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Research Article

An Approach to Measure Tibia Movements in Human Locomotion

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Abstract

Tibia movements in human gait are three-dimensional (3-D) motions including internal-external rotation, flexion-extension, and abduction-adduction. Due to the nature of marker locations, skin movement, and image lens distortion, it is difficult to accurately measure and assess tibia movements, especially the tibia rotation in a simple and practical way. The purpose of this study was to develop an accurate and simple method to measure 3-D tibia movements in human locomotion.

Three reflective markers formed the local horizontal (Y') axis and vertical (Z') axis and were fixed on a carton board (12 x 12 cm), which was attached to a mechanical segment or human tibia. The Z' axis was aligned to the longitudinal axis of mechanical segment or human tibia and used to determine the tibia flexion/extension and abduction/adduction. The X' axis was formed by the cross product of the unit vectors of Y' and Z' to indicate tibia rotations. A 3-D Qualisys motion capture system with two cameras was setup from the front to film (100 Hz) the mechanical segment (range, 0 to 90 degrees of the predetermined angles) and human tibia in walking and jogging.

The validity and reliability of measurements for the mechanical segment in 3-D represented by Pearson Product Correlation Coefficients (Rs) were statistically significant with all Rs being 1.000 (p < 0.01). The absolute errors between the preset and measured angles ranged from 0.00 degrees to 1.68 degrees including manual angle set, lens distortion, and computer automatic digitizing errors.

Therefore, this approach to measure human tibia movements has high validity and reliability and is simple and accurate for human locomotion research in clinical/sports settings.

Keywords: Angle; Measurement; Reliability; Three-dimension; Tibia; Validity

Introduction

The measurement of tibia rotation has been always a challenge in normal or pathological human locomotion research. Tibia movements in human gait are three-dimensional (3-D) motions including tibia internal-external rotation, flexion-extension, and abduction-adduction. However, due to the nature of the marker locations, skin movement, image lens distortion, and the anatomical structure and the movement of tibia in human locomotion, it is rather difficult to accurately measure and assess tibia movements, especially the tibia rotation in a simple and practical way. There are several studies which have attempted to assess the tibia rotation in human gait and each has some merits to the literature and helps us understand the tibia rotation in human gait [1-4].

Cornwall and McPoil [2] investigated the relationship between horizontal tibia rotation and rearfoot motion during the stance phase of normal walking. In their study, a tibia pointer device (consisted of a 25 x 25 x 25 mm aluminum block with two 110-mm aluminum rods positioned at a 90-degree angle to each other, and two reflective markers attached to the ends of each rod) was developed to measure tibia rotation in horizontal plane (Figure 1). This device was attached to the tibia tubercle with Velcro straps and the movement of the tibia pointer device was recorded by a video camera from the front. It was concluded that the rearfoot inversion-eversion and tibia rotation were highly related with $r = 0.953$, and a rigid orthotic produced a maximum internal tibia rotation of 13 degrees [2]. The measurement of tibia rotation with the tibia pointer device was a simple way to estimate tibia rotation during walking. However, this tibia pointer device was a two-dimensional measurement instrument which may not accurately represent the real tibia rotation when tibia flexion/extension and/or abduction/adduction occur simultaneously.

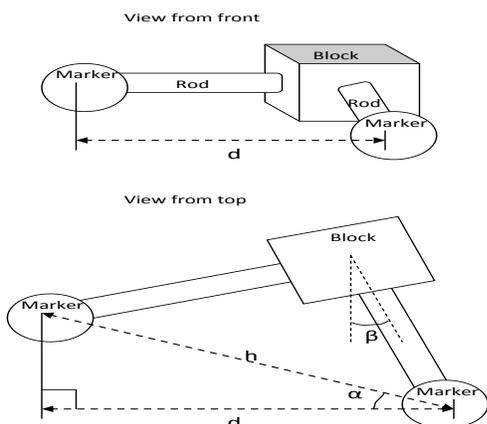


Figure 1. Two-dimensional measurement device of tibia rotation, where d is the perceived distance of vertical lines of two reflect markers from the video, h is the actual distance measured between two reflect markers, α is the angle defined by the relationship between h and d ($\alpha = \cos^{-1}(d/h)$), and β is the angle of tibia rotation ($\beta = 45^\circ - \alpha$).

