

## Original article

# Three-dimensional lower extremity alignment in the weight-bearing standing position in healthy elderly subjects

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## Abstract

**Background.** Although assessment of lower extremity alignment is important for the treatment and evaluation of diseases that present with malalignment of the lower extremity, it has generally been performed using only plain radiographs seen in two dimensions (2D). In addition, there is no consensus regarding the criteria for quantitative three-dimensional (3D) evaluation of the relative angle between the femur and tibia. The purpose of this study was to establish assessment methods and criteria for quantitatively evaluating lower extremity alignment in 3D and to obtain reference data from normal elderly subjects.

**Methods.** The normal alignment of 82 limbs of 45 healthy elderly subjects (24 women, 21 men; mean age 65 years, range 60–81 years) was analyzed in 3D with regard to flexion, adduction–abduction, and rotational angle of the knee in the weight-bearing, standing position. The obtained computed tomography (CT) and biplanar computed radiography (CR) data were used to define several anatomical axes of the femur and tibia as references.

**Results.** In the sagittal plane, the mean extension–flexion angle was significantly more recurvatum in women than in men. In the coronal plane, the mean 3D hip–knee–ankle angle was more varus by several degrees in this Japanese series than that in a Caucasian series reported previously. Regarding rotational alignment, the mean angle between the anteroposterior axis of the tibia and the transepicondylar axis of the femur in this series was slightly larger (externally rotated) than that of previously reported Japanese series examined in the supine position.

**Conclusions.** These data are believed to represent important references for 3D evaluation of morbid lower extremity alignment in the weight-bearing, standing position and are important for biomechanical research (e.g., 3D analyses of knee kinematics) because the relative angles between the femur and tibia are assessed three-dimensionally.

## Introduction

Lower extremity alignment is determined by both the spatial relation between the femur and tibia and by the geometry of these bones. Assessment of lower extremity alignment is important when determining and evaluating treatment for diseases that present with abnormal alignment in the lower extremities, such as knee and hip arthritis, patellar dislocation, and congenital malalignment.<sup>1–13</sup> In the field of orthopedic surgery, lower extremity alignment is generally assessed two-dimensionally (2D) on plain radiographs using the hip–knee–ankle angle or the tibiofemoral angle in the coronal plane alone.<sup>11,14,15</sup> However, 2D radiographic measurements are affected by the position of the radiation source and the orientation of the subject's pelvis and lower extremities.<sup>16</sup> Therefore, the accuracy and reproducibility of this method are insufficient for detailed investigations. In addition, rotational alignment cannot be assessed on plain radiographs.

Despite remarkable recent developments in medical imaging technologies that enable visualization of the three-dimensional (3D) geometry of bone and alignment of the lower extremity, few studies have reported quantitative 3D evaluations of lower extremity alignment in the weight-bearing, standing position using 3D digital bone models. In addition, there remains a lack of consensus regarding the criteria for quantitative 3D assessment.

As previously reported, we developed a method for assessing 3D lower extremity alignment in the standing position using 3D digital bone models; this system has been in clinical use since 2002.<sup>17,18</sup> To evaluate morbid alignment in the lower extremities of patients with hip and knee arthritis and other diseases, it is vital to obtain normal data of lower extremity alignment from healthy subjects as a reference. One of the purposes of this study was to obtain these reference data by

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quantitative, 3D evaluation of lower extremity alignment in healthy elderly subjects so we could compare them with data from osteoarthritis patients' alignment, thereby increasing our knowledge of the clinical state of the disease in future research. Another purpose was to establish the criteria for these evaluations.

## Materials and methods

This study was performed according to the protocol approved by the investigational review board of our hospital and Niigata University. All subjects gave informed consent to participate in this study.

### Subjects

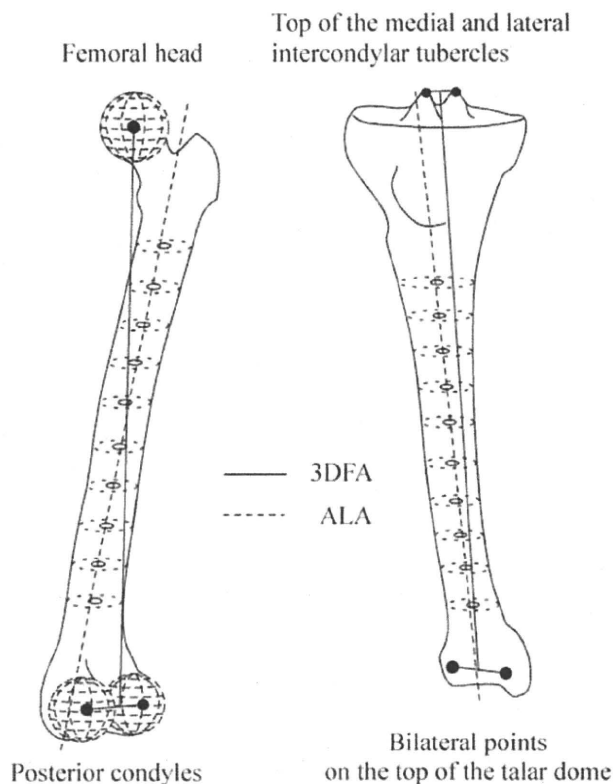
We assessed 82 limbs of 45 healthy elderly subjects (24 women, 21 men; 37 bilateral and 8 unilateral) who had no pain, history of trauma, knee injury, knee complaints, or radiographic abnormality in the lower limb; they also had no osteoarthritis or rheumatoid arthritis. Unilateral data had been previously collected for another study, and the subjects' opposite lower limbs did not have any of the above-mentioned disorders. The average age of the subjects was 65 years (range 60–81 years).

### Three-dimensional digital bone models

Computed tomography (CT) scans with a 2-mm interval were obtained of the femur and tibia of each subject. A 3D digital model of each femur and tibia was reconstructed from the CT data using 3D visualization and modeling software (Zedview; LEXI, Tokyo, Japan) and displayed as a point group. The anatomical coordinate systems were established using 3D model digitizing software (Model Viewer; LEXI) according to the method of Sato et al.<sup>17,18</sup> (Fig. 1). Several anatomical reference points (described below) were digitized, and the reference axes used in the present study were then installed.

### Three-dimensional image-matching procedure

Biplanar computed radiography (CR) images of the subjects' lower extremities were obtained in the weight-bearing, standing position with the knee fully extended and toes in the neutral position using the 3D lower-extremity alignment assessment system previously reported.<sup>17–19</sup> These images were downloaded to a personal computer. Using the camera calibration technique,<sup>17</sup> we projected the cited 3D digital bone models onto the biplanar CR images by matching the silhouettes of the digital models to the contours of the respective CR bone images via 3D rotation and translation.



