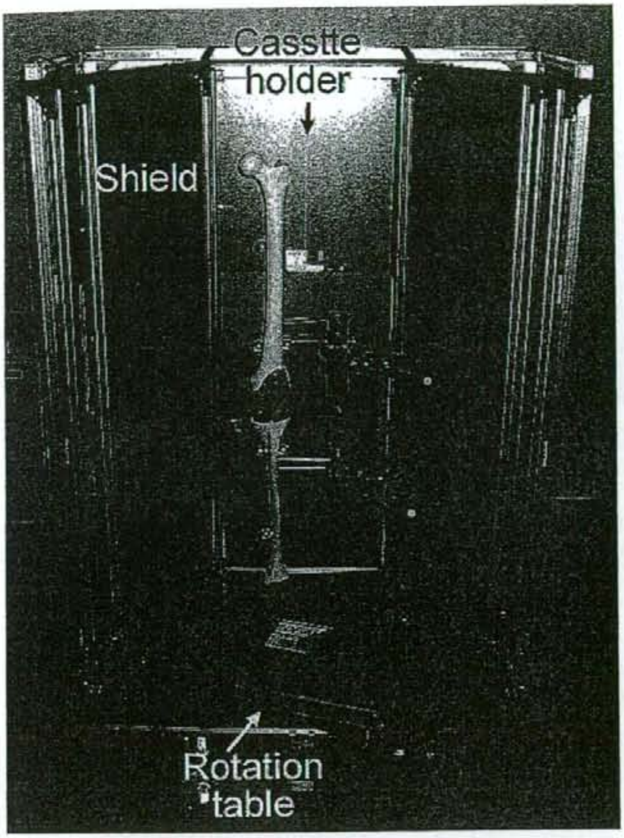

図3．Experimental set-up.

表1．Average error, standard deviation and [RSME] of estimating translation parameters of relative pose.

	x (mm)	y (mm)	z (mm)
Femur/tibia	-0.31±0.50[0.57]	-0.28±0.61[0.64]	-0.31±0.19[0.36]
Femoral component/ tibial component	-0.38±0.13[0.40]	-0.86±0.38[0.93]	-0.35±0.06[0.36]
Femoral component/ femur	-0.77±0.17[0.73]	0.35±0.13[0.31]	0.56±0.20[0.55]
Tibial component/ tibia	-0.27±0.18[0.32]	-0.06±0.18[0.19]	0.24±0.20[0.30]

表2．Average error, standard deviation and [RSME] of estimating rotation parameters of relative pose.

	x (°)	y (°)	z (°)
Femur/tibia	0.17±0.56[0.56]	-0.12±0.23[0.25]	-0.53±1.1[1.1]
Femoral component/ tibial component	0.44±0.42[0.59]	-0.11±0.22[0.24]	-0.41±0.60[0.70]
Femoral component/ femur	-0.76±0.33[0.80]	0.62±0.20[0.63]	-0.73±0.58[0.91]
Tibial component/ tibia	-0.47±0.40[0.60]	0.39±0.66[0.74]	0.46±0.14[0.48]

する大腿骨コンポーネントの相対位置，③大腿骨を基準とする大腿骨コンポーネントの相対位置および④脛骨を基準とする脛骨コンポーネントの相対位置を算出した．

自動イメージマッチングでは大腿骨，脛骨，大腿骨コンポーネントおよび脛骨コンポーネントの3次元位置姿勢（6自由度パラメータ）を推定し，上述の4つの相対位置を求めた．6自由度パラメータの初期値として，真値から±5 mm，±5°の範囲でランダムに10個選んだ．

結果と考察

表1と表2に推定された各相対位置の並進ならびに回転パラメータにおける平均誤差±標準誤差と二乗平均誤差（RMSE）を示した．これより，脛骨に対する大腿骨の相対位置は−0.31mm±0.50mm，−0.5°±1.1°以内で推定可能であることが分かった．同様に，脛骨コンポーネントに対する大腿骨コンポーネントの相対位置は−0.9mm±0.4mm，0.4°±0.4°以内，大腿骨に対する大腿骨コンポーネントの相対位置は−0.8mm±0.2mm，0.8°±0.3°以内，脛骨に対する脛骨コンポーネントの相対位置は−0.3mm±0.2mm，0.5°±0.4°以内で推定可能であった．RMSEについては並進パラメータにおける最大値が上述の相対位置の順に0.64mm，0.93mm，0.73mm，0.32mmであった．回転パラメータについては1.14°，0.70°，0.91°，0.74°であった．イメージマッチングに要する計算時間はパーソナルコンピュータ（Windows® XP，XEON™ processor，3GHz，2GB