A 3-D method was developed using angular displacements of the knee joint as a model with three noncollinear reflective marks on the femur and three on the tibia and fibula [5,6]. The femoral coordinate system was mathematically considered fixed so that the movement of tibia coordinate system was measured with respect to the femoral coordinate system, i.e., the tibia rotation (moving body rotation) relative to the femur (fixed body) from position 1 to position 2 was calculated using an Eulerian angle system [6]. The tested movement was performed by one participant who actively moved his leg from an initial position of knee flexion and internal rotation to a final position of full knee extension. The results showed approximately 21 degrees of external rotation, 64 degrees of extension and 6 degrees of abduction relative to femur [6]. This method provided a 3-D measurement about knee joint with reference to the femur including tibia rotation. However, the procedure for measuring 3-D angular displacements of the knee joint is somewhat difficult to follow since three coordinate systems including global and local coordinate systems were constructed in the model. As Wei et al. [6] pointed out that “Although this technique may produce mathematically error-free terms, the problem is that the terms are less easily understood by medical practitioners”. More importantly, the validity of the aforementioned techniques [2,6] for measuring tibia rotation has not been provided since it is rather difficult to validate human tibia rotation when “the true human tibia rotation” could not be predetermined.

Therefore, the purpose of this study was to develop an accurate and simple method to measure 3-D tibia movements including internal/external rotation, flexion/extension, abduction/adduction and to examine the validity and reliability of this method from a mechanical segment, and to determine the reliability of measurements in human tibia movements during the stance phase of walking and jogging.

Method

Experimental Setup

In order to measure tibia rotation in human gait, a minimum of three noncollinear points in a local reference coordinate system were used to attach to the tibia. This local reference coordinate system consisted of a 12 x 12 cm carton board (0.635 cm or 0.25 inches in thickness), three reflective markers (1 cm in diameter) adhered on the three corners of the carton board, and a 45-degree wooden block used to fill the partial gap between the tibia and the carton board. Three reflective marks were adhered to the carton board with 10 cm distances in the horizontal and vertical dimensions, and double side adhesive tape was used to fix the carton board to the right tibia with the two vertical reflective markers being positioned along the longitudinal axis of the tibia, and the two cameras were setup in front of (approximately 5 meters in distance) the mechanical

segment or the human tibia in Figure 2.

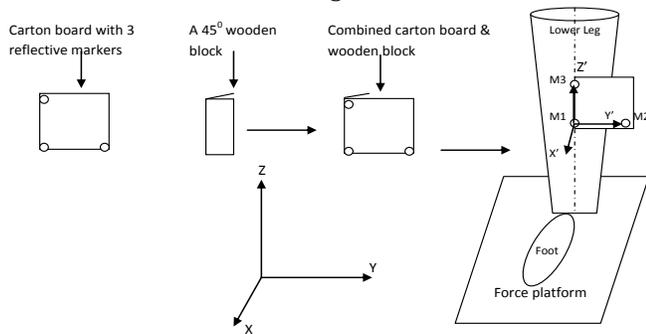


Figure 2. Illustration of tibia rotation measurement device with global coordinate system XYZ, and local coordinate system X'Y'Z', M1-marker 1, M2-marker 2, M3-marker 3.

In the local coordinate system, marker 1 is the origin, Y' axis was formed from marker 1 to marker 2 and is orientated from lateral to medial and perpendicular to the tibia, Z' axis was formed from marker 1 to marker 3 and was along and parallel to the longitudinal axis of the tibia. Then, X' axis which was an imaginary axis was generated by the cross product, $i = j \times k$ in equation (1) from the unit vectors Y' and Z', and was

$$j \times k = \begin{bmatrix} j & k & i \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} = \begin{vmatrix} 0 & 0 \\ 1 & 0 \end{vmatrix} j - \begin{vmatrix} 1 & 0 \\ 0 & 0 \end{vmatrix} k + \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} i = i$$

perpendicular to the plane formed by Y' and Z' axes and pointing from posterior to anterior. The unit vector i was always perpendicular to the tibia longitudinal axis and was used to indicate the tibia rotation. Then, the projection of the unit vector i on the X-Y plane (the horizontal plan) in the global coordinate system was used to determine the angle of tibia rotation at any given position with reference to the neutral standing position. The orientation of the Z' axis which was always parallel to the longitudinal axis of the tibia was used to determine the flexion/extension and abduction/adduction with reference to the global coordinate system XYZ (floor). The projection of Z' axis on X-Z plane of the global coordinate system was used to determine the tibia flexion/extension, and the projection of Z' axis on the Y-Z plane of the global coordinate system was used to determine the tibia abduction/adduction.

