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Validity and comparisons of tibiofemoral orientations and displacement using a femoral tracking device during early to mid stance of walking

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Abstract

First, this study compares tibiofemoral motion during walking using a new femoral tracking device (FTD) and bone mounted markers in a single subject ($n=1$). The results suggest errors of $<3^\circ$ in tibiofemoral angles using the FTD method over the first 85% of stance. Second, this study compares tibiofemoral angles and displacement during walking using the FTD method and a modified Helen Hayes method to track the femur in 13 subjects ($n=13$). The results suggest similar tibiofemoral angles in the sagittal and frontal planes using the two methods (average root mean square (RMS) differences $<3.6\pm1.5^\circ$), and a large decrease in the transverse plane angles (average RMS differences $=6.5\pm1.9^\circ$) and estimates of tibiofemoral displacement ($P<0.05$) using the FTD method. The FTD method presents a practical alternative to recording tibiofemoral transverse plane angles and displacement over the first 85% of stance.

Keywords: Validity; Bone pins; Surface markers; Knee kinematics; Gait

1. Introduction

Our ability to improve the accuracy of three-dimensional models of the lower limb in clinical and research studies hinges on the development of non-invasive strategies to track the skeletal system. At the knee and hip, difficulties in tracking the femur and tibia translate into problems of accurately measuring frontal and transverse plane rotations, impeding the application of three-dimensional modeling to some clinical problems [1–11].

Those investigators who have looked at tracking errors associated with the thigh and shank segments suggest that, on balance, errors in tracking the femur overwhelm tibiofemoral joint angles in the frontal and transverse planes [1–8,11]. Cappozzo et al. [2] found that compared to bone mounted markers, surface markers placed in conventional locations [12] on the shank, tended to move 1–1.5 cm relative to the tibia. This translates into average root mean square (RMS) segment orientation errors of around 2–3° during walking, although individual maximal errors are reported as high as 8° [4,5,9,10]. In contrast, thigh surface markers move up to 4 cm relative to the femur, resulting in peak segment orientation errors about twice as large as those of the shank during walking and running [1,2,4,5]. These same shank and thigh segment tracking errors overwhelm tibiofemoral joint displacement estimates that are <1 cm during walking [3]. This difficulty in estimating knee kinematics is not surprising given the anatomy of the thigh, where access to superficial bony landmarks is limited. Studies suggest tracking problems underlying these errors are dependent on the marker system used and on individual subject soft tissue characteristics [1,2,4,5,7,9,10]. It is understandable, therefore, that investigators lack confidence in the validity of knee displacement and transverse plane kinematic data obtained with surface markers.

Recently, we attempted to improve the recording of tibiofemoral angles and displacements by developing a new femoral tracking device (FTD) that clamps onto the femoral condyles and is suitable for mounting surface markers. As a preliminary test of the FTD method we

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compared tibiofemoral angles using a conventional femoral tracking method to the FTD method during a hip internal/external rotation movement with the knee extended [13]. The tibiofemoral orientation angles were significantly less ($< 3°$) for transverse plane rotations using the FTD method [13], suggesting the potential for less skin artifact using the FTD method. Using a similar device to track femoral motion and a sensor on the medial border of the tibia, Sati et al. [11] also reported low RMS errors of tibiofemoral orientation of 2.7° (max errors estimated at 6°) during a knee flexion movement and squatting in three subjects.

Although, these studies suggest a possible benefit for tracking tibiofemoral motion using a FTD method, recordings of tibiofemoral kinematics using similar surface marker methods for the femur, have not been compared to a gold standard during walking, which could more definitively estimate the errors using this approach. In addition, comparisons of the FTD method to a conventional femoral tracking method during walking might suggest which kinematic differences are due to the tracking method selected. The first goal of this study was to compare tibiofemoral joint sagittal, frontal and transverse plane angles and displacement during walking recorded using a surface marker method that incorporates the FTD method to bone mounted markers. The second goal was to compare the tibiofemoral sagittal, frontal and transverse plane angles and displacements using the FTD method and a modified Helen Hayes (MHH) tracking method.

2. Methods of experiment

2.1. Comparison of surface and bone markers

Two subjects who were 35 and 38 years old, mass 80 and 81.8 kg, and standing 1.73 and 1.81 m tall successfully completed the gait trials. The data from the second subject was used to assess movement of surface markers on the tibia only since the intracortical pin inserted into the superior aspect of the greater trochanter loosened during the gait trials. Subjects were free from known lower extremity pain and pathology prior to the testing. The human subjects committee of McMaster University, Hamilton, Ontario, Canada, approved the study and subjects gave their consent prior to insertion of the bone pins.