RAM）上で，モデル骨に対して約270秒，コンポーネントに対して約30秒であった．以上の結果より，従来人工膝関節コンポーネント[5]，膝関節[2]および足関節[6]といった比較的狭い部位を対象に適用されてきた２方向画像による自動イメージマッチング手法を下肢全長に適用し，臨床的に十分な精度と再現性が得られたと考える．

推定精度について過去の研究と比較すると，人工膝関節の位置姿勢について本研究より精度の高い結果[5]が報告されている．これは校正フレームと人工膝関節を同時撮影しているためと考えられる．３次元下肢アライメント評価システムでは，下肢全長を撮影対象とするため校正フレームも大型になり，被験者と同時に撮影することができない．よって，回転台やカセッテホルダのわずかなガタにより，校正時とカメラ定数に差異が生じたことで誤差が増加したと考えられる．一方，骨の位置姿勢については他の報告[11]と同様の推定精度であった．ここでも回転台やカセッテホルダのガタによる誤差はあるものの，３次元骨形状モデルの誤差とX線像において骨輪郭が不明瞭であることの影響の方が大きかったので，全体として他の報告と同様の結果となったと推察する．骨と人工膝関節の相対位置については，人工膝関節設置後のCT撮影による結果[3]と同程度の再現性であった．従って，本法により術後のCT撮影による被爆を無くすることができるので臨床的意義は大きい．

結　　言

３次元下肢アライメント評価システムにおける３次元形状モデルと２方向X線像を用いたイメージマッチングの省力化と再現性確保を図るため，滑降シンプレックス法を利用した自動イメージマッチング手法を提示した．その結果，同手法は臨床的に十分な精度と再現性を有することが分かった．

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文　　献

1）Canny A : A computational approach to edge detection. IEEE Trans Pattr Anal Machine Intel 8 : 679-698, 1986.
2）DeFrate LE, Sun H, Gill TJ, Rubash HE et al : In vivo tibiofemoral contact analysis using 3D MRI-based knee models. J Biomech 37 : 1499-1504, 2004.
3）Jazrawi LM, Birdzell L et al : The accuracy of computed tomography for determining femoral and tibial total knee arthroplasty component rotation. J Arthroplasty 15-6 : 761-766, 2000.
4）徐剛，辻三郎：３次元ビジョン，東京，共立出版，79，1998.
5）Kaptein BL, Valstar ER et al : A new model-based RSA method validated using CAD models and models from reverse engineering. J Biomech 36 : 873-882, 2003.
6）Li G, Wan L, Kozanek M : Determination of real-time in-vivo cartilage contact deformation in the ankle joint. J Biomech 41 : 128-136, 2008.
7）Nelder JA, Mead R : A simplex method for function minimization. Computer Journal 7 : 308-313, 1965.
8）Sato T, Koga Y et al : Three-dimensional lower extremity alignment assessment system. Application to evaluation of component position after total knee arthroplasty. J Arthroplasty 19-5 : 620-628, 2004.
9）Sato T, Koga Y et al : Quantitative 3-dimensional analysis of preoperative and postoperative joint lines in total knee arthroplasty. J Arthroplasty 22-4 : 560-568, 2007.
10）Singerman R, Heiple KG et al : Effect of tibial component position on patella strain following total knee arthroplasty. J Arthroplasty 10-5 : 651-656, 1995.
11）You B, Siy P et al : In vivo measurement of 3-d skeletal kinematics from sequences of biplane radiographs. Application to knee kinematics. IEEE Trans Med Img 20-6 : 514-525, 2001.

関節鏡ナビゲーション手術システムにおける骨モデルの鏡視画像への重ね合わせ精度評価

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Accuracy evaluation of a technique for superimposing a 3D bone-model on its arthroscopic image.

