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A comparison of lower-extremity skeletal kinematics measured using skin- and pin-mounted markers

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Abstract

Measurement of three-dimensional, skeletal kinematics is important for clinicians and engineers alike. Most *in vivo* motion data are acquired using skin-mounted markers or marker arrays. Experiments were carried out to quantitatively evaluate the validity of using skin-mounted markers to measure the three-dimensional kinematics of the underlying bone. Kinematic data for marker arrays mounted on skeletal pins screwed directly into the bone were compared with data for markers, and arrays of markers, mounted on the skin. Findings included: (1) Task-dependent soft tissue motion relative to the underlying bone of up to twenty millimeters was measured; (2) The accuracy of segmental rigid body velocity estimates was inadequate for determining instantaneous helical axis (IHA) parameters; (3) Power spectra for skin- and pin-mounted arrays cover similar frequency bands and there was no evidence of a distinct, frequency domain soft tissue artifact; (4) Joint angles calculated from the relative rotation of skin-mounted arrays had significant differences compared to the expected values due to soft tissue effects; and (5) Skin-mounted marker data exhibited a transient response to heel strike in gait, but for low-mass markers the transient was well-damped and could be removed with optimal smoothing.

PsycINFO classification: 2260

Keywords: Validity of skin-mounted marker kinematic measurements; Skeletal kinematics measurement; Three-dimensional skeletal kinematics; Soft tissue motion; Lower extremity kinematics

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1. Introduction

A complete understanding of lower extremity kinematics is important for assisting clinicians and engineers in both the prevention, diagnosis, and treatment of knee disorders and the design of better prosthetic devices with longer mean times to failure. In order to determine the skeletal kinematics accurately the acquisition of reliable data representing the bone motion is essential. Only after accurate data have been obtained can the clinician and engineer begin to fully understand the kinematic behavior of the lower extremity, particularly that of the human knee.

Several researchers have used markers mounted on skeletal pins inserted into the bones or markers inserted directly into the bones of the lower extremity to measure *in vivo* kinematics (Chan, 1993; Kärrholm, 1989; Lafortune et al., 1992; Murphy and Mann, 1991). The trajectories of these markers are tracked to estimate the position, velocity, and acceleration of the markers and bones. While this approach generates a valid representation of the motion of the skeletal components of a joint, several characteristics of this method make it inappropriate for everyday clinical measurements. These include: (1) the subject might experience pain during the procedure, causing the alteration of otherwise painless motions; (2) the risk of infection; (3) the risk of pin loosening during the experiments, which could corrupt the accuracy of the data.

The most widely used method of data collection in biomechanics are skin-mounted markers (Kaufman et al., 1991; Lafortune and Lake, 1991; Macleod and Morris, 1987; Trujillo and Busby, 1990). Skin-mounted markers are unquestionably safer and easier to use than pin markers, but there are only limited data addressing the validity of skin-mounted marker kinematic data as an accurate representation of lower extremity skeletal motions.

This paper presents the initial results of two comparative studies of skin-mounted and pin-mounted marker kinematic data for the lower extremity. Analysis will center around the kinematics of of the femur and the tibia, the two largest bones of the human lower extremity. The purpose is to report on the validity of skin-mounted markers for the estimation of skeletal kinematics.

2. Background

The limitations of skin-mounted markers for measuring skeletal kinematics have long been tacitly acknowledged. Most of the research into quantifying the magnitude of the problem has been reported in the past decade, as access to motion analysis systems has increased.

Some of the earliest quantitative work on the motion of skin markers was reported by Macleod and Morris (1987). Markers were placed at bony landmarks and along the thigh and shank. The movement of the markers was recorded during normal gait. Relative displacements between markers due to soft-tissue motion and impact were observed and found to be non-random. While this study recognized that significant errors generated during data collection employing skin-mounted markers were due to soft tissue motion relative to the underlying bone, no bone-mounted markers were used to obtain the true skeletal kinematics and, consequently, the magnitude and nature of this motion.

Van den Bogert et al. (1990) reported on the skin displacement errors encountered during analysis of the motion of a horse. Again, the error introduced by the skin motion was cited as a major source of inaccuracy in the kinematic analysis and the authors developed two-dimensional correction factors to adequately adjust the skin marker measurements. They speculated that similar procedures would be necessary in studying human motion, although the magnitudes of soft tissue displacements were expected to be smaller though still significant. Also, the two-dimensional correction algorithm ignored the out-of-plane motions present in a spatial joint such as the human knee. Lafortune (1991) measured tibial acceleration using a pin-mounted accelerometer attached to the free end of a Steinmann pin inserted into a subject's right tibia. He suggested that simultaneous measurements with pin- and skin-mounted markers should produce enough data to determine a transfer function relating the two signals, allowing the use of skin-mounted markers to predict the acceleration of the underlying bone. In another study, Lafortune and Lake (1991) reported that skin markers do not accurately measure 3-D joint kinematics, due to the substantial displacements of the skin-mounted markers relative to the underlying bone which occur during joint motion. Reinschmidt et al. (1995) studied the relationship between skin and pin-mounted markers during running. The data showed that while the shapes of the pin- and skin-mounted data were similar, the skin markers tended to overpredict the actual skeletal motion, indicating soft tissue motion relative to the underlying bone.

The effects of skin motion on different measurement systems have also been reported. Kaufman et al. (1991) reported that it is possible to place skin-mounted markers within five degrees of the anatomically defined axes derived from computer models.