The bone and surface markers were tracked using an Optotrak (Model 3020, Northern Digital, Waterloo, Canada) motion analysis system at a sampling rate of 60 Hz and subsequently filtered at 6 Hz using a zero phase lag, fourth order, Butterworth low pass filter. A residual analysis technique previously described [14] was used to evaluate all of the trials to confirm that a 6 Hz cut off frequency was appropriate for filtering position data. The residual analysis technique takes into account potential vibration of the wand on the FTD when determining the optimal cut off frequency for position data. The field of view of the Optotrak is 2.25 m^2 at a distance of 2 m. At this distance the manufacturer reports an accuracy of ± 0.1 mm. Successful gait trials required subjects to land naturally on the force plate, as judged by visual observation. Force plate data were sampled at 300 Hz and, subsequently, vertical forces were used to determine heel strike and toe off based on a threshold of 10 N. All filtering and calculations of joint angles and displacement were carried out using the KINGAIT 3 software package (Mishac, Inc, Waterloo, Canada).

Intracortical pins (4.5 mm in diameter) were inserted approximately 7 cm into the lateral tibial condyle and the superior aspect of the greater trochanter (Fig. 1). Prior to insertion of the pins, the skin, subcutaneous tissue, and periosteum were anesthetized with local anesthetic of 2% xylocaine administered via a 20 cc syringe. In order to prevent loosening, the orthopedic surgeon attempted to seat the tips of the threaded pins into the cortical bone on the medial side, without penetrating the periosteum. Clusters of four markers, separated by about 10 cm, were attached to the distal end of the bone pins.

Surface markers were used to track the pelvis, thigh, and shank. The pelvic markers included two infrared emitting diodes (IREDS) mounted on form fitted bases, attached over the right and left anterior superior iliac spines to the skin using adhesive tape. The third pelvic marker was attached to a wand that extended from a form fitted base attached to the skin overlying the subject's sacrum. The femoral marker system consisted of two IREDS on the FTD and a third IRED

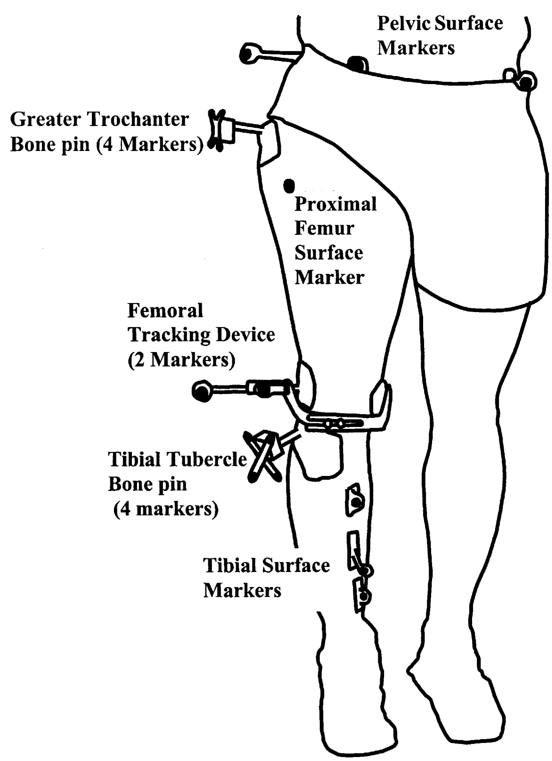

Fig. 1. The placement of the bone and surface mounted markers for experiment #1 are illustrated.