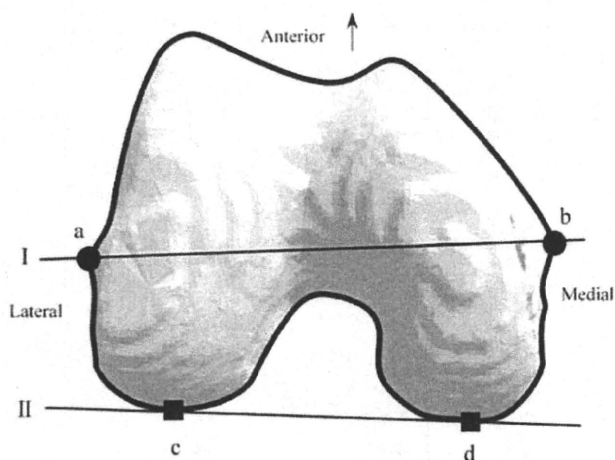
**Fig. 1.** Bony reference points and anatomical axes defined on the femur and tibia. *Continuous lines*, three-dimensional functional axes (3DFA) [11]; *dotted lines*, anatomical longitudinal axes (ALA)

After these image-matching procedures, a 3D view of the digital bone model that accurately reproduced the spatial relation between the femur and the tibia at the time of CR projection was displayed; and all alignment parameters (described below) were automatically calculated. The maximum spatial errors of this procedure were 0.5 mm when determining distance and  $0.8^\circ$  when determining orientation.<sup>17</sup> The maximum errors in the proposed image matching procedure for determining the relative pose and position between the femur and tibia were 1.6 mm distance and  $1.5^\circ$  orientation.<sup>19</sup> With regard to the reproducibility of the calculated angles, the maximum interobserver error, including all processes of the analysis, was  $1.9^\circ$ , and the maximum intraobserver error was  $0.8^\circ$ .

### Definitions of anatomical parameters

#### Anatomical axes

For true 3D evaluation of lower extremity alignment, the anatomical reference axes themselves must also be defined in 3D. To define the anatomical longitudinal axes of the femur (ALA-f) and tibia (ALA-t) in 3D, a

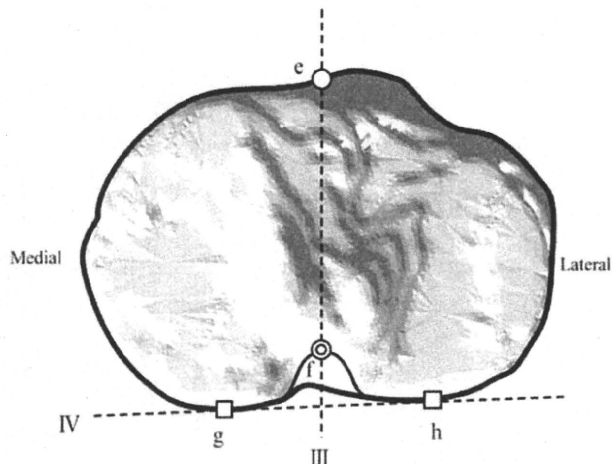


**Fig. 2.** View of the distal femur. *a, b*, prominences of the medial and lateral femoral epicondyles; *c, d*, posterior-most points of the medial and lateral femoral condyles; *I*, clinical transepicondylar axis (CTEA); *II*, femoral posterior condylar axis (PCA-f)

point group centroid was calculated automatically for the 10 respective cross-sectional planes that divide the diaphysis into 11 equal sections. The ALA was defined as a regression line obtained from approximating distances from these 10 centroids by the least square method (Fig. 1). The 3D functional axes of the femur (3DFA-f) and tibia (3DFA-t) were defined according to the method proposed by Sato et al.<sup>18</sup> 3DFA-f was defined as a line connecting the center of the femoral head and the midpoint of the spheres that represent the medial and lateral posterior femoral condyles. 3DFA-t was defined as a line connecting the midpoint of the eminences of the medial and lateral tibial spines and the center of the ankle joint. Additional axes were defined to assess rotational alignment. For the femur, the posterior condylar axis (PCA-f)<sup>20,21</sup> was defined as a line connecting the posterior-most points of the medial and lateral femoral condyles; and the clinical transepicondylar axis (CTEA)<sup>22,23</sup> was defined as a line connecting the prominences of the medial and lateral epicondyles (Fig. 2). For the tibia, the posterior condylar axis (PCA-t)<sup>24</sup> was defined as a line connecting the posterior-most points of the medial and lateral tibial condyles. The anteroposterior axis of the tibia (APA-t)<sup>25</sup> was defined as a line connecting the anterior-most point of the tibial insertion of the posterior cruciate ligament (PCL) and the medial edge of the tibial tubercle<sup>26</sup> projected onto the axial plane of the tibial coordinate system (Fig. 3).

#### Extension–flexion angle

The anatomical extension–flexion angle of the knee was defined in two ways: (1) as the angle between ALA-f and ALA-t projected onto the sagittal plane of the



**Fig. 3.** View of the proximal tibia. *e*, medial edge of tibial tubercle; *f*, anterior-most point of insertion of the posterior cruciate ligament; *g, h*, posterior-most points of medial and lateral condyles. *III*, anteroposterior axis of the tibia (APA-t); *IV*, tibial posterior condylar axis (PCA-t)

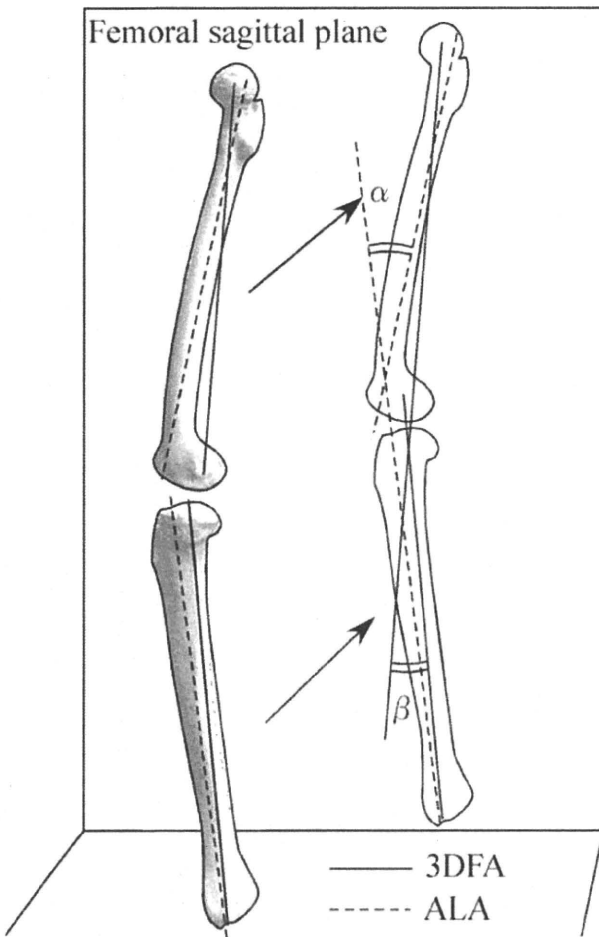
femoral coordinate system, termed the 3D anatomical flexion angle (3DAFA); and (2) as the angle between 3DFA-f and 3DFA-t projected onto the same plane, termed the 3D mechanical flexion angle (3DMFA) (Fig. 4). We believe that these angles are each alternative for conventional parameters for evaluating limb alignment: 3DAFA is the 3D version of the definition of knee flexion angle, which is generally utilized for clinical examination; and 3DMFA is the 3D and sagittal version of the conventional hip-knee-ankle angle (HKA).

