction angles were different between the two<Figure 7>.

between marker set 1 and marker set 2 were  $4.746^\circ$  and the differences in the peak external rotation angles between marker set 1 and marker set 2 were  $15.628^\circ$ <Table 1>.

The differences in the peak knee flexion angles

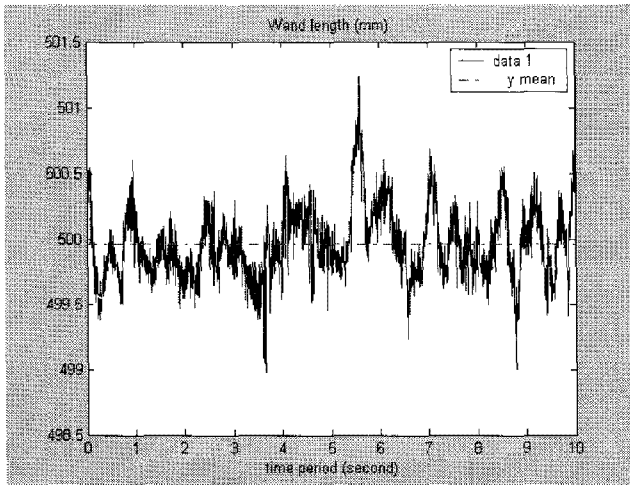


Figure 5. Wand length over calibration time. (Solid line indicated actual, dotted line represents mean length)

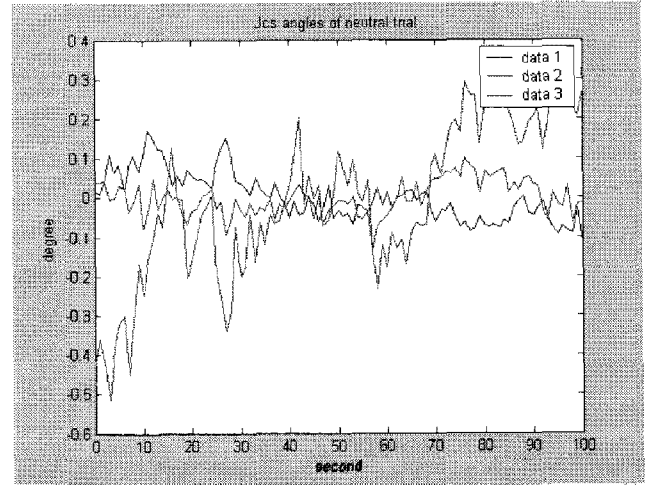


Figure 6. JCS angles of a neutral trial  
blue: flex (-)/extension (+), green : external rotation (-)/internal rotation (+)  
red: abduction (-)/adduction (+)