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Abstract

Computer-assisted orthopaedic surgery (CAOS) is one of the advanced medical engineering technologies developed in order to obtain better surgical outcomes nearly independent from operator skill. Its application to arthroscopic surgery, however, has not become widely used, due to technical difficulties. To achieve this, we have been developing a technique of superimposing 3D bone-model reconstructed from preoperative tomographic images upon its arthroscopic image on a real-time basis. Such superimposition allows the visualization of the surgical plan using intraoperative arthroscopic images, if it is incorporated into the bone model before operation. The present study evaluated the overall accuracy of the superimpostion system. In an attempt to validate the overall accuracy of the system, we evaluated the positional error of three target points set in the attachment site of anterior cruciate ligament (ACL) of both femoral and tibial bone models. These points were digitized manually using a probe mounted on an arthroscope, according to the arthroscopic image provided with a target location. Empirical results demonstrated that the error of every target was less than or equal to 1.04 [mm] on average, suggesting the clinical applicability of the system.

Key words : CAOS, arthroscopic surgery, 3D bone-model, superimposing technique.

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はじめに

コンピュータ支援整形外科手術（CAOS：Computer-Assisted Orthopaedic Surgery）は，医師の経験度に影響されることなく高精度な骨関節手術を実現し，より良好な術成果を得ることを目的としている．我々は，関節鏡視下手術へのCAOSの導入を目的として，術中の鏡視画像にリアルタイムで「骨モデル」を重ね合わせ表示するシステムを開発してきた．「骨モデル」とは，術前に断層画像から作成した骨の形状モデルである．その上に術前計画で決定した情報を与えておけば，本システムを用いることにより，術中において鏡視画像上に術前計画を可視化できる．今回は，大腿骨・脛骨モデルボーンを対象としてシステムの総合精度を実験的に評価した．

対象および方法

1．リアルタイム重ね合わせ表示システム

1－1．システム概要

本システムは，30°斜視鏡（Smith & Nephew社，Germany），モニタ，トラッキング装置（ProReflex MCU240，Qualisys社，Sweden），

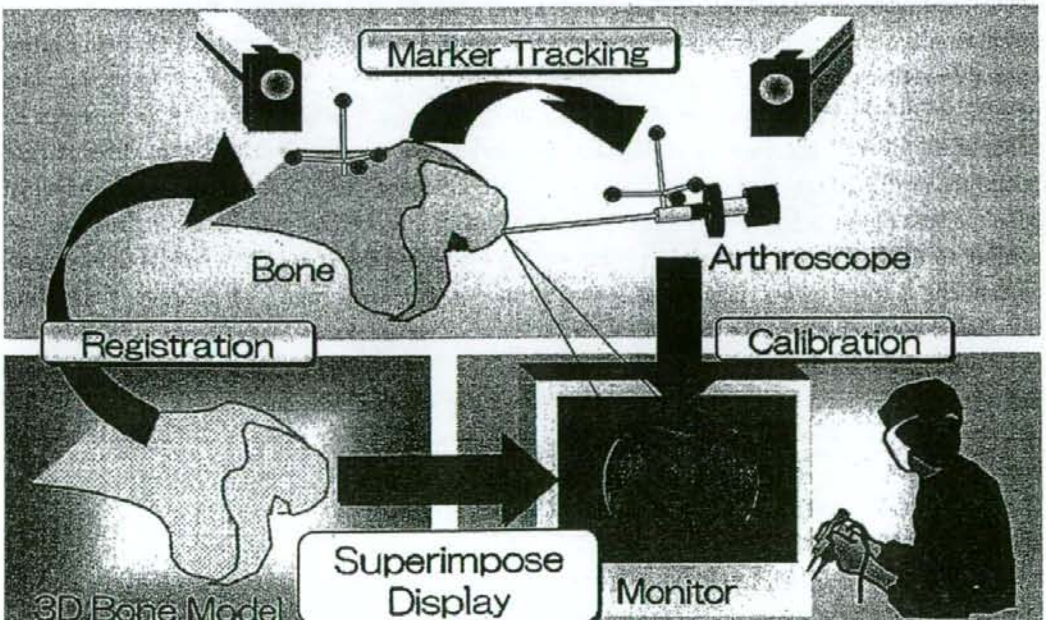
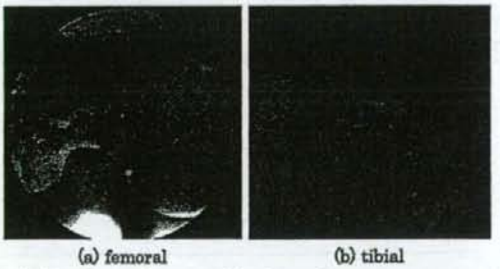


図1．System configuration.