#### Adduction–abduction angle

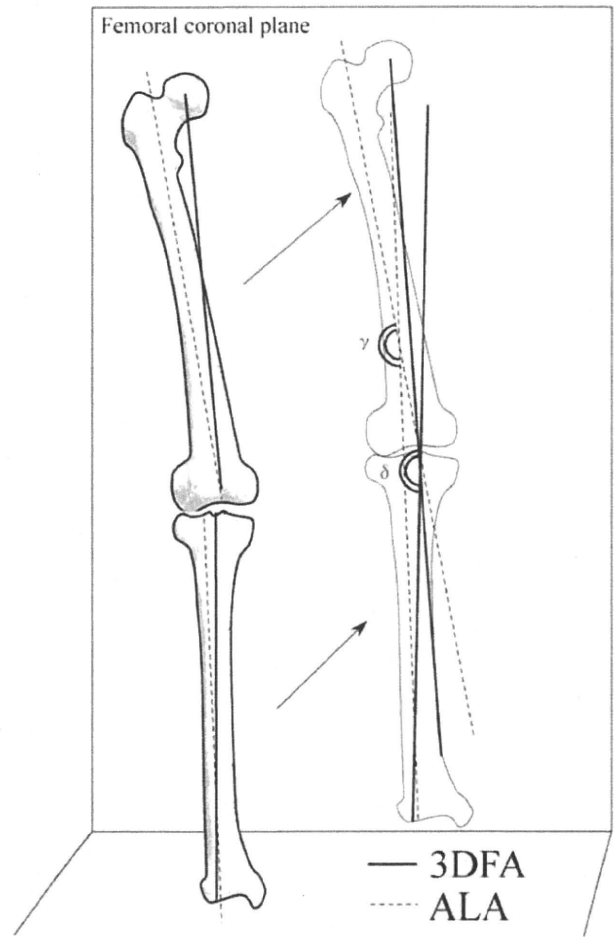
The adduction–abduction angle was also defined in two ways: (1) as the angle between ALA-f and ALA-t projected onto the femoral coronal plane, termed the 3D tibiofemoral angle (3DTFA); and (2) as the angle between 3DFA-f and 3DFA-t projected onto the same plane, termed the 3D hip-knee-ankle angle (3DHKA) (Fig. 5). These two angles are literally 3D versions of TFA and HKA, respectively.

#### Rotational angle

The relative rotational angle between the femur and tibia at the knee joint was defined in two ways: (1) as the angle between PCA-f and PCA-t projected onto the axial plane of the femoral coordinate system, termed the posterior rotational angle (PRA); and (2) as the angle between CTEA and APA-t projected onto the same plane, termed the functional rotational angle (FRA). We defined PRA as a stable angle for accurate assessment, such as motion analysis. FRA was defined particularly for considering the target alignment of the implants of total knee arthroplasty (Fig. 6).



**Fig. 4.** Reference axes projected onto the femoral sagittal plane.  $\alpha$ , 3D anatomical flexion angle (3DAFA), defined as the angle between the ALA-f and ALA-t;  $\beta$ , 3D mechanical flexion angle (3DMFA), defined as the angle between 3DFA-f and 3DFA-t



**Fig. 5.** Reference axes projected onto the femoral coronal plane.  $\gamma$ , 3D tibiofemoral angle (3DTFA), defined as the angle between the ALA-f and ALA-t;  $\delta$ , 3D hip-knee-ankle angle (3DHKA), defined as the angle between the 3DFA-f and 3DFA-t

#### Statistical analyses

Differences in all of the angles for sex were assessed using Student's *t*-test, with the level of significance set at  $P < 0.05$ . The associations between each plane were investigated using regression analysis.

#### Results

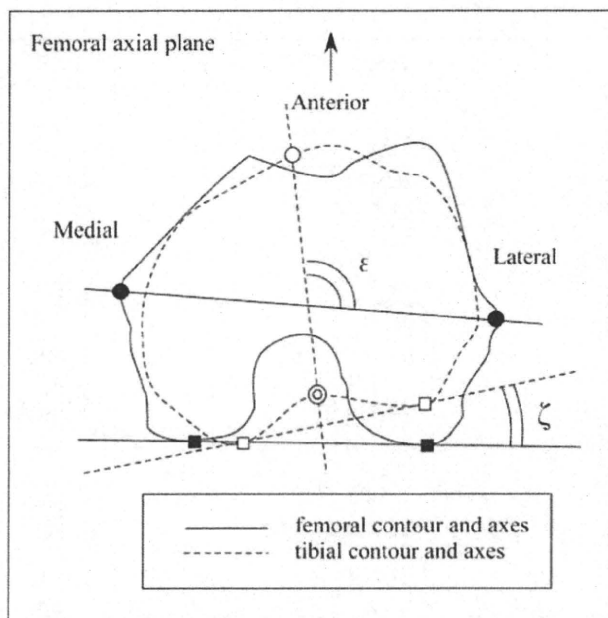
The mean value and standard deviation of each parameter are described in Table 1. Both of the extension-flexion angles (3DMFA and 3DAFA) were significantly ( $P = 0.03$ ) lower (genu recurvatum) in women than in men; in contrast, no difference was found for adduction-abduction or rotational angles with regard to sex. There were no significant correlations between any

combinations of three planes with either of the total or by sex. Although all the angles demonstrated near-normal distributions, wide variations were shown for all angles.

#### Discussion

We conducted a 3D assessment of alignment of the lower extremities in healthy subjects in weight-bearing, standing position using an anatomical coordinate system established by various bony landmarks on 3D digital bone models. The use of 3D digital models reconstructed from CT data enabled accurate assessment of several clinically important bony landmarks, including the femoral epicondyles and insertion of the posterior cru-





**Fig. 6.** Reference axes projected onto the femoral axial plane.  $\epsilon$ , functional rotational angle (FRA), defined as the angle between the PCA-f and PCA-t;  $\zeta$ , posterior rotational angle (PRA), defined as the angle between the CTEA and APA-t

ciate ligament (PCL), which are particularly useful for evaluating rotational alignment between the femur and tibia. Cooke et al.<sup>14</sup> also reported a 3D evaluation of lower extremity alignment in the standing position using a similarly calibrated frame but without utilizing the 3D geometry of bone; thus, the important landmarks described above could not be evaluated and accurate evaluation of rotational alignment could not be achieved. Taking into account that recent remarkable development in CT and magnetic resonance imaging (MRI) technology enables accurate 3D information of bone geometry to be obtained relatively easily, we think that it is reasonable to use this 3D information for precise evaluations of lower extremity alignment.

Regarding the definitions of the parameters for alignment evaluations, all angles that describe a relative angle between the femur and tibia were projected onto respective planes of the femoral coordinate system in the present study. Although it was a relatively complicated procedure, we believe that all angles should be projected onto the planes of any anatomical coordinate system of the subject's own bone, and that it was the only way to eliminate the measuring errors caused by the postures of the subjects and the positions of the radiation sources used for conventional 2D evaluation by plain radiography.<sup>16</sup>

Although we found no previous studies that reported evaluation of lower extremity alignment using the same

3D concept as that proposed in the present study, several authors have reported their findings of entire lower extremity alignment in each plane, as follows. With regard to sagittal alignment, Minoda et al. were the first to report a 2D evaluation<sup>10</sup> of healthy subjects in the standing weight-bearing position; they used lateral plain radiography, which revealed a knee flexion angle of  $0.8^\circ \pm 4.2^\circ$  (range  $-6.2^\circ$  to  $9.2^\circ$ ). Compared with the results of their study, the mean 3DMFA in the present study is slightly more recurvatum, probably reflecting differences in the definitions of the reference axes in the two studies: In the present study, all reference axes were defined three-dimensionally, whereas in Minoda's study they were defined two-dimensionally. Another factor possibly reflecting the difference in the results between the two studies was that they used the fibula as the lower limb axis, whereas we used the tibia (ALA-t). With regard to differences between the sexes, our results found significantly more extension (genu recurvatum) in women, as reported by Nguyen and Shultz.<sup>27</sup> We believe that the results of the present study regarding the knee extension-flexion angle (e.g., 3DAFA and 3DMFA) may be used as reference data when evaluating the knee flexion angle anatomically in such situations as knee motion analysis or accurate clinical assessment of range of motion.