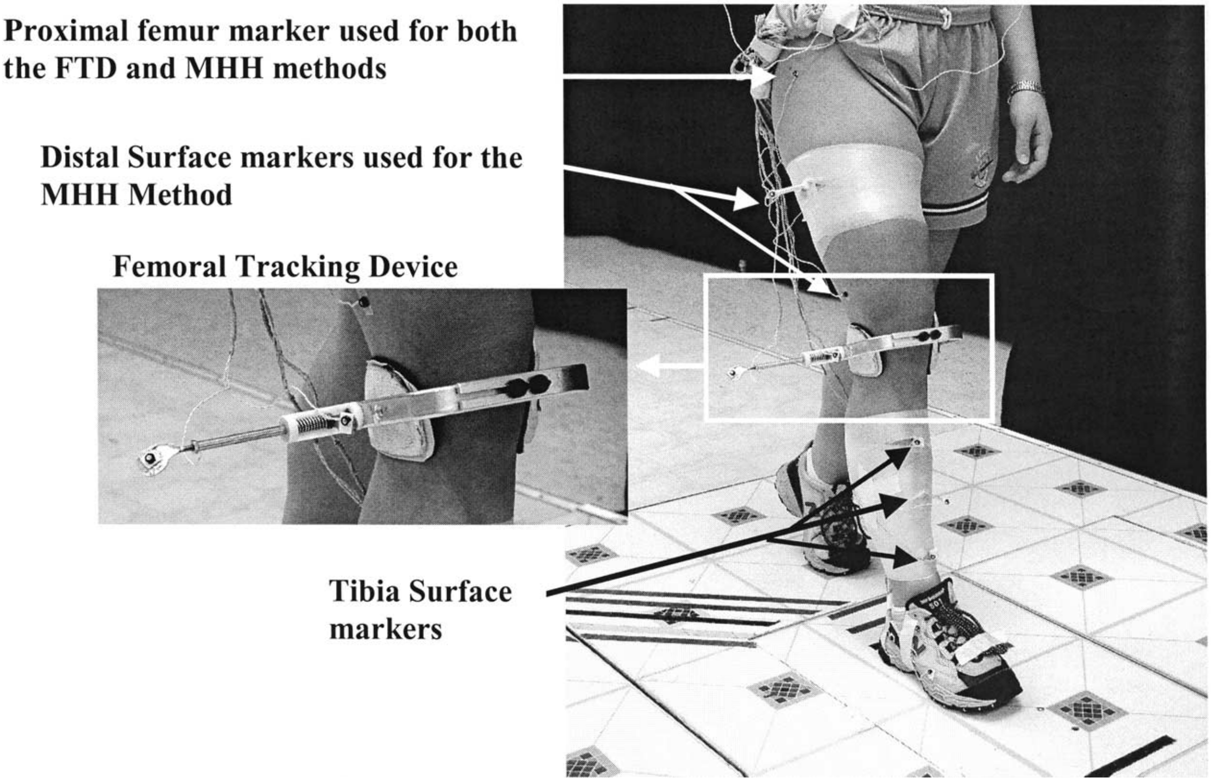

Fig. 2. An oblique lateral view of marker placements used for comparison of the FTD and MHH femoral tracking methods. The inset is a close up of the FTD.

placed 10 cm distal and anterior to the greater trochanter (Fig. 2). The frame of the FTD is made of 6.3-mm thick bar aluminum and is U shaped to allow for mounting of medial and lateral femoral condyle pads. The medial and lateral femoral condyle pads are constructed of plaster casting material molded to a generic model of the distal femur and padded with 6.3-mm dense foam. The medial pad is attached to the frame via a universal joint to allow different tilting angles for each subject and is fixed in place with a setscrew. The lateral pad connects to the frame via a 15-cm rod that has mounting brackets for the IREDS. The rod passes through a spring ($k = 7.5$ N/cm), contained in a plastic housing, and the aluminum frame via a brass bushing. The spring is configured to resist movement of the rod and apply pressure through the lateral pad. The distance between the medial and lateral pads, and hence the tension in the spring, is adjusted by altering the width of the frame via slots cut into the frame anteriorly. The 180 gm FTD device depends on appropriate pressure through the condyles as well as pad/condyle congruity to effectively track the condyles (Figs. 1 and 2). The tibial surface markers included three IREDS placed along the medial border of the tibia, with the middle marker mounted on a 10 cm wand made of hallow aluminum (Figs. 1 and 2). The surface and bone marker placements allowed for simultaneous recording during walking trials.

To describe the relative motion between the tibia and femur, the following reference frames were defined: the global reference frame, marker reference frames, and anatomic reference frames. The anatomic reference frames of the femur and tibia were established by digitizing bony landmarks relative to the marker reference frames of each segment [15]. The definitions of the anatomic reference frames relative to the marker reference frames are annotated in the Appendix A.

A standing trial with the subjects' feet placed in a jig aligned with the global anterior/posterior axis ($\mathbf{I}_{\text{global}}$) was used to establish marker reference frames for the bone mounted and surface femoral and tibial markers. The same procedures and digitized points were used to establish the anatomical reference frames, irrespective of the femoral and tibial tracking methods employed, ensuring differences were unique to the tracking method used. Studies using these methods show good reliability of patterns and peak amplitudes of tibiofemoral angles (ICC > 0.8) during walking [16,17], running [18] and a turning maneuver [16].

To obtain relative tibiofemoral angles the orientation matrix (a 3×3 matrix for each segment) of the femoral and tibial anatomic reference frame relative to the global reference frame was calculated from the filtered position data [19]. Once the orientation of the anatomic tibial and femoral reference frames were established relative to the global reference frame, the joint rotation convention proposed by Grood and Suntay [20] was used to resolve tibiofemoral orientation into the sagittal, frontal and transverse planes. Tibiofemoral displacement was calculated as the distance

Table 1
The average RMS and maximum differences in tibiofemoral orientations and displacement when using bone mounted and surface markers to track the tibia and femur

Marker sets compared		Differences in tibiofemoral orientation and displacement							
		Sagittal (°)		Frontal (°)		Transverse (°)		Displacement (mm)	
		RMS	Max	RMS	Max	RMS	Max	RMS	Max
Tibial surface+femoral surface subject #1	Tibial bone+femoral surface	0.9	1.4	0.6	1.1	0.5	1.0	1.9	3.9
Tibial surface+femoral surface subject #2	Tibial bone+femoral surface	0.6	1.4	0.8	2.6	3.2	4.2	1.5	3.7
Tibial bone+femoral surface subject #1	Tibial bone+femoral bone	1.1	1.5	1.3	2.3	0.9	1.8	10.0	14.7
Tibial surface+femoral surface subject #1	Tibial bone+femoral bone	1.3	2.2	1.5	2.7	1.0	1.8	9.0	13.9

Data are the average of three trials over the first 85% of stance for two individuals (subject 1 and 2). (Tibial surface, three tibial surface markers; femoral surface, femoral tracking method (2 markers) and greater trochanter marker; tibial bone, tibial bone mounted markers and femoral bone, femoral bone mounted markers).

between the two knee joint center locations estimated from the femoral reference frame and tibial reference frame.