コンピュータ，オーバーレイ表示機能付ダウンコンバータ（Tempest SX PC VIDEO OVERLAY, ADTECHNO社, 東京）からなる（図1）．関節鏡と骨には，トラッキング用のマーカを4個ずつ固定する．事前にコンピュータに与えるデータは，関節鏡の内部・外部変数，3次元骨モデル，実空間における3次元骨モデルの位置・姿勢，マーカ間距離である．術中における骨・関節鏡の位置関係は，マーカ・トラッキングによりリアルタイム計測する（計測精度0.71±0.09［mm］）．各マーカの識別にはマーカ間距離データを用いる．図1に示すように，骨モデルの実空間における位置・姿勢をレジストレーションにより推定し，それを関節鏡に仮想投影することにより，骨モデルの仮想鏡視画像を得る．それを実際の鏡視画像に重ね合わせて表示する（図2）．

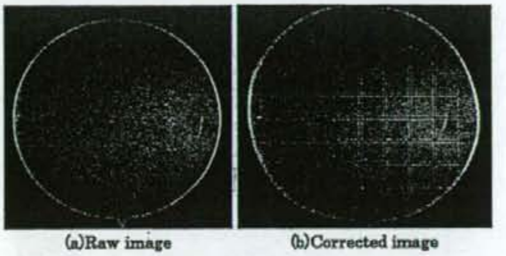


(a) femoral　　(b) tibial

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

1－2．関節鏡カメラ校正

事前にカメラ校正を行うことにより，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）を推定する．校正には，直径1［mm］の鋼球マーカを10［mm］間隔で7×7個配置したボードを用いた（図3）．それを，精密移動ステージを用いてボードに垂直な方向に5［mm］間隔で25［mm］並進移動し，7×7×6個の3次元点列を生成した．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測定器（MICROCORD BH504, 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．次に画像中の鋼球マーカをディジタイズし，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，中村らが開発したカメラ校正法[4]を用いた（校正精度0.23±0.02［mm］）．



(a)Raw image　　(b)Corrected image

図3．Distortion correction of arthroscopic image by camera calibration.

1－3．骨モデルの作成と座標系の設定

骨モデルは，CT撮像データ（Sensation16, SIEMENS社，Germany）から専用ソフトウェアZed View（LEXI社，東京）を用いて作成する．その解剖学的座標系（Σ_{Ana}）は次のように設定する．まず大腿骨頭・内側後顆・外側後顆をそれぞれ球近似し，その球中心の3点を求める．球近似には，専用ソフトウェアModel Viewer（LEXI社，東京）を用いる．原点Oは，内側・外側後顆近似球の中点とした．X軸は，外側後顆近似球中心から内側後顆近似球中心に向かうベクトル方向に設定した．次に，外側後顆近似球中心から骨頭近似球中心に向かうベクトルとX軸との外積を求め，得られたベクトル方向をY軸とした．Z軸は，X軸とY軸の外積から求めた．

1－4．レジストレーション

骨を2方向透視X線撮影（BV Libra, Phillips社，Netherlands）する．その透視X線撮影を再現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．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．次に，同じ仮想空間におけるマーカ位置を投影像から推定し，その上にΣ_{Mar}を

設定する．これらの手順から，Σ_{Ana}からΣ_{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精度は，予備実験より屈曲伸展0.59±0.14［deg］，内反外反0.03±0.14［deg］，回旋0.27±0.14［deg］，内外方向0.60±0.75［mm］，前後方向0.27±0.34［mm］，遠近方向0.10±0.33［mm］であった（図5）．

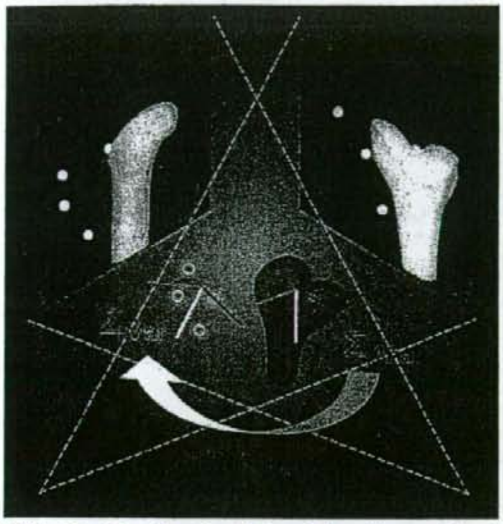


図4．Registration for determining the positional relationship between two different coordinate systems set on the marker set and 3-D bone model.