Regarding coronal alignment, Moreland et al. reported that the mean knee adduction-abduction angle measured on plain long-leg anteroposterior radiography was  $178.5^\circ$  for the right and  $178.9^\circ$  for the left.<sup>11</sup> Cooke et al. also reported coronal alignment of the lower extremity as the HKA angle in healthy subjects in the standing position<sup>14</sup> and described almost the same alignment as that reported by Moreland et al. Compared with these studies, the mean adduction-abduction angle (3DHKA) in the present study was slightly greater (genu varum). The results of coronal alignment (3DHKA and 3DTFA) in the present study were almost the same as the results of two previous studies<sup>13,28</sup> that reported coronal alignment of lower extremities in Asian populations. Therefore, we believe that the difference in coronal alignment between the results of our series and that of Moreland et al.'s study reflected a racial difference, rather than a difference in the methodologies.

Akagi et al.<sup>26</sup> measured the rotation angle of the knee joint in healthy subjects in the supine position, reporting a value of  $0^\circ \pm 2.8^\circ$  (range  $-6.3^\circ$  to  $5.2^\circ$ ). Compared with this previous study, the results of the present study show slightly greater external rotation of the tibia against the femur, probably reflecting differences in the definitions of the reference axis of the femur and in the subjects' posture in the two studies. In the Akagi et al. study, the surgical transepicondylar axis<sup>26</sup> (SEA) — defined as the line connecting the sulcus of the medial epicondyle and

**Table 1.** Angles: means, standard deviations, and ranges

Parameter	Male	Female	Total
Age			
Mean	65.6	64.8	65.1
SD	5.0	5.0	5.0
Range	60–74	60–77	60–77
Extension–flexion angle (°)			
3DAFA			
Mean	6.1	4.0	5.0
SD	5.1	6.0	5.6
Range	–6.5 to 5.1	–6.8 to 6.0	–6.8 to 18.3
3DMFA			
Mean	–2.2	–5.1	–3.8
SD	5.3	6.0	5.9
Range	–15.7 to 5.3	–15.5 to 6	–15.7 to 9.7
Adduction–abduction angle (°)			
3DTFA			
Mean	177.5	176.6	177
SD	2.5	2.5	2.5
Range	172.1–182	171.7–182	171–182
3DHKA			
Mean	181.8	181.8	181.8
SD	2.2	2.6	2.4
Range	177.8–186.5	176.6–188.4	176.6–188.4
Rotation angle (°)			
PRA			
Mean	–1.4	–2.6	–2.1
SD	6.9	6.4	6.6
Range	–14.1 to 12.1	–14.8 to 14.3	–14.8 to 14.3
FRA			
Mean	87.3	84.4	85.7
SD	4.5	6.0	5.1
Range	70.5–104	62.5–99.1	64.9–106.0

AFA, anatomical flexion axis; MFA, mechanical flexion axis; TFA, tibiofemoral angle; HKA, hip-knee-ankle angle; PRA, posterior rotation angle; FRA, functional rotation angle

the lateral epicondyle — was utilized, whereas the CTEA was utilized in the present study because the sulcus of the medial epicondyle was sometimes not present.<sup>29</sup> With regard to the subject's posture, the present study is the first in which the relative rotational angle between the femur and tibia was assessed in the weight-bearing, standing position with the knee fully extended; this angle was assessed in the supine position in the previous studies. Therefore, we believe that the tibia was more externally rotated against the femur in this position than in the supine position, achieving "screw-home movement" during terminal extension of the knee.<sup>30</sup>

Throughout the results, the present study shows marked variability among individuals, and there was no clear correlation between each plane. These facts suggest the difficulty of anticipating entire limb alignment from one parameter in any plane. Assessment of each parameter is thought to be required for detail inspections.

There were several limitations in this study. First, the number of subjects was relatively small because it was difficulty finding a large number of volunteers of the required age who were healthy and who were willing to

undergo a CT scan of the entire lower extremity. A larger number of subjects is considered necessary to provide more reliable reference data. Second, the radiation dose delivered during this procedure was higher than that for a plain radiograph because CT scanning was used. New methods for producing 3D digital bone models from images taken by other radiation-free devices, such as MRI, are currently under development. Finally, the definition of "healthy" subjects in this study was based on our subjective determinations. It is possible that subjects who did not have any pain or disease in the lower extremity during the period of this research may develop disease later. Elderly subjects were investigated in this study because we thought that the above possibility would be reduced if the ages of the subjects were relatively high.

In the present study, normal alignment of the lower extremities was analyzed in three dimensions in the weight-bearing, standing position using several anatomical axes defined three-dimensionally. We also suggested definitions of anatomical extension–flexion, adduction–abduction, and rotational angle of the knee, which were then measured three-dimensionally in

healthy subjects. These data are believed to represent important references for determining the above angles in 3D knee motion analysis and in other accurate evaluations regarding 3D knee alignment.

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# 全身振動刺激装置を用いた トレーニングが筋力と筋量に及ぼす影響

Effect of whole body vibration training on muscle strength and lean body mass

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キー・ワード : whole body vibration, muscle strength, lean body mass

全身振動刺激, 筋力, 筋量

〔要旨〕 全身振動刺激トレーニング(WBVT)が筋力と筋量に与える影響について検討した。健常男子大学生20名を対象とし、無作為に WBVT 実施群と非実施群に分け、12週間のトレーニング導入前後の下肢等速性・求心性筋力および下肢筋量について比較、検討を行った。その結果、WBVT 実施群に筋力、筋量とも若干の増加が認められたが、有意な差は見られなかった。運動選手に対する WBVT 効果について、今後さらにトレーニング強度や期間を再検討し、継続して調査を行う必要がある。

## ■ 緒 言

全身振動刺激トレーニング(Whole Body Vibration Training : WBVT)は、振動板の上に立つことによって身体機能を向上させるトレーニング方法である。振動板の上に立つことで加えられる振動刺激は、筋の反射性収縮を誘発し、運動効果をもたらすと考えられており、これまでは高齢者の運動機能向上や転倒予防トレーニングとしての報告が多かったが、近年は、スポーツ競技における新しいトレーニングとして導入され始めている。トレーニング効果の即時的な報告では、身体の血液循環が促進され、筋柔軟性が向上したとする報告<sup>1)</sup>や、神経筋協調性の改善に対する効果の報告<sup>2)</sup>などが見られる。一方、筋力についてはト

レーニング期間や評価項目も様々であり、効果に相違が見られる<sup>3~7)</sup>。また若年健常人に対する報告は少なく、トレーニングによる筋量の変化は明らかとなっていない。今後、トレーニング処方に活用するためにも筋力と筋量の関連を明らかにする必要があると考えられる。そこで本研究では、健常成人男性に対して WBVT を実施し、筋力と筋量の変化を調べ、その有効性を検討することを目的とし、トレーニングの実施による影響について分析を行った。

## ■ 対象と方法

### 1. 対 象

運動部所属の健常男子大学生20名(年齢 $20.8 \pm 1.2$ 歳; 平均 $\pm$ 標準偏差)を対象とした。これらを、通常練習内容に加え WBVT を実施する者10名(以下 WBVT 群)と、通常練習のみで WBVT を実施しない者10名(以下非実施群)の2群に無作為に分類した。このうち、測定開始後に試合等で外傷発生し、トレーニング継続不可能になった3

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表1 対象者の身体特性

	WBVT 群 (n = 9)	非実施群 (n = 8)	p-value
身長(cm)	171.6±2.7	169.5±5.3	n.s
体重(kg)	67.6±7.7	68.4±8.4	n.s
BMI(kg/m <sup>2</sup> )	23.0±2.6	23.7±1.8	n.s

平均値±標準偏差

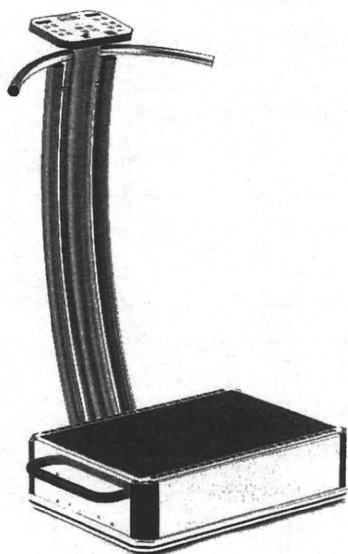


図1 振動刺激装置  
G-Sport® (Novotec Medical GmbH,  
Germany).