A 3-D imaging system (Qualisys AB, Gothenburg, Sweden) with two cameras was setup in front to film the tibia movements (. A force platform (Bertec Corporation, Columbus, OH) was synchronized with the imaging system by an external trigger to determine the stance phase during walking or jogging.

Experimental Procedure

Measurement of tibia movement from a mechanical segment

In order to examine the validity and reliability of this method in measuring tibia rotation, a mechanical segment with pre-determined angles of internal/external rotations, flexion/extension, and abduction/adduction was used. The mechanical segment was carefully set in 0 degrees, 15 degrees, 30 degrees and 45 degrees of internal/external rotations simultaneously with 0 degrees, 15 degrees, 30 degrees and 45 degrees of flexion/extension and abduction/adduction, respectively. The internal rotation, flexion and abduction were set to be negative and the external rotation, extension and adduction were set to be positive. The 3-D Qualisys imaging system with two cameras was setup in front to film the three dimensional positions of this mechanical segments at 100 Hz. Three trials at each combined angle condition were recorded and the same measurement procedure of the mechanical segment was repeated on the next day.

Measurement of tibia movements in walking and jogging

Two college students served as participants by signing consent forms approved by the university institutional review board for their voluntary participation. The aforementioned carton board local coordinate system and the 45 degrees wooden block were adhered to the right tibia of the participants by highly adhesive double-sided 3M tape. The two vertical reflective markers were positioned along the longitudinal axis of the tibia. The Bertec force platform was placed in the middle of a runway of 12 meters long and the two cameras was setup (the same sitting for the mechanical segment) in front and faced to the tibia. The participants performed self-paced walking and jogging on the runway. Each participant performed five trials of walking and jogging, respectively. Two stand trials per participant were also recorded and used as a baseline for tibia rotation. The data recording was set for 3 seconds at 100 Hz and was triggered before the participant's right heel touched the force platform during walking or jogging.

Data Analysis

Based on the data from heel strike to toe-off recorded from the force platform, the stance phase of the right leg was selected from the film data. Then, the data was automatically digitized and then smoothed by means of moving average technique [7]. A computer program was developed in Visual Basic in Excel to calculate tibia rotation, flexion/extension, and abduction/adduction for the mechanical segment and for tibias as well. The validity of the measurement of mechanical segment movements was examined between the preset angles and the calculated angles by means of Pearson Production correlation analysis, and reliability of the measurement was examined between the different days with intraclass correlation analysis. The human trials of stance phase identified through force platform were normalized. The normalization method was based on the approximation method which was dependent on linear

interpolation with the first, last and turning points being fixed [1,8]. Then, the reliabilities of the measurement of human 3-D tibia movements in walking and jogging were examined between the normalized trials by means of intraclass correlation analysis ($p < 0.05$).

Results

Validity and reliability of the measurements from the mechanical tibia segment:

The preset angles and measured angles by means of the cross product methods in terms of means and standard deviation for the mechanical segment in internal/external rotation, flexion/extension, and abduction/adduction are presented in Table 1.

Table 1. Means and standard deviation (SD) of mechanical segment of tibia in internal-external rotation, flexion-extension, and abduction-adduction in degrees.