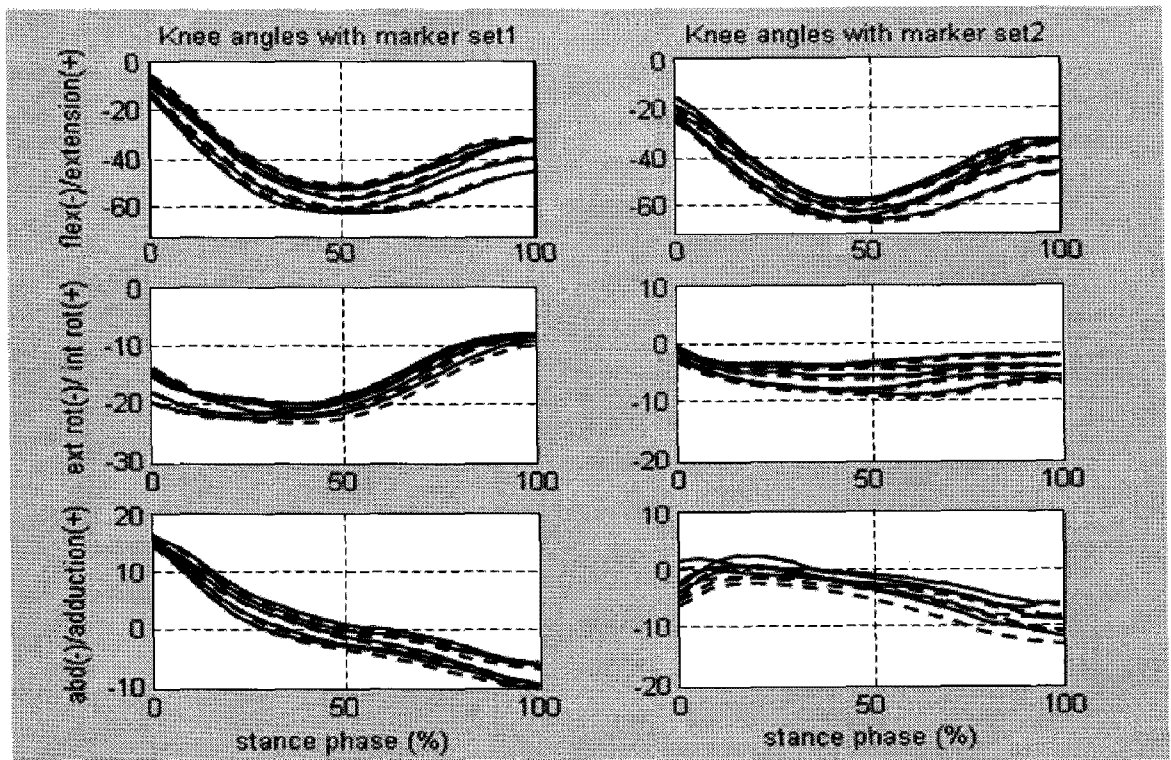


Figure 7. Knee angles in all 3 rotations for both joint center calculations (solid line: knee joint center 1, dotted line: knee joint center 2)

Table 1. Knee joint center comparisons between 2 marker sets

Conditions	Marker set 1			Marker set 2		
	Knee jc1	Knee jc2	Differences (°)	Knee jc1	Knee jc2	differences(°)
Peak flexion (°) (Mean ± SD)	56.399 ± 4.219	56.961 ± 4.213	0.562	61.613 ± 3.662	61.239 ± 3.645	0.374
Peak ext rotation (°) (Mean ± SD)	22.042 ± 1.057	21.492 ± 1.021	*0.549	6.294 ± 1.949	5.984 ± 1.955	*0.309

\*significant difference by a paired t-test:  $p < 0.05$ , knee jc1(knee joint center1): lateral and medial femoral epicondyle, knee jc2(knee joint center2): lateral femoral epicondyle and the center of patella.

The marker set1 was set to the bony structures of the tibia and the femur. The marker set2 was set to the bony structure of the fibula and muscle belly of the thigh <Figure 2>.

Within marker set 1, the differences in the peak external rotation angles between knee joint center1 and knee joint center2 were significant( $p < 0.05$ ). Within marker set 2, the differences of peak external rotation angle between knee joint center1 and knee joint center2 were also significant( $p < 0.05$ ). The differences in the peak knee abduction/adduction were not compared due to different patterns.

## Discussion

The purpose of this study was to investigate the sensitivity of marker setup and position of knee joint center on three dimensional orientations at the knee during a cutting. When three knee angles were compared between two marker sets, different patterns of three knee angles were found.

In flexion / extension angles of the knee, approximately 5° difference was found between two marker sets. This difference in the above results would significantly alter the findings. However, similar to other locomotion patterns such as walking and running, the extension angle was dominant during the stance phase in a cutting movement. In external/internal knee rotation, the external knee

rotation angles were dominant during the stance phase in both marker sets, but the magnitudes of external knee rotation angles were significantly different. In addition, there were different patterns between two marker sets in the abduction/adduction knee angles. Thus, it was found that different marker sets gave rise to significantly different results.

There were greater influences on the orientations of longitudinal and anterior/posterior axes. The same marker set is recommended for every condition during an investigation as changes in marker sets introduces large variations and discrepancies on the knee joint angle calculations.

Within the marker set, the knee joint angle showed little difference between two different knee joint center definitions: less than 1 difference in the peak extension angles (difference in marker set 1: 0.562°) was found in both cases. This difference was not significant whereas, there were differences in the peak external rotation between knee joint center1 and knee joint center2 in both marker sets.

The comparison of the abduction/adduction knee angle between two knee joint centers was not performed because there were no peak points that could be used for a statistical analysis.

However, there were greater differences of abduction /adduction angles between knee joint center1 and knee joint center 2 in marker set 2. The effect of different applications of knee center on the knee extension angles was small, but showed

significant differences in the knee external rotation angles. In a neutral trial, the position of knee joint center1 was (391.214 mm, 163.550 mm, 452.390 mm) and the position of knee joint center 2 was (387.612 mm, 162.179 mm, 439.170 mm) in the LCS(x axis: posterior to anterior, y axis: lateral to medial, and z axis: down to up). The differences in x and y axis positions were not large, but there was more than 1cm difference in the z axis (vertical direction). When a neutral position was applied to the calculation of knee angles, the position in z axis had a greater influence on the longitudinal axis and anterior/posterior axis rather than hinge axis. In other words, a vertical position of the knee joint center is more sensitive to external/internal rotation and abduction/adduction angles.

In this study, data was collected in 5 trials from only one subject; as such, there are not enough subjects and trials to conclude whether the knee angles observed was a typical of cutting movements. In previous studies of cutting movements, 60° extension, 10° to 20° internal rotation, and 5° abduction/adduction were found during the stance phase (Malinzak R.A., Colby S.M., Kirkendall D. T., Yu B., and Garrett W.E, 2001; McLean S.G., Lipfert S.W., and Van Den Bogert A.J., 2004; Pollard C.D., Davis I.M, and Hamill J., 2004).

However, the internal/external rotation and the abduction/adduction angles are relatively smaller than the extension angles. Because these variables are very subject dependent, greater number of subjects and trials is necessary to verify the knee angles of this specific movement. Additionally, it was found that the knee angles during a cutting movement were sensitive to the marker set and knee joint center.