Application of instantaneous helical axes (IHAs) to the analysis of joint motion in the presence of skin motion has been described by Karlsson et al. (1991) and Angetoni et al. (1993). Karlsson compared kinematics measured with skin-mounted marker arrays to those obtained using pin-mounted marker arrays surgical screws to the greater trochanter, femoral condyle, and mid-tibia. The arrays were identical in shape and size to the skin-mounted arrays placed at the same locations in the earlier set of experiments. In addition, the two rigid arrays were again strapped to the subject's right hip and foot for a total of thirty LEDs. Fig. 1 is a photograph of the test subject's lower extremity with the skeletal pin arrays mounted, as well as the hip and foot arrays. The following tasks were performed for data collection of the pin-mounted markers: standing voluntary swing, normal gait, a seated mobility trial, and a ninety-degree pivot step. The subject experienced no pain during this phase of the data collection and no awkwardness was noted in the subject's movements. The pins were removed immediately following the experiment.

Data processing was identical for both the pin-mounted markers and the skin-mounted markers. A body-fixed coordinate system was established by having the subject stand erect in the center of the viewing volume, taking the mean of each individual LED, and transforming that from the laboratory coordinate system origin to the respective array coordinate system origin, located at the centroid of each array. Data were collected and processed using TRACK III software (Antonsson and Mann, 1989) modified to incorporate Schut's original unit quaternion formulation (Schut, 1960), and Dohrmann's algorithm for GCV-based cubic spline smoothing (Dohrmann et al., 1988).

A simple estimate of the flexion angle, similar to that used in most gait laboratories, was used as a standard for comparing the flexion angles calculated

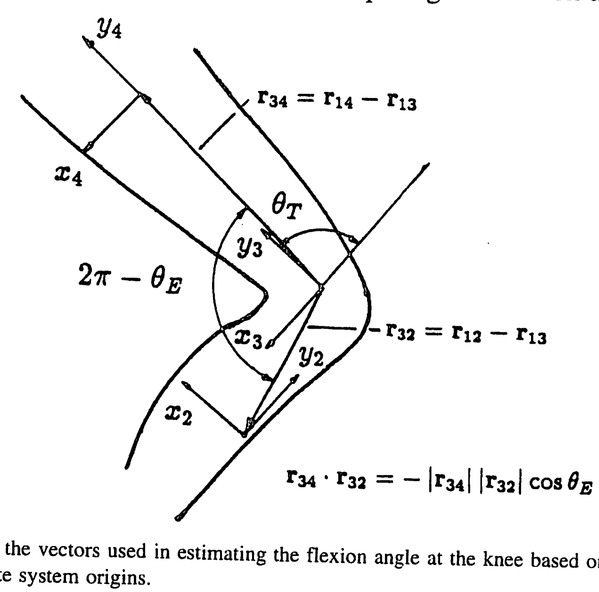


Fig. 2. Schematic of the vectors used in estimating the flexion angle at the knee based on the positions of the array-fixed coordinate system origins.

from the relative rotations of the marker arrays in the two sessions of the first experiment. The relative positions of the origins of the array-fixed coordinate systems were used to evaluate the approximate range of flexion and extension. The scalar product of the vector from the center of the lateral condyle array to the center of the greater trochanter array and the vector from the center of the lateral condyle array to the center of the tibial array provided an estimate of the flexion angle during the swing task (Fig. 2).

3.2. Experiment 2

The second data set was taken from a 1.88 m white male with a mass of approximately 104 kg. The subject was between 35 and 40 years of age with no

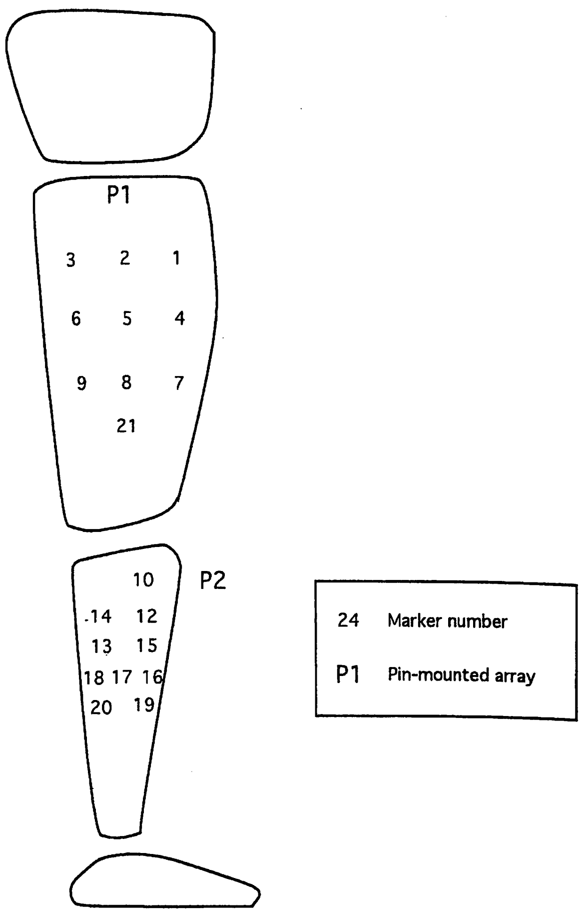


Fig. 3. Schematic of pin array and skin marker distributions for Experiment 2.

known prior lower extremity injuries. Kinematic data acquisition was accomplished with the TRACK V/Selspot II kinematic measurement system. The TRACK V/Selspot II system consisted of two optoelectronic cameras capable of tracking up to 32 near-infrared emitting markers and a Kistler piezoelectric force platform synchronized with the kinematic measurement system. Each marker consisted of a triad of LEDs in order to produce higher intensities for following out-of-plane motions, and the sampling frequency for all LEDs in this experiment was 156.2 Hz. The spatial resolution of the system at the center of the viewing volume was 0.25 mm on each axis. Calibration of the TRACK V/Selspot II system is discussed in Mansfield (1990).