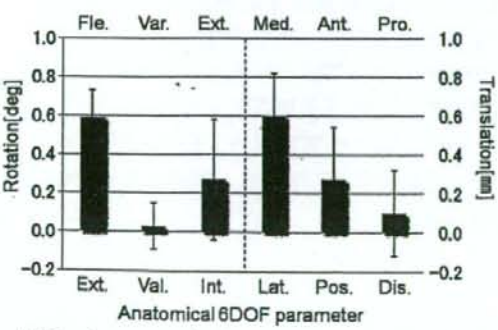
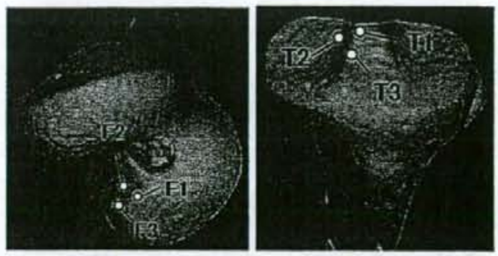


図5．Accuracy in the position and orientation obtained from 2D/3Dregistration.

2．システム総合精度の評価法

対象は，大腿骨・脛骨モデルボーンとした．重ね合わせ精度は，骨上の点（精度評価点）の3次元座標で評価した．その精度評価点は，大腿骨・脛骨のACL付着部付近の3点（F1-F3，T1-T3）とした（図6）．それら精度評価点のΣAnaにおける3次元座標を「参照値」とする．そのデータを骨モデル上にも与えておけば，本システムにより精度評価点を鏡視画像に重ね合わせて表示できる．その評価点像を見ながら検者が関節鏡先端に設置したプローブで骨表面をディジタイズし，得られたプローブ先端の3次元座標を「測定値」とする．誤差は「参照値と測定値の距離」で評価した．トラッキング装置のカメラ台数は2台，検者は2名，ディジタイズ回数は10回とした．



(a) femoral (b) tibial

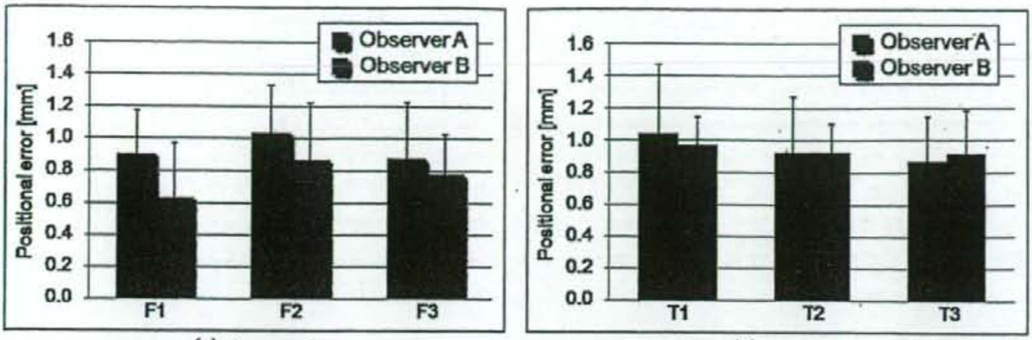
図6．Target points for overall accuracy evaluation.