Following insertion of the pins, subjects had a minimum of 30 min to accommodate to the testing situation, and traversed the walkway several (~10) times prior to participating in the data collection. Subjects did not complain of pain during the movement trials and appeared to walk normally. Three walking trials were collected at a self-selected walking speed (1.56 and 1.79 m/s) and subsequently used in the analysis.

To estimate errors in tibiofemoral orientations and displacements combinations of bone and surface markers were used (Table 1). To determine the errors from the tibia surface method, for both subjects, tibiofemoral orientations and displacements using tibial surface and the FTD method were compared to tibiofemoral orientations and displacements using the tibial bone and FTD method. To determine the errors from the FTD method for subject #1, the tibiofemoral orientations and displacements using the tibial bone markers and FTD method were compared to tibiofemoral orientations and displacements using the tibial bone and femoral bone markers. To determine the combined errors of the tibial surface and FTD method for subject #1, the tibiofemoral orientations and displacements using the tibial surface and FTD method were compared to tibiofemoral orientations and displacements using the tibia bone and femoral bone mounted markers.

The MHH tracking method [12] included the same proximal marker used for the FTD method (10 cm distal and anterior to the greater trochanter). The two additional markers included a marker placed on a 10 cm wand extending laterally from the mid thigh and a marker 5 cm proximal to the lateral femoral condyle (Fig. 2). The proximal and distal marker locations have been identified as sites with less skin artifact [2] than those originally proposed [12]. The same surface markers used in experiment one to track the femur (FTD method), constituted the second method to track the femur. Also, the same tibial surface markers were utilized as in experiment one. The instrumentation used and calculations of tibiofemoral angles and displacement were identical to experiment one.

For walking trials using only surface markers, subjects completed 5–10 practice trials before traversing a 15 m walkway at a speed of 1.34 m/s, controlled by having subjects keep pace with an overhead tracking system. In order to determine if wearing the FTD had any affect on walking patterns, eight subjects performed five walking trials without the FTD prior to data collection with the device. All successful trials required subjects to land naturally on a force plate (Kistler, Instrument Corp., Amherst, NY, Model 9865B) embedded in the floor. The FTD and MHH femoral tracking methods were compared by estimating tibiofemoral angles and displacement using surface tibial markers for the same walking trials.

3. Methods of experiment

3.1. Comparison of surface markers used to track the femur

Subjects included 13 healthy volunteers (6 women, 7 men) with an average mass of 76.9 ± 21.6 Kg, height 1.77 ± 0.13 m and age of 37.9 ± 13.1 years. Subjects were excluded if they had lower extremity pain or pathology; however, subjects of a wide range of heights (1.5–1.95 m), mass (40.9–122.7 kg) and age (21–59 y. o.) were recruited to gain an impression of how the femoral tracking methods perform across a variety of subjects.

4. Data analysis

The RMS and peak differences for tibiofemoral angles (sagittal, frontal and transverse) and joint displacement among sets of markers and the gold standard were estimated across stance and subsequently averaged for the three trials acquired with the subject walking with bone mounted markers for experiment one (Table 1). A component of experiment two included the effect of wearing the FTD on walking patterns ($n = 8$ subjects). The average RMS peak differences between the tibiofemoral angles with and without the FTD on were calculated using only the MHH tracking method. For hypotheses related to experiment two (the comparison of the FTD and MHH femoral surface markers) the tibiofemoral angles (sagittal, frontal and transverse) and displacement of the five walking trials were ensemble averaged across stance at 2% intervals for each subject. Subsequently, the average RMS difference for each point (2%) of stance was also calculated and compared for each plane of movement (sagittal, frontal and transverse). Paired t-tests were used to compare the average and maximum joint displacement over the first 85% of stance and over the entire stance phase. Significance was set at $\alpha = 0.05$ for each of the 3 t-tests performed.

5. Results

5.1. Experiment one: comparisons of surface and bone mounted marker sets

Initially the RMS errors using the FTD method were large ($>5°$) when calculated across stance. However, further examination of the patterns of errors suggested the large errors primarily occurred over the last 15% of stance (Fig. 3). Subsequently, the RMS differences in tibiofemoral angles were reported over the first 85% of stance, and were consistently $<2°$ irrespective of the various sets of surface markers used for subject #1 (Table 1). The highest RMS difference between the tibia bone mounted and surface markers for subject #2 were 3.2° with a maximum difference of 4.2°(Table 1). Comparisons of the joint displacement using the gold standard to joint displacement using surface markers resulted in RMS errors of <1 cm and a maximum error of 1.4 cm.