The subject's right leg was instrumented with two arrays of six markers each

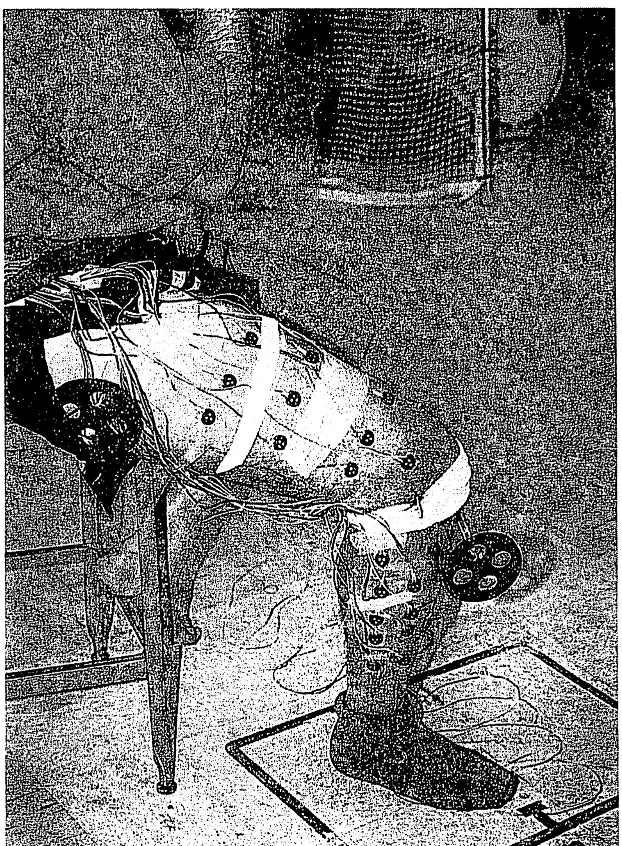


Fig. 4. Skeletal pin- and skin-mounted arrays for Experiment 2.

mounted on skeletal pins inserted into the tibia and femur at the tibial tubercle and greater trochanter, respectively. The remaining twenty markers were distributed evenly along the thigh and shank and attached directly to the skin with double-sided tape (3M 1512). Fig. 3 is a schematic of the subjects lower extremity which indicates the approximate locations of the skin- and pin-mounted markers on the thigh and shank. A photograph of the instrumented leg is shown in Fig. 4. The additional skeletal pins which can be seen in the photograph were used in second set of experiments on skeletal joint kinematics which have been partially reported in Chan (1993).

Four tasks were performed: stationary bicycling, squatting, normal gait, and a voluntary swing movement. Data were recorded using the TRACK V software package (Mansfield, 1990). The method of calculating the 3-D point coordinates was identical for both the pin- and skin-mounted marker data sets.

The pin-mounted kinematic data were further processed to provide rigid body kinematics of the femur and tibia using TRACK V. Three-dimensional point

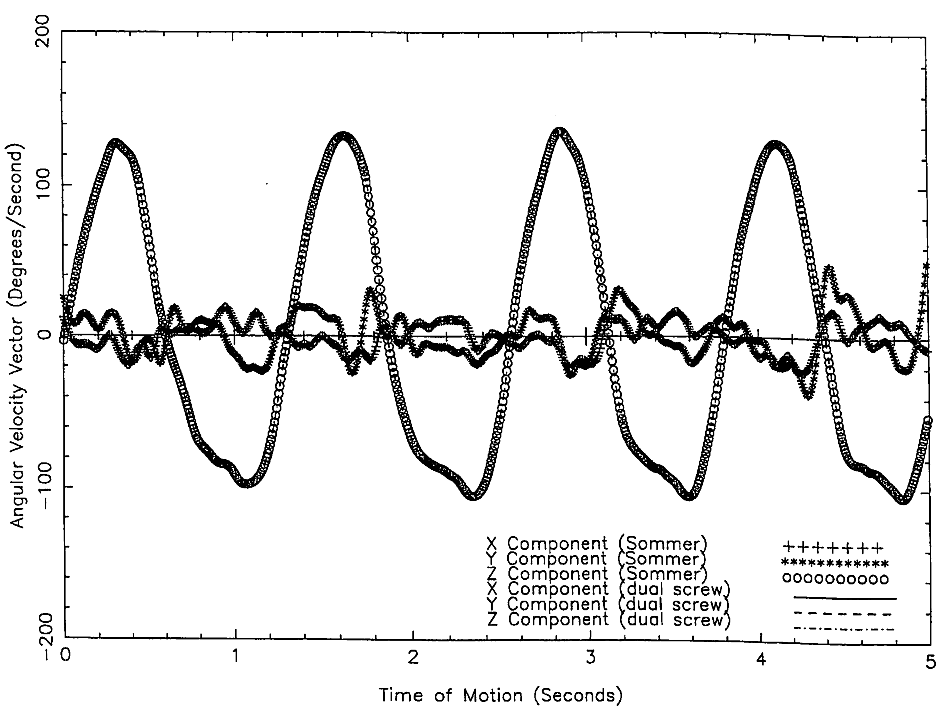


Fig. 5. Comparison of the angular velocity vector components in global coordinates of the femur for the bicycle task of Experiment 2 calculated using both TRACK V and Sommer's method.

coordinates were smoothed using the Dohrmann algorithm for GCV-based cubic spline smoothing (Dohrmann et al., 1988). Conversion to rigid body coordinates was accomplished by applying the Schut algorithm (Schut, 1960), which is incorporated into the TRACK V software. The algorithm assumes that the individual markers are fixed in a rigid array with a specified geometry and generates a rotation transformation in the form of a quaternion. A Lanczos