結　果

図7にシステムの総合精度評価の結果を示す．大腿骨側における誤差は，F1〜F3でそれぞれ0.90［mm］以下，1.04［mm］以下，0.88［mm］以下であった．一方，脛骨側における誤差は，T1〜T3でそれぞれ1.04［mm］以下，0.93［mm］以下，0.92［mm］以下であった．t検定を行った結果，全ての精度評価点（F1〜F3，T1〜T3）において検者間で有意差は見られなかった．

考　察

従来の手術ナビゲーションシステムの表示は，鏡視画像とは視点が異なるため，鏡視下手術において術者が情報を理解しにくいと考えられる．そこで我々は，骨モデルを術中の鏡視画像にリアルタイムで重ね合わせて表示するシステムを開発した．本システムの特性は，骨モデルに術前計画の情報を与えておくことで，術中



(a) femoral　　(b) tibial

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

の鏡視画像上に術前計画を可視化できることである．この特性により，従来の手術ナビゲーションシステムよりも直感的に理解しやすい情報提供が可能である．また，鏡視画像を表示するモニタとナビゲーション用のモニタを交互に確認する必要がないため，術者の負担を低減できると考えられる．

本システムの誤差要因には，2D/3Dレジストレーション誤差，カメラ校正残差，トラッキング精度の3つがある．それら3つの誤差は，最終的には鏡視画像に映ったモデルボーンと重ね合わせて表示した3次元骨モデル表面との"ずれ"となって表れる．今回，このずれを総合的に定量評価するために，モデルの関節面上に精度評価点を3つ設定し，その既知の座標を「参照値」とした．次に，関節鏡画像を見ながら骨表面をディジタイズして得られたプローブ先端の3次元座標を「測定値」とした．この測定値には上述の3つの誤差と術者によるディジタイズ誤差が含まれている．つまり，参照値と測定値との距離には，これら誤差がすべて含まれていることになる．なお，この距離は検者間で有意差が見られなかった．このことから，ディジタイズ誤差はランダムに生じるため，距離の標準偏差は，主に検者のディジタイズの再現性を表し，平均値は，主にそれ以外の誤差による偏位を表しているものと考えられる．

本システムの総合精度は，平均1.04［mm］以下であり，臨床応用のための条件（1.0［mm］以内）をほぼ満たしていた．このことから，本システムの臨床応用の可能性が示唆された．

リアルタイムオーバーレイ機能を有した本システムは，3次元術前計画を術中に再現できる関節鏡ナビゲーション手術の可能性を有しており，前十字靭帯再建術における骨孔位置や骨軟骨柱移植術における移植の位置や方向，さらにはMR画像を用いた関節モデルの重ね合わせが可能となれば，靭帯再建そのものや半月板縫合など関節鏡手術における広い臨床応用が期待されると考えられる．

結　言

我々は，鏡視下手術へのCAOS導入を目的として，骨モデルを鏡視画像にリアルタイムに重ね合わせ表示するシステムを開発した．システムの総合精度は，実験の結果，臨床応用可能なレベルに達していた．今後の課題は，切断肢を用いた総合精度評価，および軟骨を加えたMRモデルの応用である．

文　献

1）根本篤志，平澤信 他：膝関節面の形状推定法の開発とそのサーフェス・レジストレーションへの応用．日本臨床バイオメカニクス学会誌 25：285－290，2004．

2）Paolo D, Maria C et al. : A Novel Mechatronic Tool for Computer-Assisted Arthroscopy. IEEE

Transaction on Information Technology in Biomedicine 4 (1) : 15-29, 2000.

3) Picard F, DiGioia AM et al. : Accuracy in Tunnel Placement for ACL Reconstruction. Comparison of Traditional Arthroscopic and Computer-Assisted Navigation Techniques, Computer Aided Surgery 6 : 279-289, 2001.

4) Toyohiko H, Katsutoshi N et al. : Visualization of the articulation of replaced knee joint surfaces after total knee arthroplasty. Journal of Japanese Society for Clinical Biomechanics and Related Researches 18 : 47-56, 1997.

5) Yasuo N, Toyohiko H et al. : Automatic head positioning system using PSD-equipped camera-based photostereometry and a 5-degree-of-freeedom robotized chair : calibration and accuracy verification. Frontiers Med Biol Engng 8 (1) : 47-63, 1997.