Set Angles in Int/Ext Rot, Flex/Ext and Abd/Add	Day1 Measured Angles			Day2 Measured Angles		
	Int/Ext Rot	Flex/Ext	Abd/Add	Int/Ext Rot	Flex/Ext	Abd/Add
-45	-46.04	-46.49	-44.03	-46.12	-46.44	-46.59
-45	-46.17	-46.51	-43.95	-46.03	-46.68	-46.62
-45	-46.27	-46.46	-44.32	-45.72	-46.52	-46.63
-30	-30.74	-31.23	-29.54	-30.74	-30.7	-30.98
-30	-30.99	-31.19	-29.54	-28.99	-30.68	-30.81
-30	-30.36	-31.23	-28.89	-30.21	-30.09	-30.86
-15	-15.33	-16.56	-15.19	-15.35	-16.49	-16.55
-15	-16.01	-16.58	-15.22	-16.12	-16.52	-16.5
-15	-16.09	-16.52	-14.39	-15.86	-16.45	-16.48
0	-0.90	-0.80	0.12	-0.94	-0.8	0.12
0	0.71	-0.82	0.11	0.54	-0.76	0.13
0	0.65	-0.82	0.12	0.82	-0.81	0.17
15	13.76	14.84	14.66	13.8	13.83	13.80
15	15.64	14.81	14.67	15.56	14.82	13.82
15	16.68	15.06	14.40	16.6	14.81	13.36
30	30.55	30.62	30.05	30.92	30.62	28.71
30	28.49	30.68	30.11	28.45	30.58	28.77
30	31.35	30.58	29.10	31.47	30.28	28.80
45	46.13	45.13	44.93	45.55	44.64	45.23
45	46.47	45.10	45.00	45.44	44.19	45.26
45	46.09	43.98	44.04	46.09	44.82	45.25
Absolute difference in mean	0.98	0.70	0.44	0.90	0.57	0.63
Absolute minimum difference	0.33	0.06	0.00	0.21	0.09	0.12
Absolute maximum difference	1.68	1.58	1.11	1.6	1.68	1.64
Correlation coefficients (R) between set angles and measured angles	1.000**	1.000**	1.000**	1.000**	1.000**	1.000**
R ² between set angles and measured angles	1.000**	1.000**	1.000**	1.000**	1.000**	1.000**
Correlation coefficients between the measurements in Day1 and Day2	-----	-----	-----	1.000**	1.000**	1.000**
R ² between the measurements in Day1 and Day2	-----	-----	-----	1.000**	1.000**	1.000**

$n = 21$, negative values are internal rotation, flexion and abduction and positive values are external rotation, flexion and abduction, int/ext rot --- internal/external rotation, flex/ext --- flexion/extension, abd/add --- abduction/adduction.

** --- Significant at $p < 0.01$ level.

flexion/extension and abduction/adduction were all statistically significant with $R = 1.000^{**}$ ($p < 0.01$), and $R^2 = 1.000$.

The correlation coefficients representing the validity between the preset angles and measured angles from the mechanical segment in a range of -45 degrees to 45 degrees in internal/external rotation, flexion/extension and abduction/adduction were all statistically significant with $R = 1.000^{**}$ ($p < 0.01$), and $R^2 = 1.000$. The absolute errors between the present angles and measured angles in internal-external ranged from 0.21 degree to 1.68 degrees, in flexion-extension from 0.06 degree to 1.68 degrees, and in abduction-adduction from 0.00 degree to 1.64 degrees, respectively.

The correlation coefficients representing the reliability of the tests of the mechanical segment between Day 1 and Day 2 in internal/external rotation.

Reliability of the measurements from human tibias in walking and jogging

The average trial-to-trial intraclass correlation coefficients in walking and jogging are presented in Table 2. The average correlation coefficients between the trials from these two participants in walking and jogging ranged from 0.992** to 1.000** ($p < 0.01$) in tibia flexion/extension, from 0.789** to 0.990** ($p < 0.01$) in tibia abduction/adduction, and from 0.764** to 0.957** ($p < 0.01$) in tibia internal/external rotation, respectively.

Table 2. Average trial-to-trial intraclass correlation coefficients among three trails in walking and jogging from two human participants.

	Flexion/extension	Abduction/adduction	Internal/external rotation
Walking			
Participant 1	0.996**	0.990**	0.835**
Participant 2	0.999**	0.989**	0.955**
Jogging			
Participant 1	1.000**	0.815**	0.957**
Participant 2	0.992**	0.789**	0.764**

** --- Significant at $p < 0.01$ level.

Discussion

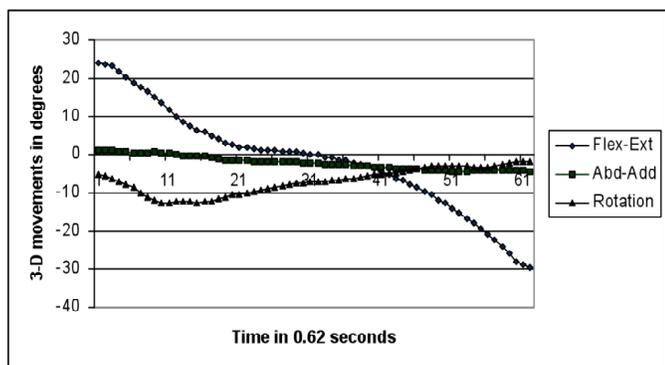
This study was to develop an accurate and simple method to measure three dimensional tibia movements including internal/external rotation, flexion/extension, abduction/adduction with reference to floor (global coordinate system) to examine the validity and reliability from a mechanical segment and to

determine the reliability of the measurement of human tibia movements during the stance phase of walking and jogging.