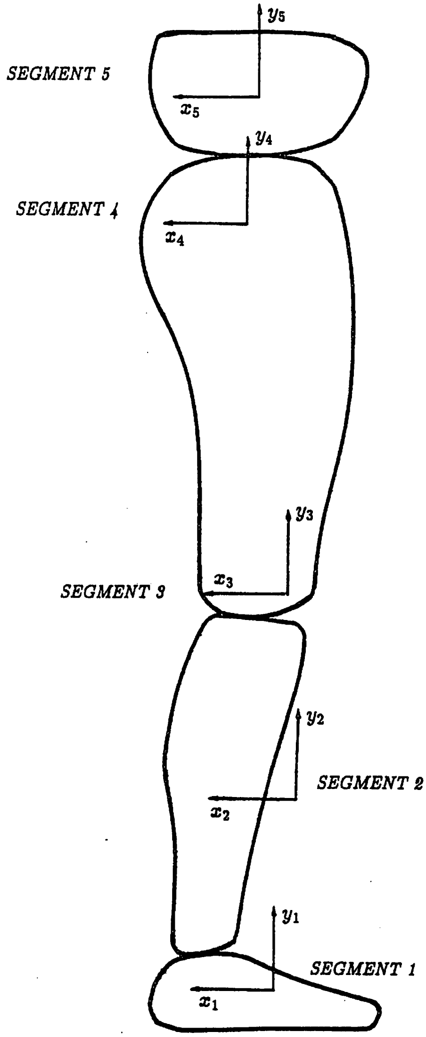
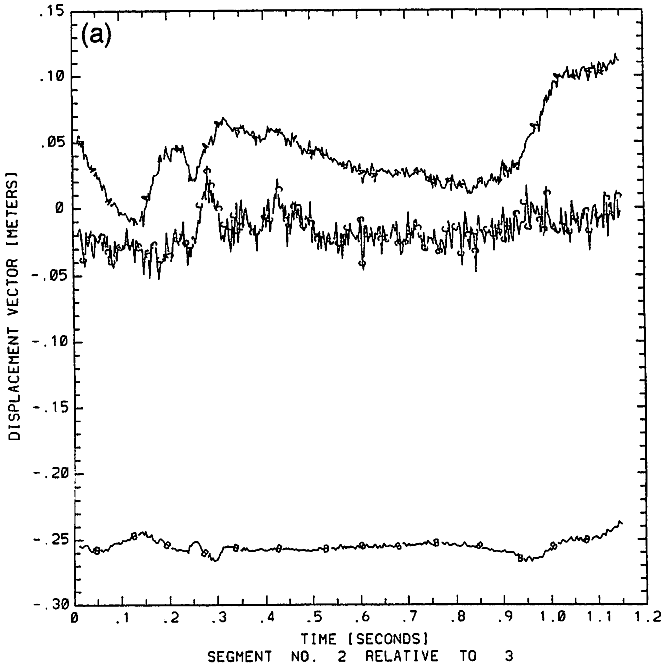
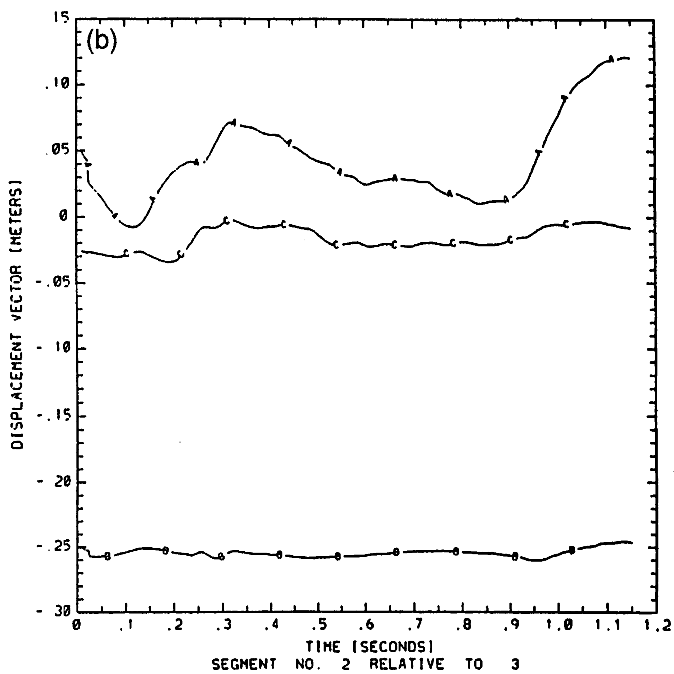


Fig. 6. Location and orientation of the embedded segmental coordinate sysyems for Experiment 1.



(a)
.15
.10
.05
0
-.05
-.10
-.15
-.20
-.25
-.30
DISPLACEMENT VECTOR [METERS]
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0 1.1 1.2
TIME [SECONDS]
SEGMENT NO. 2 RELATIVE TO 3



(b)
15
.10
.05
0
-.05
-10
-.15
-20
-.25
-30
DISPLACEMENT VECTOR [METERS]
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1.0 1.1 1.2
TIME [SECONDS]
SEGMENT NO. 2 RELATIVE TO 3

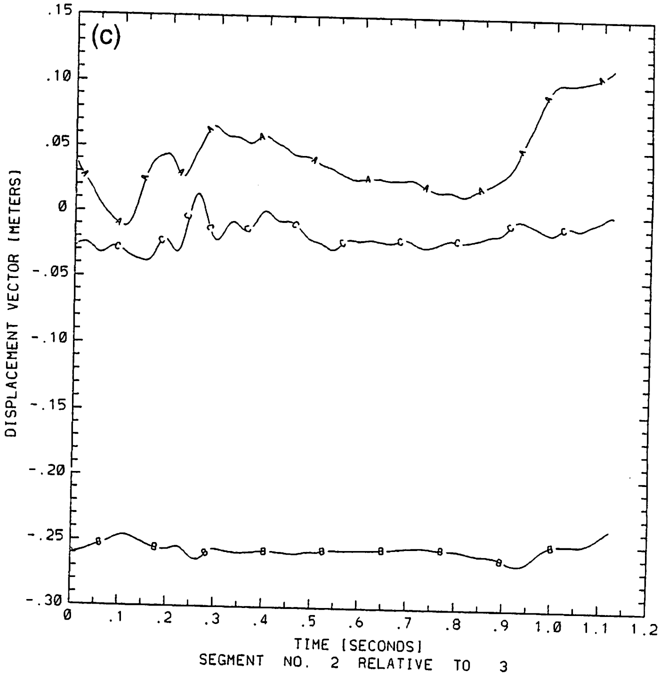


Fig. 7. Relative displacement vector at the knee for Trial 1 of the normal gait task in Experiment 1 using the skin-mounted arrays: (a) Unsmoothed, (b) Smoothed with natural cubic spline ($p = 3$, $m = 2$), and (c) Smoothed with quintic spline ($p = 5$, $m = 4$). Key: A – x-axis displacement; B – y-axis displacement; C – z-axis displacement.

four-point differentiation filter was used to obtain angular and translational velocity vectors of the pin markers.