5.2. Experiment two: comparisons of femoral surface mounted marker sets

Comparison of tibiofemoral angles using the MHH method to track the femur with and without the FTD attached on eight subjects revealed average RMS peak differences of $1.6 \pm 0.3°$ in the transverse plane, $1.4 \pm 0.6°$ in the frontal plane and $1.7 \pm 0.5°$ in the sagittal plane. The mean correlation was 0.94 ± 0.04 in the transverse plane, 0.92 ± 0.06 in the frontal plane and 0.99 ± 0.02 in the sagittal plane.

Comparison of tibiofemoral angles using both the MHH and the FTD methods to track the same walking trials resulted in large RMS and peak differences across subjects in the transverse plane, with smaller differences in the frontal and sagittal planes (Fig. 4). The average RMS difference between the two tracking methods across subjects was $6.5 \pm 1.9°$ (range = 4–9°) in the transverse plane, $2.1 \pm 1.1°$(peak RMS difference $<3.5°$) in the frontal plane and $1.8 \pm 1.1°$(peak RMS difference $<2.5°$) in the sagittal plane. The average maximum differences across subjects were also greater for the transverse plane ($10.5 \pm 3.4°$, range = 6.0–17.3°) compared to the frontal ($3.6 \pm 1.5°$, range = 1.3–6.8°) and the sagittal ($3.1 \pm 1.7°$, range = 1.0–6.5°) planes. The patterns of average RMS differences for each point of stance also suggested larger differences in the transverse plane compared to the sagittal and frontal planes (Fig. 4). Examination of the patterns of tibiofemoral transverse plane angles using the MHH femoral tracking method suggests there is a large (≅5–15°) tibiofemoral internal rotation in early stance followed by an external rotation (≅0–10°) that peaks near 80% of stance (Fig. 5). In contrast to the MHH method, the tibiofemoral transverse plane angles using the FTD method suggests

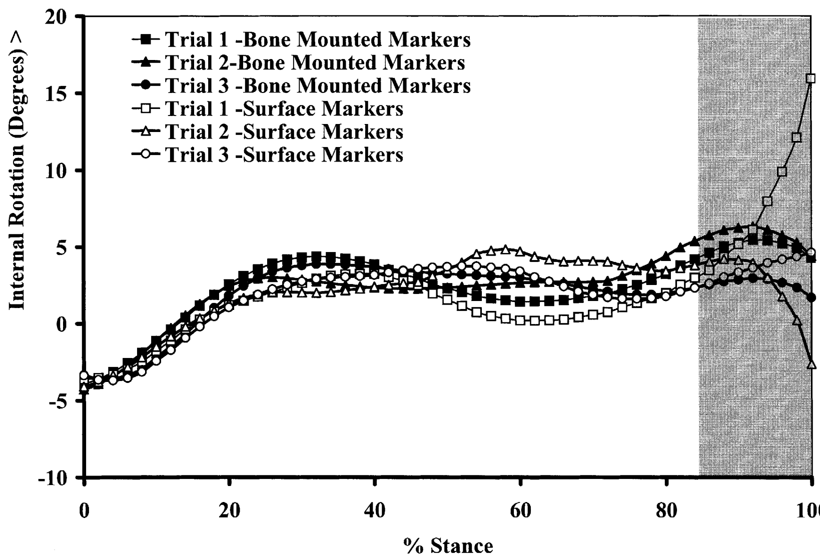

Fig. 3. The transverse plane tibiofemoral angles across stance estimated from the bone mounted markers (gold standard) and surface markers used to track the femur (FTD method) and tibia. There is close agreement except during the last 15% when large differences in tracking occur (shaded area).

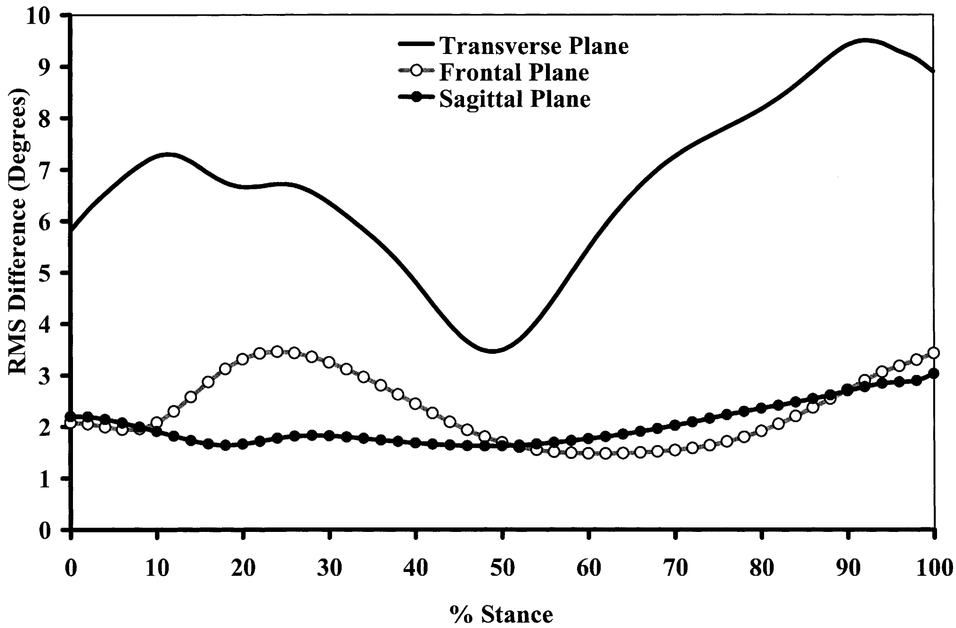

Fig. 4. The average RMS differences between the FTD and MHH femoral tracking methods in the tibiofemoral sagittal, frontal and transverse planes are plotted across stance ($n = 13$).