名を除いた17名を今回の分析対象とした(表1)。  
対象者には研究概要の説明を口頭および文書にて

行い、同意を得た上で測定を行った。

## 2. 方法

### a. 使用機器

使用機器は振動刺激トレーニング装置 G-Sport® (Novotec Medical GmbH, Germany) とした。本装置の振動板は正中部を中心に左右交互に振動する。被験者は振動板上で姿勢を維持する。そこで振動刺激による緊張性収縮が促進され、高頻度で筋収縮の学習効果を得ることができる。振動周波数は5～30Hzで変更可能で、振幅は開脚幅を変えることによって調整することができる(図1)。

### b. トレーニング内容

振動板上における姿勢保持および動作は先行研究<sup>1)</sup>に準じ、以下の6課題を設定した。①②18Hz, 26Hzの2種類の周波数を用いた30秒間軽度膝関節屈曲位の閉脚静止立位保持, ③26Hz, 60秒間軽度膝関節屈曲位の開脚静止立位保持, ④26Hz, 60秒間の静止スクワッティング保持, ⑤26Hz, 60秒間で4秒に1回膝関節屈曲60°までの反復スクワッティング動作, ⑥左右各30秒間のフォワードランジ姿勢保持(図2)。振動板上の開脚位置は中心から左右32cmの幅(振幅: 6mm, 最大変位: 12mm)で統一した。

トレーニング期間は12週間、頻度は週3回、1回の実施時間は5分とし、対象者の部活動練習時間の前後いずれかに WBVT を行うものとした。対象者の部活動における練習内容は特に指定せず、2群とも同じ練習を実施した。

- ①閉脚静止立位(軽度膝屈曲): 18Hz, 30秒保持
- ②閉脚静止立位(軽度膝屈曲): 26Hz, 30秒保持
- ③開脚静止立位(軽度膝屈曲): 26Hz, 60秒保持
- ④静止スクワッティング: 26Hz, 60秒保持
- ⑤反復スクワッティング(膝関節60°屈曲)を4秒に1回, 26Hz, 60秒間
- ⑥フォワードランジ姿勢保持(左右): 26Hz, 各30秒間

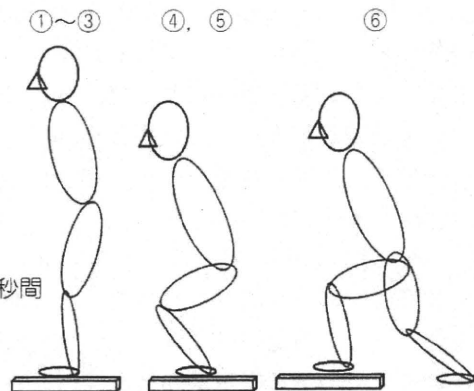


図2 実験試技  
WBVT 群に上記プログラムを実施した。



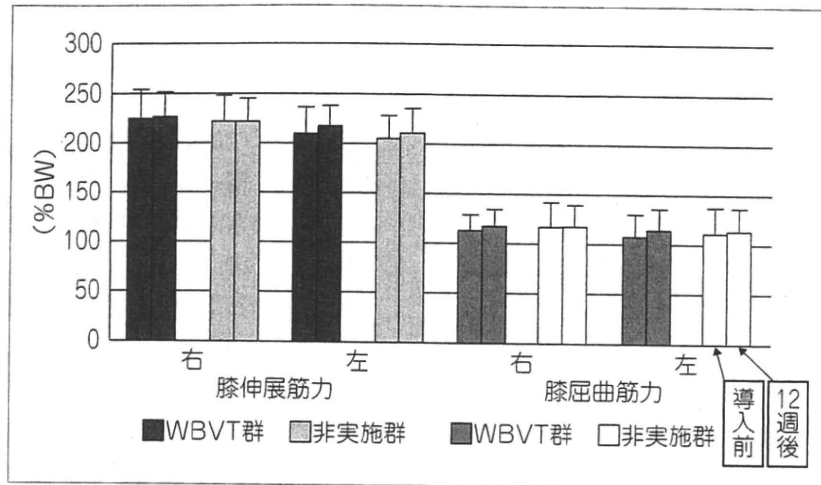


図3 各群のWBVT導入前後における体重比膝屈伸筋力(180°/sec)の比較

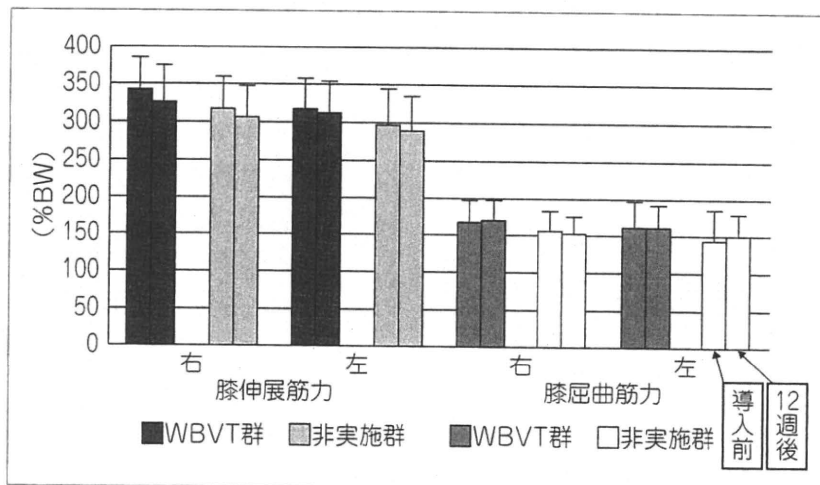


図4 各群のWBVT導入前後における体重比膝屈伸筋力(60°/sec)の比較

### c. 評価項目

筋力は角速度60°/秒および180°/秒における等速性・求心性筋力とし、膝関節屈曲・伸展最大トルクとした。測定にはBIODEX SYSTEM3(BIO-DEX社製)を使用した。下肢筋量の測定には、QRP4500A(HOLOGIC社製)を使用した。各評価項目は、対象者全員に対し、トレーニング導入前および12週間後に計測した。分析にあたり、膝屈伸筋力値および下肢筋量について、得られた計測値を対象者の体重で除した値を用いた。

### d. 統計処理

得られた値について、WBVT群、非実施群の2群間で比較・検討を行った。2群間における筋力、筋量の検定にはウィルコクソン符号付順位和検定を用いた。有意水準は5%とした。