This approach was not suitable for processing the skin-mounted marker data, because the markers could not be placed in a pre-defined geometry to the necessary tolerance. An alternative algorithm for the estimation of rigid body kinematics developed by Sommer uses only three-dimensional marker coordinates and does not require specification of the marker array geometry (Sommer, 1992). For evaluation, Sommer's algorithm was used to process the pin-mounted data. Fig. 5 shows a representative comparision of the angular velocity vector components of the femur during the bicycle task calculated using both Sommer's algorithm and the Schut algorithm. Essentially no difference was noted in the rigid body kinematics of the femur and the tibia estimated by Sommer's algorithm and those obtained from TRACK V, using the Schut algorithm, for any task. Sommer's algorithm was then used to estimate the rigid body kinematics of the femur and tibia based on the measured 3-D displacements of the skin-mounted markers. Comparison of the two sets of rigid body kinematics for the femur and tibia were made in order to determine the validity of data obtained using skin-mounted markers for estimating three-dimensional skeletal kinematics.

4. Results and discussion

4.1. Experiment 1

The primary objective of the first experiment was to obtain data on the relative skeletal movements at the knee. All data show the motion of the tibia relative to the femur in the body-fixed femoral condyle array coordinate system. In the neutral position used to define the array-fixed coordinate systems, the nominal directions of the body-fixed coordinate axes were toward the subject's rear for x, up for y, and normal to the axis between cameras in the direction of the forceplate for z (see Fig. 6). The effects of soft tissue motion were investigated for the gait and standing voluntary swing tasks.

The unsmoothed relative displacement vector for motion of the tibia relative to the femur for the gait trials with the skin-mounted markers showed a distinct,

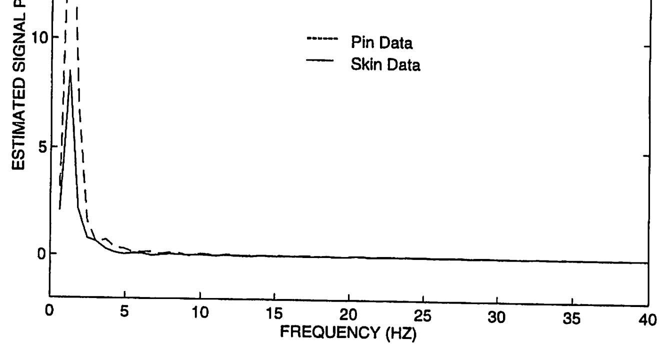


Fig. 8. Power spectral estimates for the z displacement of the origin of the array-fixed coordinate system on the femoral condyle in Experiment 1.