The validity of this measurement method used in mechanical segment was proved significantly high with $R=1.000^{**}$ and $R^2 = 1.000^{**}$ ($p < 0.01$) in all 3-D motions: tibia flexion/extension, abduction/adduction and internal/external rotation. The results of correlation coefficients demonstrated that the preset angles for the mechanical segment can be accurately measured by the aforementioned three-point technique. $R^2 = 1.000^{**}$ meant that the total variations (changed angles in the range of 90 degrees in 3-D) in the preset angles are 100% consistent with the variations in the measured angles of the mechanical segment [4]. Furthermore, the absolute error between the preset angles and measured angles were less than 2 degrees (in the range from 0.00 degrees to 1.68 degrees) and these errors included manual angle set error, lens distortion error, and computer reflective marker automatic digitizing error. The validity of the other measurement techniques [3,7] in human tibia rotation has not been reported since it is rather difficult to validate human tibia rotation when “the true human tibia rotation” could not be predetermined. The results of the reliability (Table 1) of the measurements of the mechanical segment between the different days indicated the present measurement technique was highly consistent and replicable with $R=1.000^{**}$ ($R^2=1.000^{**}$).

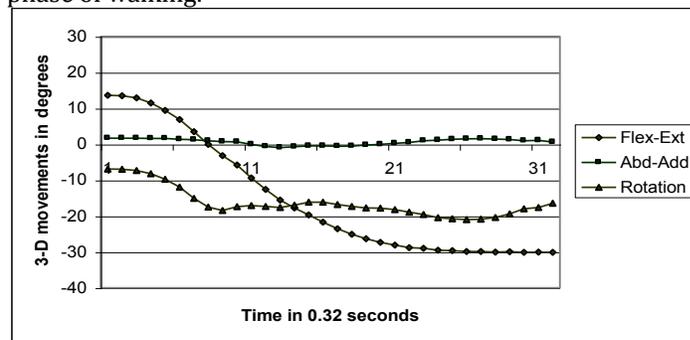
The reliabilities of human trials in walking and jogging represented by the trial-to-trial intraclass correlation coefficients were highly consistent. The intraclass correlation coefficients in 3-D tibia movements were ranged from 0.835** to 0.999** in walking and 0.764** to 1.000** in jogging (Table 2). The high reliabilities demonstrated that this measurement technique is consistent and replicable in the applications of human walking and jogging.

A typical trial of 3-D ranges of motion of the tibia in the stance phase of walking and jogging is presented in Figure 3. It is shown that the tibia started with extension and internal



a. Three-dimensional ranges of motion of tibia in the stance

phase of walking.



b. Three-dimensional ranges of motion of tibia in the stance phase of jogging.

Figure 3. Ranges of motion of tibia flexion/extension, abduction/adduction and internal/external rotation in the stance phase of walking and jogging.

rotation, and ended with flexion and external rotation in the stance phase of walking or jogging. The total ranges of motion of the tibia in Figure 3 had 54 degrees (30 degrees flexion and 24 degrees extension) in flexion/extension, 10 degrees (2 degrees to 12 degrees) in internal rotation in walking, and 44 degrees (30 degrees flexion and 14 degrees extension) in flexion/extension, and 15 degrees (7 degrees to 22 degrees) in internal rotation in jogging. The maximum internal tibia rotation during normal walking has been reported to be 13 degrees in literature [3]. Furthermore, the results demonstrated that the tibia had small ranges of motion (3 degrees to 5 degrees) in abduction/adduction in walking and jogging (Figure 3).

Summary

In summary, the measurement technique developed in this study is a simple and accurate approach to measure the tibia movements in human locomotion. However, the limitation of this technique was that the contribution of femur to tibia rotation cannot be determined since the tibia was the only segment being measured. It is possible to use the similar technique to measure the 3-D movements of the femur. Therefore, it is concluded that the present approach to measure tibia movements, especially in tibia rotation had high validity and reliability since the carton board attached to the tibia reduced the error of skin movement and the markers were aligned along the longitudinal axis of tibia, and this simple and accurate tibia movement measurement method is an ideal option for human locomotion research in clinical and sports settings.

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