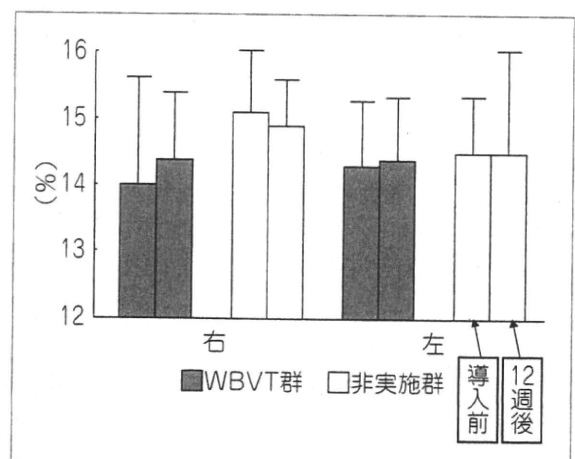


図5 各群のWBVT導入前後における体重当たり下肢筋量の比較

## ■ 結 果

体重当たり膝屈伸筋力について、角速度 $180^{\circ}/\text{秒}$ では膝関節屈曲・伸展とも WBVT 群においてトレーニング導入前に対する12週後の値は増加していたが、有意な差はみられなかった(図3)。一方、角速度 $60^{\circ}/\text{秒}$ では12週後の値は両群とも減少する傾向がみられたが、有意な差はみられなかった(図4)。

体重当たり下肢筋量は、WBVT 群においてトレーニング導入前に対する12週後の値は増加していたが、有意な差はみられなかった(図5)。

## ■ 考 察

全身振動刺激トレーニング(WBVT)では、筋収縮に対する身体の反射的な作用により、その効果が得られると言われている。微細振動が与えられた筋は感覚受容器からの信号によって緊張性の筋収縮を引き起こすと考えられており、筋緊張性反射や緊張性振動反射(Tonic Vibration Reflex: TVR)と呼ばれる。緊張性振動反射により、収縮筋の持続的収縮と、拮抗筋の筋活動の抑制が生じる<sup>8)</sup>。

これまで、WBVT による即時的な効果として筋血流量の増加による柔軟性の向上や、筋出力の増加を認めるとする報告<sup>1,2)</sup>、筋温上昇によるウォーミングアップ効果<sup>9)</sup>などが報告されている。また中・長期間の振動刺激トレーニング効果に対する先行研究では、健常男性に対する11週間の WBVT 実施において、筋力・ジャンプ力に有意な変化を認めない<sup>6)</sup>との報告がある一方、運動習慣のない若年健常女性に対する12週間の WBVT 実施において、筋力に有意な増加を認めたとの報告<sup>5)</sup>や、若年スキー選手に対する6週間の WBVT 実施において、下腿後面筋力の有意な増加を認めたものの姿勢保持については変化を認めないとする報告<sup>10)</sup>などがある。これらは、対象者の性別、年齢や競技種目、全身振動刺激を伴うトレーニングの内容や種類、あるいは運動経験などにおいて様々であり、未だ見解の一致を見ない。

今回、運動部所属の健常成人男性に対し、12週間の WBVT の効果について筋力、筋量における検討を行った。まず、筋力では膝関節屈伸角速度 $180^{\circ}/\text{秒}$ において、体重当たりの膝関節屈曲・伸

展筋力に若干の増加が見られたが、有意な差は認められなかった。角速度 $60^{\circ}/\text{秒}$ よりも $180^{\circ}/\text{秒}$ の増加が大きかったことについて、振動トレーニングで生じる収縮は緊張性振動反射によるものであり、反射で優先的に用いられる組織は速筋線維であることから、速い動きに対応する筋出力が増加したものと考えられる。また、筋力トレーニングでは、その初期において筋収縮に参加する筋線維数の増加により神経筋活動が改善し、その後、筋線維の肥大により発揮筋力が増大するとされている<sup>11)</sup>ことから、今回の結果はトレーニング強度と頻度が、筋肥大効果を得るための刺激に至らなかったものと考えられる。またトレーニング導入方法に関して、今回は時間帯の指定をせず、通常の練習内容に WBVT を加え実施したが、WBVT 群では通常練習後に WBVT を実施する対象者が多かった。そのため、筋疲労後の振動刺激による微細血流量増加に伴う筋のリラクセーション効果の影響が生じたことも考えられる。しかしながら WBVT 群に若干でも増加が見られたことは、今後トレーニングの強度や頻度を検討することでスポーツ選手へのトレーニング効果が得られる可能性を示唆している。一方、筋量に関しては、著しい増加は認められなかった。筋量の増加は筋線維の肥大と筋線維数の増加によるとされており、筋肥大は6～8週以降に生じやすいとの報告があるものの、アイソメトリック筋活動の時間と強度の両者に依存する<sup>12)</sup>ことから、今回の設定はトレーニング期間として肥大が可能な期間であったが、強度や頻度の設定では筋量増加に対する影響が少なかったものと考えられる。

また、今回の測定において、トレーニング方法はクローズドキネティックチェーン(CKC)である一方、筋力測定はオープンキネティックチェーン(OKC)であり、単純な等速性・求心性筋力測定だけでは筋力増強効果が評価しにくいことも考慮する必要がある。したがって、今後、WBVT を用いたトレーニング方法や評価方法などを検討し、さらに WBVT が筋力と筋量に与える効果を検証する必要があると考える。

## ■ 結 語

健常男子大学生17名に対する12週間の WBVT の効果を検証した。筋量、筋力とも若干増加が見られたが、有意差は認めなかった。今後、トレ

ニング強度や期間を検討し, WBVT の身体効果を明らかにする必要がある。

# 謝 辞

今回の研究にあたり, (株)エルクコーポレーションのご協力を頂きましたこと, 厚く御礼申し上げます。

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## Effect of whole body vibration training on muscle strength and lean body mass

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**Key words** : whole body vibration, muscle strength, lean body mass

**[Abstract]** This study aimed to investigate 12 weeks of whole body vibration training (WBVT) in healthy subjects. Twenty subjects were divided into two groups at random : normal practice with the whole body vibration training group (WBVT group, n = 10) and only normal practice group (control group, n = 10). The WBVT group trained three times a week and continued for twelve weeks. After the exercise program, 8 in the WBVT group and 9 in the control group remained. For the subjects, lower muscle strength and lean body mass of the lower extremities were measured before the start of the experiment and after 12 weeks. No significant difference was observed though the numbers of the WBVT group increased slightly regarding muscle strength and lean body mass. In conclusion, effectiveness of the vibratory stimulation in increasing lower muscle strength and lean body mass could not be clarified. It is necessary to verify the effect continuously in the future.

## 関節鏡視下手術支援システムを用いた大腿骨孔位置の決定

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谷藤 理<sup>※5</sup> 佐藤 卓<sup>※5</sup> 古賀 良生<sup>※5</sup>

Determination of the femoral tunnel placement using a navigation system for arthroscopic surgery.

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Osamu TANIFUJI, MD., Takashi SATO, MD., Yoshio KOGA, MD.

### Abstract

We developed a navigation system for arthroscopic surgery so that operators could intuitively understand preoperative planning during surgery. In order to establish such a system, we have been developing a system of superimposing 3D bone-models reconstructed from preoperative tomographic images upon the arthroscopic image on a real-time basis. Such superimposition facilitates visualization of surgical planning using the intraoperative arthroscopic image if it is incorporated into the bone model before surgery. The present study evaluated the overall accuracy of the superimposing system using a cadaveric knee. For accuracy verification, we placed a target point in the femoral tunnel for anterior cruciate ligament reconstruction. In experiments, a metal pin was used as the target point. The position of the pin superimposed upon arthroscopic image of the joint filled with saline was measured by using a measuring probe. Experiments showed that the error of the target evaluated as the distance between the actual point and the measured point was 1.95 mm on average, suggesting that our system has the potential to be applied to the navigation for arthroscopic surgery. Future challenges are to improve the overall accuracy and to introduce MRI models of the cartilage into the system.

Key words : arthroscopic surgery, computer-assisted orthopaedic surgery, accuracy verification, cadaveric experiment.