In conclusion, several practical techniques in experimental design can be applied to acquire accurate information. First of all, system error must be reduced through careful calibration. Proper calibration

is dependant upon correct camera setup for appropriate capture volume to reduce the instrumental errors. The validity and performances of the calibration procedure are tested with seed and wand calibration processes.

Secondly, during the data collection, the most critical source of errors is associated with skin movement. Unless an invasive biomechanical method (such as bone pins) is used for motion analysis, there is no way to eliminate errors from skin movement. However, if optimal marker placements are applied to collect kinematic variables, errors will be dramatically reduced. Previous studies reported that bony structures are preferred as marker placements, but each marker has to be located at the short distance from the joint. Also, isotropic maker sets should be avoided because they will cause problems in the calculation of the rotation matrix.

In this study, skin movement on certain placements during movement was not studied, but the skin movement increased from the foot to the thigh (lower body to upper body) in a neutral trial. However, it is questionable if same pattern of skin movement occurs during movement.

Thirdly, there are a few other careful considerations in data collection that will help reduce experimental errors. In order for Motion analysis program recognize the centroid of reflective markers, good quality reflective tape and perfectly spherical shape of markers.

In addition, in order to keep the consistency of the data collection, it is necessary to control conditions such as avoiding the fatigue effect by resting between sessions and the learning effect by randomizing the order of presented conditions.

Since the fast movements such as running or cutting are speed-dependent, subjects should keep the same speed to minimize variation of the data due to the speed effect. If researchers consider reducing these

sources of errors, precise and accurate data will be acquired.

This study found that knee joint angles are sensitive to marker set and knee joint center during the cutting movement. It is recommended the same marker set and joint center be applied for reliable results. Therefore, the comparison between different conditions will be possible in biomechanical application even though there are some non avoidable sources of errors in the data collection.

## Appendix A

Joint Coordinate System (JCS): A summary of Cole et al. (1993)

$$\begin{bmatrix} X_{SCS1} \\ Y_{SCS1} \\ Z_{SCS1} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \times \begin{bmatrix} X_L \\ Y_L \\ Z_L \end{bmatrix}$$

$$\begin{bmatrix} X_{SCS2} \\ Y_{SCS2} \\ Z_{SCS2} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \times \begin{bmatrix} X_L \\ Y_L \\ Z_L \end{bmatrix}$$

$$e_{3ij} = [b_{21} \ b_{22} \ b_{23}]^T, \quad e_{1ij} = [a_{31} \ a_{32} \ a_{33}]^T$$

$$e_{2ij} = e_{3ij} \times e_{1ij} \quad (\text{The sign of } e_{2ij} \text{ is negative}$$

$$\text{if } (e_{3ij} \times e_{1ij}) \cdot t_j < 0 \text{ and}$$

$$((e_{3ij} \times e_{1ij}) \times e_{3ij}) \cdot f_j > 0)$$

$$e_{1ij} = f_i, \quad e_{3ij} = l_j$$

In order to ensure a right-handed JCS, an alternative labeling of segment-fixed coordinate axes is used.

F-axis is flexion-extension axis (described by the unit vector,  $f$ )

L-axis is longitudinal axis (described by the unit vector,  $l$ )

T-axis is third axis (described by the unit vector,  $t$ ,

resulting from the cross-product between  $l$  and  $f$ )

(1) One axis, with unit vector,  $e_1$ , is selected to be the medio-lateral ( $z$ ) axis of the proximal segment coordinate system. This is the rotational axis for the flexion-extension at the knee.

(2) Another axis, with unit vector,  $e_3$ , is selected to be the longitudinal axis of the distal segment. The axial rotation (internal/external rotation angles) components is measured about this axis

(3) These two segment-fixed axes define the remaining axis, with mutually perpendicular unit vector,  $e_2$ . This axis is the cross-product of the two segment-fixed axes, and it defines the axis of rotation for adduction/abduction at the knee.

The three angles that represent the three-dimensional orientation of the target segment,  $j$ , with respect to the reference segment,  $i$ , relative to a neutral position are calculated as follows.

For the angle of rotation about the axis for the flexion-extension:

$$\phi_{1ij} = \arccos(e_{2ij} \cdot t_i) \cdot \text{sign}(e_{2ij} \cdot l_i)$$

For the angle of rotation about the axis for adduction-abduction:

$$\phi_{2ij} = \arccos(r \cdot l_j) \cdot \text{sign}(e_{1ij} \cdot e_{3ij})$$

$$\text{where: } r = \left( \frac{e_{1ij} \times e_{2ij}}{|e_{1ij} \times e_{2ij}|} \right)$$

For the angle of rotation about the axis for axial rotation:

$$\phi_{3ij} = \arccos(e_{2ij} \cdot t_j) \cdot \text{sign}(e_{2ij} \cdot f_j)$$

$$\text{where: } \text{sign}(x) = 1 \text{ if } x \geq 0, -1 \text{ if } x < 0$$

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