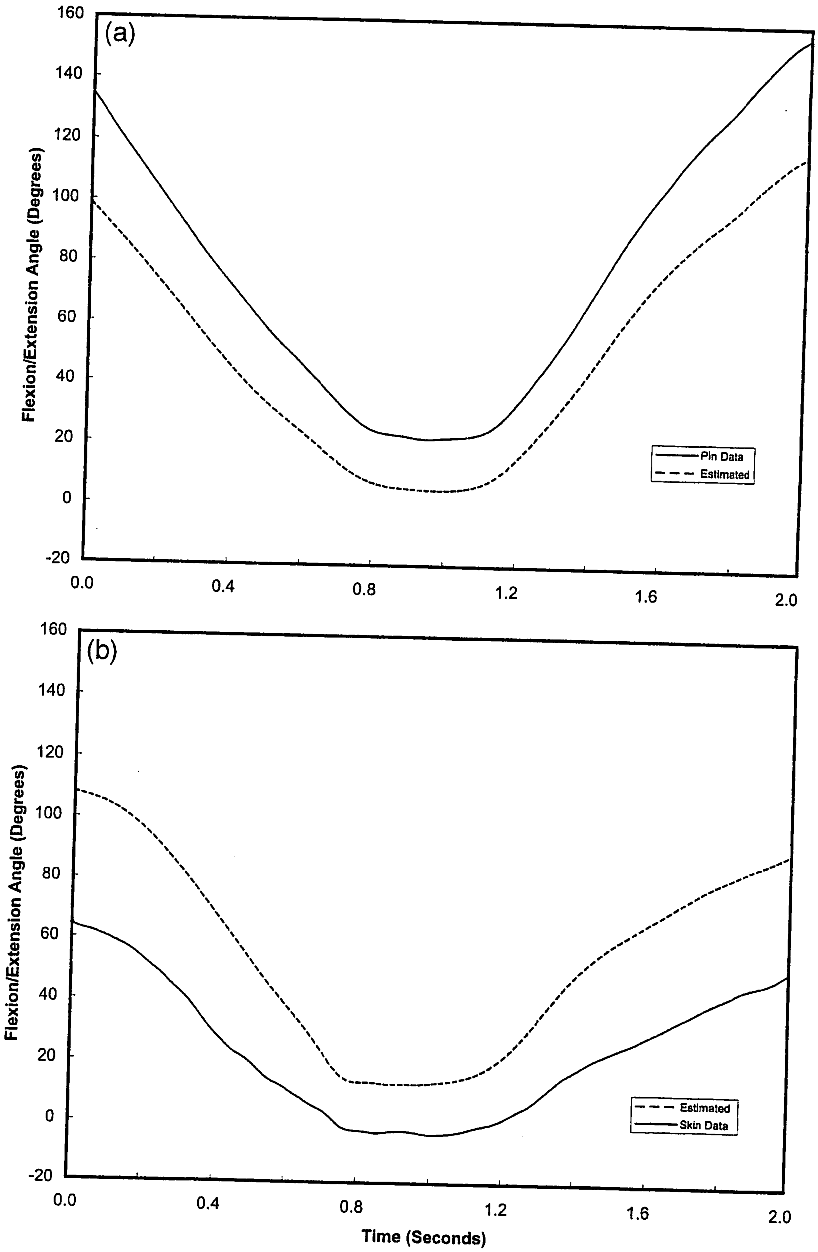


Fig. 9. Estimated and measured flexion/extension angle of the knee versus time in Experiment 1: (a) Trial 2 of the voluntary swing task (pin-mounted arrays), (b) Trial 1 of the voluntary swing task (skin-mounted arrays).

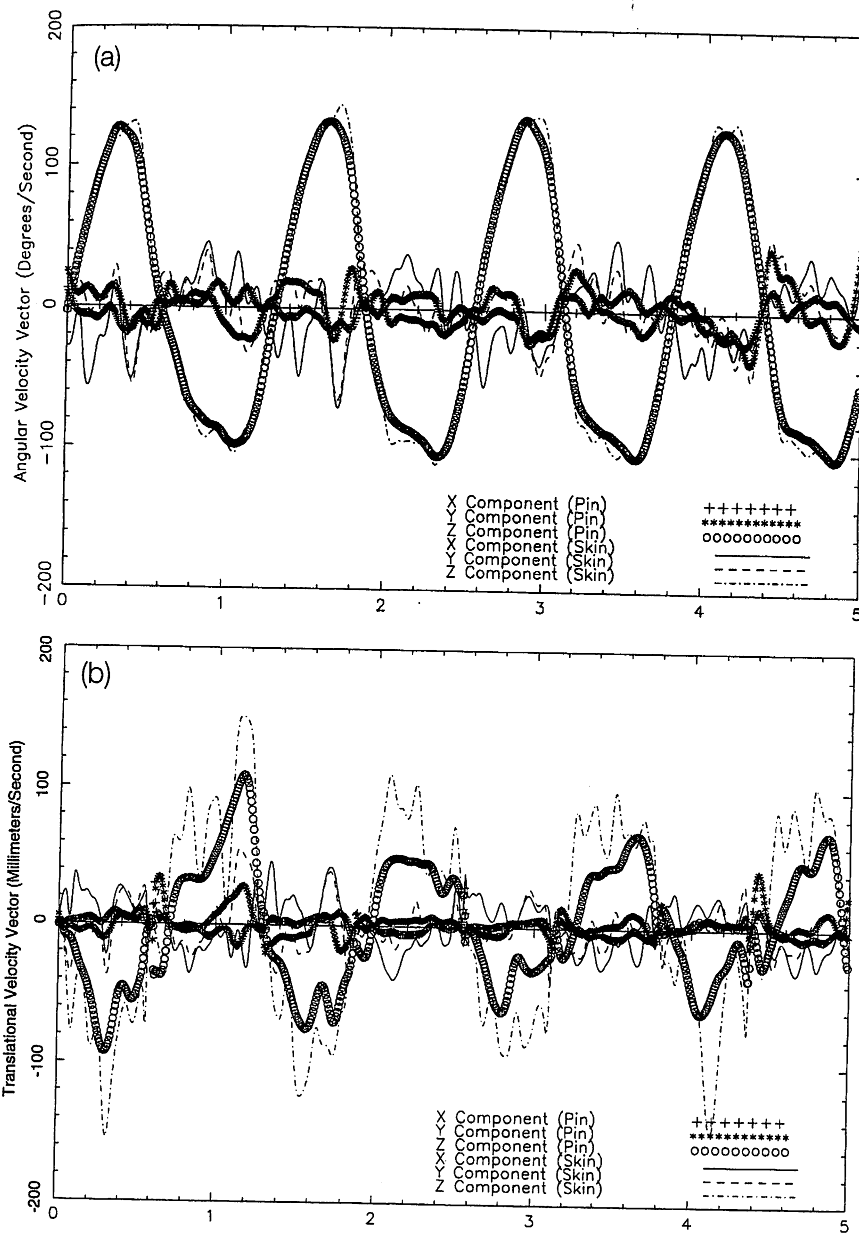


Fig. 10. Velocity vector components for the femur from the skin- and pin-mounted marker data of the bicycle task in Experiment 2 calculated using TRACK V and Sommer's method: (a) Angular velocity, and (b) Translational velocity.