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ができる。それを実際の鏡視画像にオーバーレイ表示する(図2)。

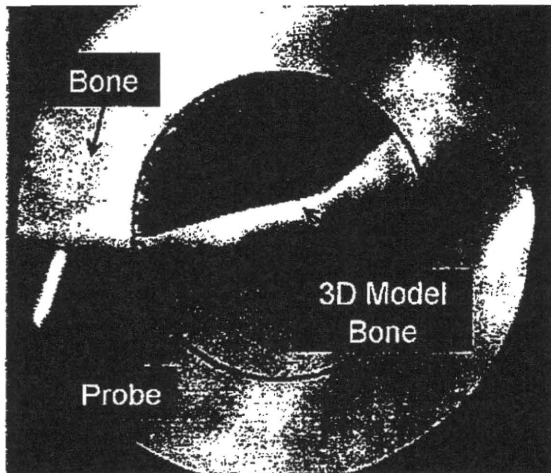


図2. Superimpose display in which a computer model of the bone was superimposed over the actual bone surface on a real-time basis.

## 2. 関節鏡カメラ校正

カメラ校正では、関節鏡の内部変数(焦点距離、画像の歪み)と外部変数(ワールド座標系に対するカメラの位置・姿勢)を求める必要がある。我々は、関節鏡先端と校正ボード間を水で満たした校正装置を製作した(図3)。校正ボードには、直径1mmの鋼球マーカを3mm間隔で7×7個配置した。校正用の3次元点列は7×7×6点とし、それらは、精密移動ステージでボードを面に垂直な方向に5mm間隔で25mm並進移動して作成した。ワールド座標系は、移動ステージ上に設定し、それに対する鋼球マーカの座標を三次元座標測定器(FALCIO-Apex707, MITUTOYO社, 神奈川)で測定した。3次元点列を関節鏡で撮影し、その鏡視画像をDVカメラ(DCR-TRV20, SONY社, 東京)を介してコンピュータに取り込んだ。次に画像中で鋼球マーカを手動デジタルサイズし、画像座標系における2次元座標を求めた。内部・外部変数の推定には、中村らのカメラ校正法<sup>7)</sup>を用いた。校正誤差(面内での2次元距離)は平均 $0.09 \pm 0.003\text{mm}$ であった。

## 3. 3次元骨モデルの作成と座標系の設定

3次元骨モデルは、CT撮像データから専用

ソフトウェアZed View (LEXI社, 東京)を用いて作成した。撮影装置はSENSATION16 (SIEMENS社, Germany)を使用し、スライス間隔は1.0mmとした。

骨モデルの解剖学的座標系 $\Sigma_{Ana}$ は、我々が従

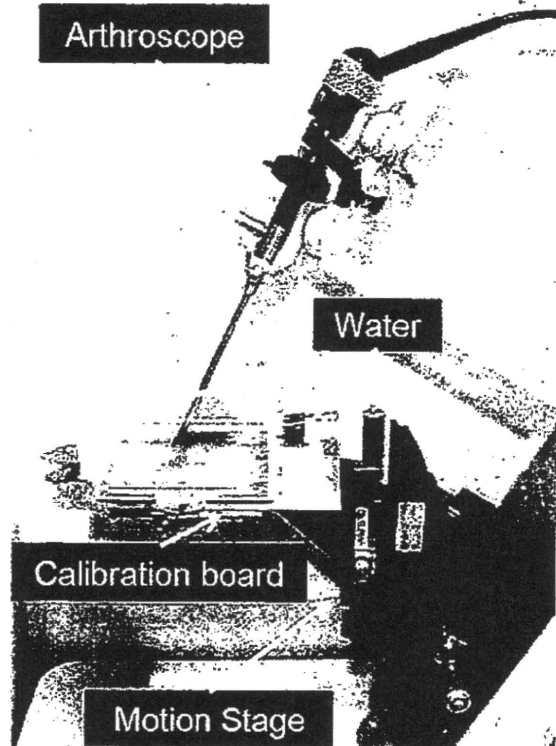


図3. Camera calibration unit.

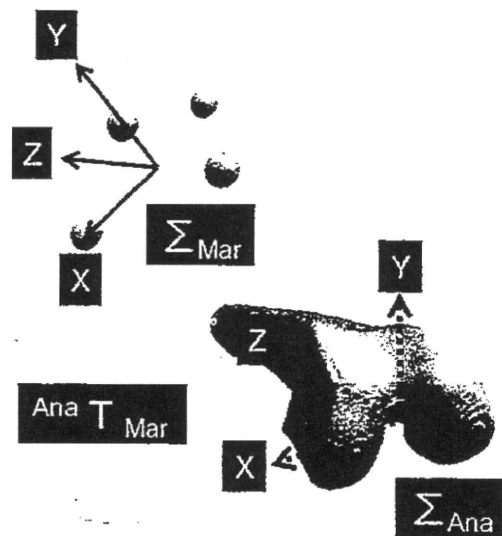


図4. 3D-bone model and coordinate systems :  ${}^{Ana}T_{Mar}$  denotes the coordinate transform for  $\Sigma_{Ana}$  to  $\Sigma_{Mar}$ .

来から用いてきた座標系<sup>3)</sup>にできるだけ近くなるように任意に設定した(図4). 座標系の設定には, 専用ソフトウェアModel Viewer (LEXI社, 東京)を用いた.

#### 4. レジストレーション

レジストレーションでは, 実空間における3次元骨モデルの位置・姿勢を推定する. そのためには, 前述の $\Sigma_{Ana}$ から骨に設置したマーカ上に設定した座標系 $\Sigma_{Mar}$ への座標変換 ${}^{Ana}T_{Mar}$ を求めればよい. レジストレーション手法は, 2方向透視X線画像と3次元骨モデルを用いた2D/3Dレジストレーションとした.

レジストレーション手順を以下に示す. まず骨及びマーカを2方向透視X線撮影 (ARTIS dTA, SIEMENS社, Germany) し, 撮影時を再現する仮想空間を設定する. 次に, マーカの3次元位置を2つの透視画像から推定し,  $\Sigma_{Mar}$ を設定する. 仮想空間に骨モデルを呼び込み, 2D/3Dレジストレーションを用いて透視X線像に骨モデルの仮想投影像を重ね合わせる<sup>1)</sup>. 透視X線画像の骨輪郭は, 半自動抽出法を用いて抽出した<sup>4)</sup>. その結果, 仮想空間における骨モデルの位置・姿勢が得られる. これらの手順から,  $\Sigma_{Ana}$ から $\Sigma_{Mar}$ への座標変換 ${}^{Ana}T_{Mar}$ が得られる. (図4). レジストレーション誤差は, 予備実験より屈曲伸展 $0.1 \pm 0.11\text{deg}$ , 内反外反 $0.1 \pm 0.24\text{deg}$ , 回旋 $0.4 \pm 0.32\text{deg}$ , 内外方向 $0.1 \pm 0.51\text{mm}$ , 前後方向 $0.1 \pm 0.25\text{mm}$ , 遠近方向 $-0.3 \pm 0.26\text{mm}$ であった.

### システム総合精度評価

#### 1. 実験方法

対象は, 新鮮凍結右切断下肢1体とした. 実験手順を以下に示す. まず切断肢の関節を切開し, ACLを切除した. ACL付着部内に目標点となるピン (径: 0.89mm, 材質: チタン・ニッケル合金) を刺入し, その後閉創した. 次に大腿骨にマーカを設置し, 2方向透視X線撮影及びCT撮影した. CT撮影データを用いて骨モデルを作成し, CTモデル上の目標点位置を設定した(図5). この3次元値を精度評価の「真値」とした. 最後に鏡視画像上に目標点を表示し,

表示された目標点をプローブでデジタル化した(図6). この3次元値を「測定値」とした. 誤差は「真値と測定値との距離」とした. 検者は整形外科医3名とし, デジタル化回数は7回とした.