early stance is associated with a small (≅2–4°) tibiofemoral internal rotation (Fig. 5), followed by relatively little change in transverse plane angles.

In addition, the average joint displacements across 85% of stance were significantly ($P < 0.01$) greater using the MHH method (9.5 ± 2.4 mm) compared to the FTD method (4.6 ± 1.4 mm) (Table 2). The average maximum joint displacement was also significantly lower ($P < 0.01$) using the FTD method (8.4 ± 2.6 mm) compared to the MHH method (18.8 ± 5.7 mm) across the first 85% of stance.

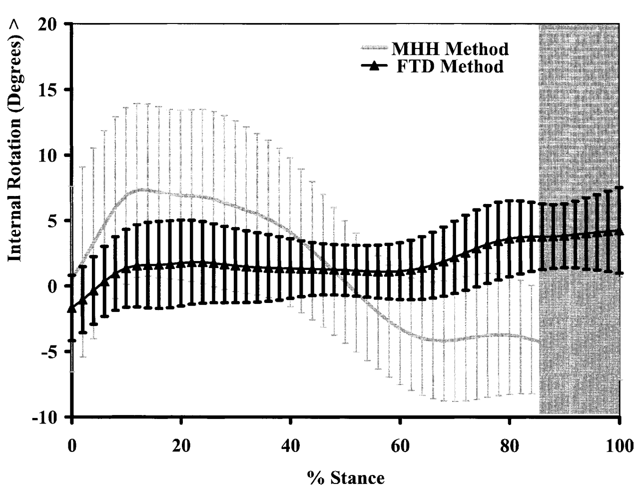

Fig. 5. The tibiofemoral transverse plane ensemble averaged angles ± 1 S.D. across stance using the MMH and femoral tracking (FTD) methods ($n = 13$).

6. Discussion

Previous studies report a range of errors using tibial and femoral surface markers to estimate tibiofemoral angles throughout stance [1–11]. Peak errors as high as 8° were reported using surface markers to track the transverse plane orientation of the tibia segment during swing [9] with smaller errors occurring during stance [9,10]. The maximum errors from 0 to 85% of stance found for our two subjects were 1° and 4.2° in agreement with previous studies that suggest low RMS errors of ≅3° and peak errors of < 5° [4,5] for tracking the tibia segment across stance.

Although some studies report movement of thigh surface markers relative to the femur [1,2,7], few studies [4,5,11] report the combined effect of tibia and femoral surface markers on tibiofemoral motion. Since the proximal thigh marker used in the current study is known to move relative to the bone [2], the improvements in tibiofemoral tracking are assumed to arise from utilization of the FTD device. The results for the FTD (Table 1 and Fig. 3) contrast with a previous study [5] that showed peak absolute errors in femoral tracking for the transverse plane of 5–10° during early to mid stance. The > 5° transverse plane errors during the last 15% of stance suggest movement of the femur relative to the FTD. The deep knee flexion associated with late stance possibly contributed to this error and is a limitation of using the FTD method, making the FTD method of questionable usefulness for swing phase kinematics. The ability to modify the lateral or medial pads to improve femoral tracking during late stance and swing is currently being investigated.

Table 2
The average and maximum tibiofemoral displacement for each subject for the first 85% of stance using the FTD and MHH are listed below

	FTD (mm)		MHH (mm)		Absolute differences (FTD–MHH)	
	Avg. ± S.D.	Max.	Avg. ± S.D.	Max.	Avg. ± S.D.	Max.
A	2.2 ± 0.7	3.4	11.9 ± 5.6	18.8	9.7 ± 5.3	16.3
B	3.4 ± 1.2	7.3	7.2 ± 2.4	13.2	3.9 ± 2.8	11.8
D	4.8 ± 1.4	7.0	5.6 ± 4.0	14.0	2.3 ± 1.8	7.8
E	6.8 ± 2.8	10.8	11.4 ± 5.8	25.7	4.7 ± 3.6	15.2
G	4.0 ± 1.5	10.1	7.6 ± 5.4	24.2	4.8 ± 5.0	20.5
I	3.8 ± 1.5	6.5	10.1 ± 4.6	16.3	6.3 ± 4.0	12.1
L	4.8 ± 1.9	9.4	9.5 ± 1.6	11.8	5.0 ± 1.6	7.4
N	6.4 ± 3.1	13.3	14.8 ± 5.8	23.5	8.5 ± 6.0	17.0
P	3.7 ± 1.3	5.9	8.7 ± 4.9	20.2	5.6 ± 4.4	15.1
R	5.1 ± 2.2	8.8	8.1 ± 2.5	11.2	3.1 ± 2.8	8.9
S	6.1 ± 1.7	8.7	9.8 ± 4.8	19.0	4.0 ± 3.4	14.0
T	3.7 ± 1.6	9.2	9.0 ± 6.3	28.0	6.0 ± 6.2	24.7
Avg. ± S.D.	4.6 ± 1.4	8.4 ± 2.6	9.5 ± 2.4	18.8 ± 5.7	5.3 ± 2.1	14.2 ± 5.1
Max.	6.8	13.3	14.8	28.0	9.7	24.7