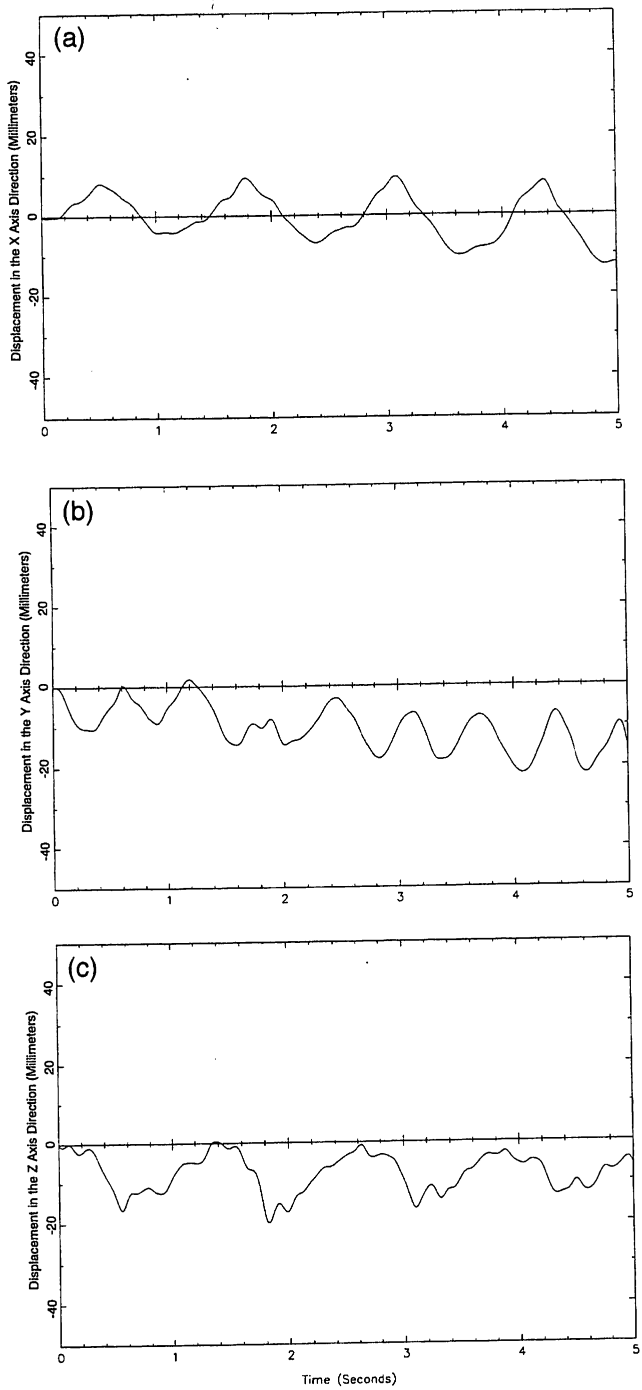
degrees as the leg was extended to a flexion angle of 155 degrees at completion of the movement. The estimated flexion angle followed a similar trajectory over a range of motion of nearly 110 degrees, but was offset by from 20 to 30 degrees from the first curve. The offset increased as the flexion angle increased, with the best agreement near maximum extension. A similar plot is presented in Fig. 9b for the skin-mounted marker experiment. The range of motion for the estimated angle was again on the order of 100 degrees, although the trajectory diverged from that observed in the pin-mounted marker experiment as the flexion angle increased. The flexion angle based on the relative rotations of the skin-mounted marker arrays exhibited a flattened trajectory with a total range of motion of approximately 60 degrees. Two possible causes of the attenuation of the flexion/extension angle measured with the skin-mounted marker arrays are either soft-tissue motion or inadequate fixation of the markers to the skin. Since the skin array appears to initially lag the skeletal motion, but eventually track the motion well, and other kinematic components do not show any obvious adverse affects the former hypothesis appears to be the more probable.

4.2. Experiment 2

The primary objective of the second experiment was to evaluate the use of skin-mounted markers in obtaining the skeletal kinematics of the lower extremity. Two comparisons of the rigid body kinematics obtained from skin- and pin-mounted marker data were made. The first was a direct comparison of the angular and translational velocity vectors for the different tasks. The second was an evaluation of the assumption of rigid body motion underlying the use of Sommer's algorithm and a direct measure of the relative displacement between the skin-mounted markers and skeletal members. All results are presented in the laboratory-fixed coordinate system and represent absolute motions of the limb segments.

Significant differences were observed between the rigid body angular velocities calculated from the skin-mounted markers and those calculated using the pin-mounted markers. Calculation of the rigid body velocities is necessary to estimate the location and orientation of the instantaneous helical axes (IHAs) of

Fig. 12. Soft tissue motion relative to the bone for LED 21 on the thigh for the bicycle task in Experiment 2: (a) x direction displacement offset, (b) y direction displacement offset, and (c) z direction displacement offset.


(a)
Displacement in the X Axis Direction (Millimeters)
40
20
0
-20
-40
0
1
2
3
4
5
(b)
Displacement in the Y Axis Direction (Millimeters)
40
20
0
-20
-40
0
1
2
3
4
5
(c)
Displacement in the Z Axis Direction (Millimeters)
40
20
0
-20
-40
0
1
2
3
4
5
Time (Seconds)