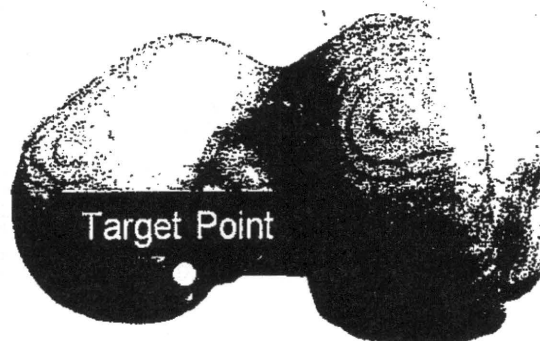


図5. Target point for total accuracy evaluation.

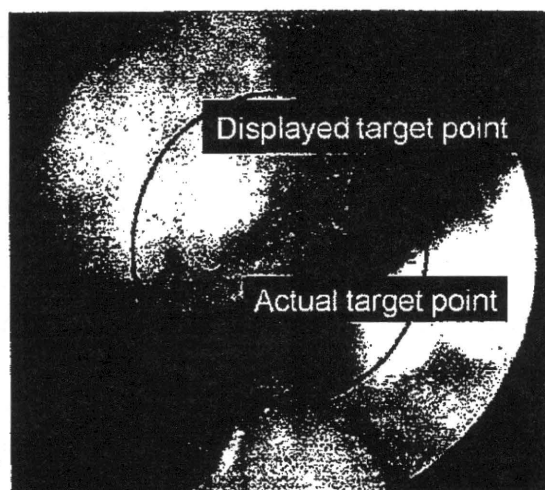


図6. Superimpose display of the target point.

#### 2. 実験結果

図7にシステム総合精度評価の結果を示す. 誤差は検者Aで $2.01 \pm 0.067\text{mm}$ , 検者Bで $1.94 \pm 0.117\text{mm}$ , 検者Cで $1.90 \pm 0.147\text{mm}$ であった.

### 考 察

我々は関節鏡視下手術の支援を目的として, 骨モデルを術中の鏡視画像に重ね合わせて表示するシステムを開発してきた<sup>2), 5), 6)</sup>. 今回はACL再建術における大腿骨孔位置を目標点に設定し, システムの総合精度を評価した. 本システムの特徴は, 術前計画を鏡視画像上にリア

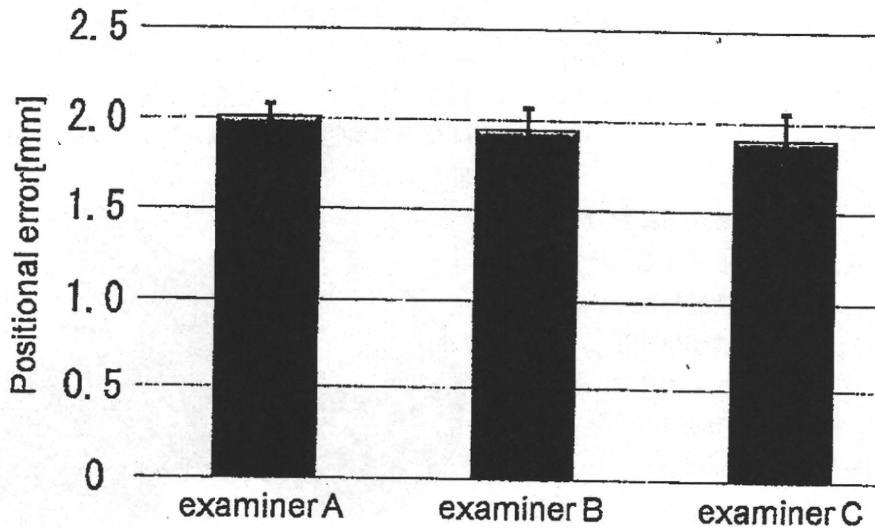


図7. Positional error of the target point: the error was evaluated as the distance between their actual position and corresponding measured position.

ルタイムで表示できることであり、過去に同様のシステムは開発されていない。実験よりACL再建術において術前に決定した大腿骨孔の位置を術中の鏡視画像に直接表示可能であり、術者にとって理解しやすい手術ナビゲーションシステムであると考えられる。さらに手術支援だけでなく、次に述べるように、関節鏡視下手術において様々な定量評価が可能になると考えられる。

3次元モデルを用いれば、局所の解剖などを反映した術前計画が可能となる。その計画結果、例えば骨孔の位置・姿勢などは、臨床で一般的に用いられるX線やCTなどの医療画像情報を用いて、多様に提示できる。例えば、関節鏡画像上に骨モデルと術前計画情報を同時に表示できるため、手術中にいくつもの画面でデータや状況を確認する必要がなくなる。関節鏡画像内での術者の判断は、経験や主観的な判断に依存しやすい。しかし、本システムを用いれば、術前計画や術後での定量評価が可能になり、さらに術式間あるいは術者間の客観的比較も可能になる。このように、本システムは関節鏡視下手術ナビゲーションに応用できる可能性が高いと考えられる。

システム総合精度は、検者3名の平均誤差で1.95mmであった。この結果は、いまだ臨床応

用には不十分であるため、さらなるシステムの改善が必要である。おもな誤差要因には、レジストレーション誤差、トラッキング誤差、関節鏡カメラ校正誤差、プローブでのデジタイズ誤差の4つがある。予備実験の結果などから、その中でもレジストレーション誤差が最も大きいと考えられる。そのため、レジストレーション手法の改善が当面の課題である。今後は、ACL再建術だけでなく、さまざまな関節鏡手術に応用を拡大したいと考えている。そのためには、軟骨や半月板といった軟部組織情報をもつMRIモデルも用いる必要がある。それも今後の課題である。

## ま と め

我々は関節鏡視下手術の支援を目的として、骨モデルを術中の鏡視画像に重ね合わせて表示するシステムを開発してきた。今回、切断肢を用いてシステムの総合精度を評価した。その結果、誤差は平均1.95mmとなった。今後の課題は、レジストレーション手法の改善、軟骨を含むMRモデルの導入である。

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## MRI骨・軟骨モデルを用いた3次元下肢アライメント 評価システムの精度評価

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### Accuracy Estimation of Three-Dimensional Lower Extremity Alignment Assessment System Using MRI Models for Bone and Cartilage.

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#### Abstract

The objective of this study was to estimate the accuracy of the three-dimensional (3D) lower extremity alignment assessment system after a bone-cartilage model from MRI was applied. We devised an automatic construction algorithm that could set an intermediate coordinate system in femoral and tibial MRI models. This automatic construction algorithm was used in CT and MRI models reconstructed from scanning data of five volunteers. After 2D-3D image registration with 3D bone models and biplanar X-ray (CR) images, we compared the MRI model application with CT model application. Errors of image matching position between CT and MRI models were within 1.0 degree and 1.5 mm, respectively. The anatomical coordinate systems of a femur and a tibia were reconstructed with three reference points in the CR coordinate system. Errors of the anatomical coordinate system between CT and MRI model application were within 1.0 degree and 1.0 mm, respectively. It was indicated that 3D lower extremity alignment could be evaluated with his combination of an MRI model and biplanar X-ray images.

Key words : MRI model. Biplanar X-ray images. Lower extremity alignment. CT model. Knee.

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