The average and maximum absolute differences between the FTD and MHH methods are also listed. (Avg., average; S.D., standard deviation; max., maximum). * and bolded numbers indicate significance ($P < 0.05$) using a paired *t*-test.

The marked differences in the transverse plane between the MHH method and FTD method may result from improved tracking of the femur using the FTD method. A potential explanation of the large difference in the transverse plane angle patterns (average maximum differences = 10.5 ± 3.4°) between the FTD method and MHH method (Figs. 4 and 5) is that the FTD method is tracking the femur better. The similarity of transverse plane patterns using the FTD method and other studies using bone mounted markers [3,5] supports this possibility. This explanation is also supported by the results of experiment #1. However, studies suggest that individual surface tracking errors for tibia and femur segment orientations vary among subjects [2,4,9,13]. Therefore, errors obtained for the bone pin data on one subject may not reflect the possible tibiofemoral orientation errors across subjects. An example of this is the larger maximum errors for the tibia segment for subject 2 (4.2°) compared to subject 1 (1°) (Table 1). For this reason further comparisons of the FTD method and bone mounted markers are desirable to confirm the ability of the FTD method to track the femur, yet, understandably are difficult due the invasive nature of mounting bone markers.

Interestingly, some authors also suggested that soft tissue artifact errors may depend on the activity tested [2,7]. A previous study using the FTD and tibia methods of this study to track motion during hip internal/external rotation through 50° also showed errors in tibiofemoral orientations of < 3° [13], compared to errors of up to 7° reported for a similar movement in another study [2]. In a previous abstract of our preliminary results of experiment #1 [21] we also reported low errors (< 3°) in tibiofemoral angles during running for subject #1, further supporting the potential of the FTD and tibia methods to record tibiofemoral angles with in a similar margin of error across a variety of activities.

A limitation of using bone pins is the possible effects of the pins and anesthesia on walking performance. Reinschmidt et al. [5] compared knee angle data from surface markers before and after insertion of bone pins in 2 subjects during walking. The differences in knee angles across stance did not exceed 2.1° for abd/adduction, 4.8° for internal/external rotation and 4.5° for flexion/extension [5]. Qualitatively the subjects in the current study appeared to walk normally, which is consistent with Reinschmidt et al. [5]. Hence, while it is possible that the walking patterns of the subjects varied from normal, this would not affect the comparisons made among marker sets in experiment #1.

The FTD method when combined with the current tibial tracking method resulted in reasonable accurate representations of tibiofemoral angles (< 3°) across the first 85% of stance during walking in a single subject. In addition, the FTD tracking method consistently resulted in transverse plane knee angles that approximate results from studies using bone mounted markers [3,5] and therefore, is a potential alternative for those studies seeking to report transverse plane angles over the first 85% of stance. However, the differences between the MHH and FTD methods in the tibiofemoral sagittal and frontal planes were < 2° and < 4°, respectively, and therefore, either femoral tracking method may result in similar findings relative to these angles. The ability to more accurately track the femur has additional implications for obtaining better estimates of hip displacements, which may prove to be worthwhile.