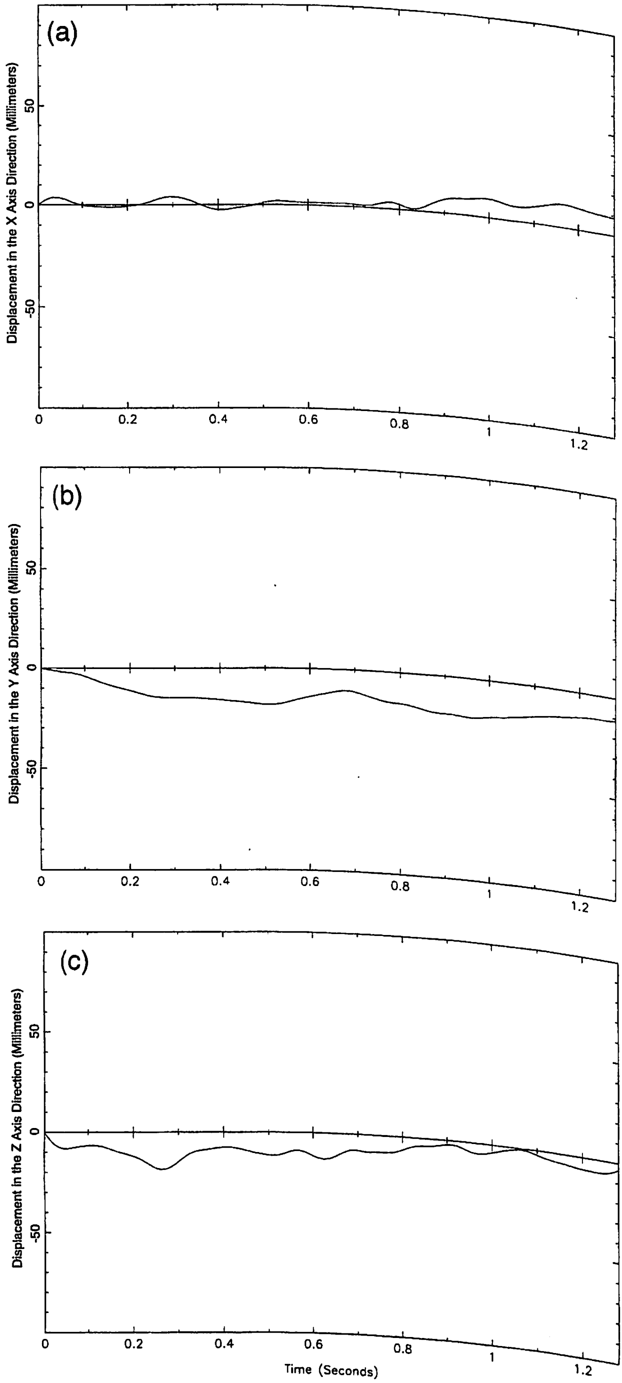
the motion. Representative data are presented in Fig. 10 for the motion of the femur during the bicycle task. A cyclic motion can be observed for all three angular velocity components calculated from the pin-mounted marker data. There is agreement between the z-axis (nominally the sagittal plane) components measured from both sets of markers, particularly at higher velocities. For the x- and y-axis components of the angular velocities, there are significant differences between the two data sets through several pedalling cycles. Similar differences were observed for the translational velocity components along all axes. Results for the angular and translational velocity components of the tibia exhibited similar variations. Comparable differences were observed for all tasks.

Direct measurements of the displacement of the soft tissue relative to the bone, which may explain the observed variations in the velocity components, were also obtained. In order to check the assumption that the skin- and pin-mounted markers were effectively on the same rigid body, the projected rigid body motion of the skin-mounted markers was calculated and compared to the measured skin-mounted marker displacements.

Each pin-mounted marker array defined a body-fixed coordinate system attached to the bone. In the neutral position, a vector from the origin of the body-fixed coordinate system to each skin marker was calculated. Assuming that all of the markers were on the same rigid body, these vectors should have a constant length and orientation relative to the body-fixed coordinate system throughout the motion. Displacement transformations for the motion of the bone at each time step in a task were obtained from the pin-mounted marker data and used to predict the rigid-body displacement of the skin-mounted markers.

The displacement of the soft tissue relative to the bone was calculated by taking the difference between the predicted position vector for each skin-mounted marker and the measured position. Representative plots for two markers on the femur during the stationary cycling task are shown in Figs. 11 and 12. LED 1 was located near the pin-mounted marker array at the greater trochanter on a portion of the thigh with a large amount of soft tissue separating the skin marker and the bone, and LED 21 was located near the bony landmark on the femoral condyle with the smallest amount of soft tissue separating the skin marker and the bone (see Figs. 3 and 4 for the marker positions). The displacements exibited a distinct cyclic nature and showed a peak displacement of the skin-mounted

Fig. 13. Soft tissue motion relative to the bone for LED 21 on the thigh for the gait task in Experiment 2: (a) x direction displacement offset, (b) y direction displacement offset, and (c) z direction displacement offset.


(a)
Displacement in the X Axis Direction (Millimeters)
50
0
-50
0
0.2
0.4
0.6
0.8
1
1.2
(b)
Displacement in the Y Axis Direction (Millimeters)
50
0
-50
0
0.2
0.4
0.6
0.8
1
1.2
(c)
Displacement in the Z Axis Direction (Millimeters)
50
0
-50
0
0.2
0.4
0.6
0.8
1
1.2
Time (Seconds)

marker relative to the bone of twenty millimeters. This cyclic displacement showed virtually identical periods of oscillation on the x, y, and z-axes, consistent with the angular and translational velocity plots for the femur during the bicycle task.

In order to further quantify soft tissue motion near the femoral condyle, a common attachment site for skin-mounted markers, the displacement of LED 21 relative to bone is presented in Fig. 13 for the gait task. Again, displacements of up to twenty millimeters were observed throughout the trial, indicating that the skin-mounted marker was not tracking the underlying bone motion accurately. Distinct differences were noted between the patterns of motion of the markers during the cycling and gait tasks, indicating that the soft tissue displacement is task dependent. The characteristic task dependence was consistent for all other markers and tasks.

5. Conclusions

Several conclusions can be drawn from the experiments about the use of skin-mounted markers for monitoring skeletal motion. First, the skin-mounted marker data are inappropriate for representing the motion of the underlying bones. *Rigid skin-mounted marker arrays* do not track rotation of the bone well, particularly on the femur. Significant differences in relative angular displacement calculations based on skin-mounted marker arrays were observed about all axes of rotation. Displacements of the *individual skin-mounted markers* relative to the underlying bone of up to twenty millimeters were observed in all tasks of the second experiment and screw axis calculations reflected the same effects. Second, although the soft tissue motion appears to be cyclic, it was task dependent. The patterns of motion differed significantly from task to task. This would make the definition of corrective transformations between the skin-mounted markers and the bone task dependent. Third, elimination of heel-strike transients in skin-mounted marker data is possible with optimal smoothing. These transients are well-damped when low-mass arrays or markers are used. Power spectra indicate that there is not a distinct soft tissue noise transient which can be filtered using conventional frequency domain techniques. Attempting to remove soft tissue artifacts through smoothing could result in the loss of pertinent data or the introduction of characteristics not present in the original data set due to the overlap between the soft tissue noise frequency band and the skeletal kinematics frequency band.

6. Ethical declaration

These experiments were carried out according to eithical guidelines laid out by and with the approval of the MIT Committee on the Use of Humans as Experimental Subjects.

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