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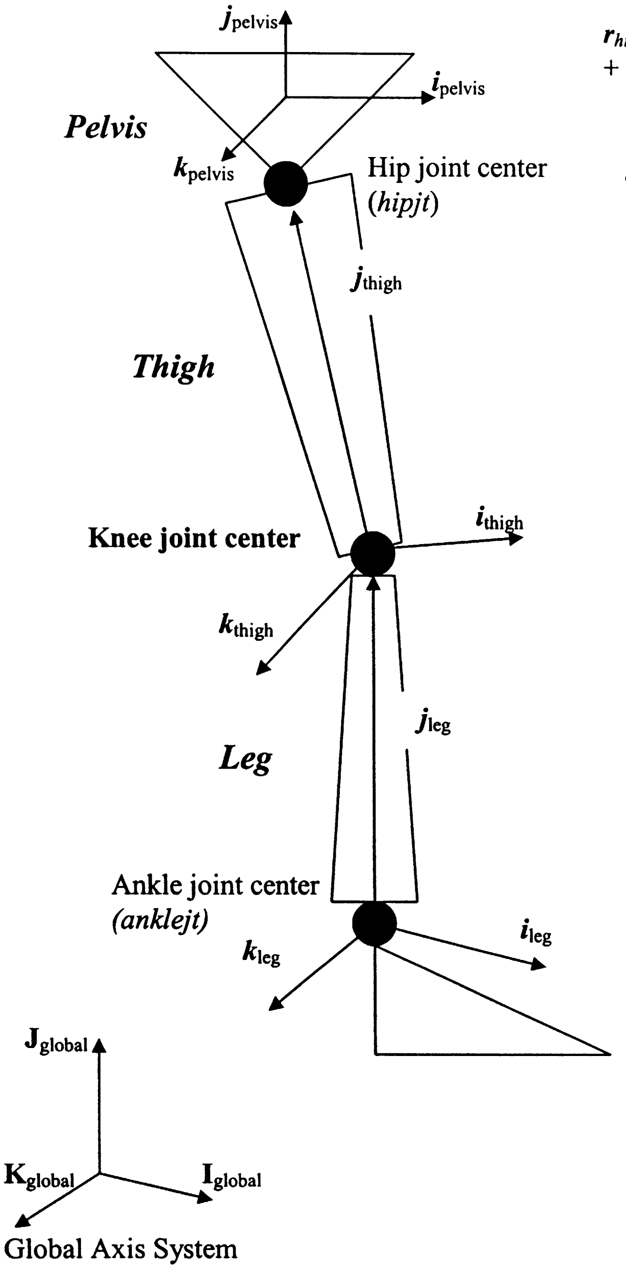
Appendix A



Hip Joint Center Estimate:

$$r_{hipjt/ASISpelvis} = (0.22 * \text{pelvicwidth}\ i_{pelvis} + 0.30 * \text{pelvicwidth}\ j_{pelvis} + 0.14 * \text{pelvicwidth}\ k_{pelvis})$$

Thigh Segment Anatomic Reference Frame:

$$j_{thigh} = \frac{(r_{hipjt/ThighIREDS} - r_{kneejt/ThighIREDs})}{|r_{hipjt/ThighIREDs} - r_{kneejt/ThighIREDs}|}$$

$$i_1 = I_{global}$$

$$k_{thigh} = \frac{(i_1 \times j_{thigh})}{|i_1 \times j_{thigh}|}$$

$$i_{thigh} = j_{thigh} \times k_{thigh}$$

Leg Segment Anatomic Reference Frame:

$$j_{leg} = \frac{(r_{kneejt/LegIREDs} - r_{anklej/LegIREDs})}{|r_{kneejt/LegIREDs} - r_{anklejt/LegIREDs}|}$$

$$i_2 = I_{global}$$

$$k_{leg} = \frac{(i_2 \times j_{leg})}{|i_2 \times j_{leg}|}$$

$$i_{leg} = j_{leg} \times k_{leg}$$

The figure above is a description of the anatomic reference frames established for the thigh and leg segments. The anatomic reference frame for each segment was established by digitizing points relative to reference frames constructed using sets of three infrared emitting diodes (IREDs) placed on each segment. The ankle joint center was estimated as the mid point between the medial and lateral malleoli. The knee joint center was estimated as the midpoint between the medial and lateral femoral condyles, and a displacement inferiorly (J_{global}) 2.5 cm to approximate the contact point between the femur and tibia. The 2.5 cm offset was established using magnetic resonance images and agrees with some published studies of the shape of the distal femur [22]. Further studies are necessary to scale this offset to various subjects. The ankle joint center was used as the origin of the leg segment and the knee joint center the origin of the femoral segment. In experiment one the same digitized points were used for different combinations of bone mounted markers and external marker sets.

Definition of terms

$\mathbf{r}_{\text{hipjt/ASISpelvis}}$	is the location (x, y, z) of the estimated hip joint center relative to the right anterior superior iliac spine (ASIS) expressed in the anatomic frame established for the pelvis.
Pelvic width	is the distance of the right ASIS to the left ASIS
$\mathbf{r}_{\text{hipjt/thighIREDs}}$	is the location (x, y, z) of the hip joint center estimated in the marker reference frame established from the thigh IREDs
$\mathbf{r}_{\text{kneejt/thighIREDs}}$	is the location (x, y, z) of the knee joint center estimated in the marker reference frame established from the thigh IREDs
$\mathbf{r}_{\text{kneejt/legIREDs}}$	is the location (x, y, z) of the knee joint center estimated in the marker reference frame established from the leg IREDs
$\mathbf{r}_{\text{Anklejt/legIREDs}}$	is the location (x, y, z) of the ankle joint center estimated in the marker reference frame established from the leg IREDs
$\mathbf{i}_n$, $\mathbf{j}_n$, $\mathbf{k}_n$	are the unit vectors of the anatomic reference frames established for each segment (n)
$\mathbf{I}_{\text{global}}$, $\mathbf{J}_{\text{global}}$, $\mathbf{K}_{\text{global}}$	are the unit vectors of the global or laboratory reference frame

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