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ORTHOPAEDIC SURGERY

Progression of osteoarthritis of the knee after unilateral total hip arthroplasty: minimum 10-year follow-up study

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Abstract
Introduction Patients undergoing total hip arthroplasty (THA) exhibit changes in the alignment of lower extremities following the procedure, and these changes may exert effects on other joints over the long-term. Therefore, we investigated the course of knee osteoarthritis in patients undergoing long-term follow up after THA, in addition to the relationship between the course of knee osteoarthritis and alignment of lower extremities.
Materials and methods We retrospectively performed radiographic evaluation of the course of knee osteoarthritis (OA) after THA. Thirty patients undergoing successful unilateral THA were followed for a minimum of 10 years.
Results Eleven (33%) subjects showed progression of medial tibiofemoral OA on the non-THA side, while only three (10%) showed progression on the THA side, and this difference was significant ($P = 0.033$). In addition, the mechanical axes on the THA side passed through more lateral regions of the tibial plateau than those on the non-THA side ($P = 0.044$).
Conclusion Medial tibiofemoral OA on the THA side was less likely to deteriorate than on the non-THA side. The reduced vulnerability to OA progression on the THA side may be due to the lower offset and resultant lateral shift in mechanical axes.

Keywords Osteoarthritis · Knee · Arthroplasties · Hip Replacement · Follow-up studies · Biomechanics · Bone malalignment

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Introduction

Total hip arthroplasty (THA) provides patients suffering from hip osteoarthritis (OA) complete pain relief and improved hip function. However, patients with hip OA have disturbed kinetics in adjacent joints and in the pelvis due to the impaired hip [14, 22]. In particular, progression of knee OA is associated with progression of hip OA [8]. Furthermore, knee OA is one of the most prevalent joint disorders in the elderly [6]. Therefore, it is of concern whether knee OA progresses after THA in patients with hip OA.

Shakoor et al. demonstrated using gait analysis that the medial compartment load of the knee was significantly higher in the contralateral knee relative to the treated side at 1–2 years after successful unilateral THA [18]. They also reported that among patients whose initial THA was followed by total knee arthroplasty (TKA), 71% underwent TKA on the contralateral side [17]. However, the progress of knee OA in patients undergoing THA has not been examined during long-term follow up.

Pre-existing knee OA, high loading of the knee and shifts in mechanical axes of the lower leg that alter load distribution are major risk factors for the progression of knee

OA, in addition to obesity and female gender [4, 5, 7, 19, 21]. Among these factors, THA can induce a shift in mechanical axes by spatially altering the head center position. Total hip prostheses have relatively high neck-shaft angles, and therefore have a tendency to reduce the femoral offset [2], possibly leading to lateral shifts in mechanical axes. The course of knee OA ipsilateral to THA may thus differ from the natural course during long-term follow up. Optimizing selection of femoral anteversion and offset are essential in providing the hip with excellent function by improving abductor muscle strength, preventing dislocation and adjusting leg length [12]. However, surgeons do not commonly consider the effects on the mechanical axes of the lower extremities.

We performed radiographic evaluation of bilateral knees in patients undergoing unilateral THA and who were subsequently observed for a minimum of 10 years, in order to investigate the effects of THA on alignment of the lower extremities and to clarify the long-term progression of knee OA after THA.

Materials and methods

Between 1986 and 1995, 411 primary THAs in 345 patients were performed at one of our institutes. Of these, 279 patients were treated with unilateral THA, and 48 of these had pre-operative radiographs of the lower extremities for the purposes of future assessment of longitudinal evaluation of alignment after THA.

In order to eliminate confounding factors, patients whose records indicated a diagnosis of systemic inflammatory disease, and those who underwent any surgical intervention in the lower extremities after THA were excluded from analysis [15]. Therefore, patients who underwent subsequent THA for advanced-stage disease in the contralateral hip were excluded. Patients who had sustained knee injuries or who had undergone knee surgery prior to THA were also excluded.

The resulting patient group consisted of 30 patients who were followed for a minimum of 10 years (Table 1). All patients were women. Mean age at the time of the surgery was 56.2 (range 48–73) years, with mean pre-operative body mass being 55.0 (SD 7.2) kg and mean pre-operative height being 1.53 (SD 0.05) m. All patients had a minimum follow-up period of 10 years and a maximum follow-up period of 19 (mean 13.7) years. Primary diagnosis included developmental dysplasia of the hip (DDH) in 27 patients, avascular necrosis of the femoral head in 2 patients and pigmented villonodular synovitis of the hip in 1 patient. In eight of the DDH patients, bilateral hips were involved in advanced arthritis. Of these, three patients had undergone Chiari osteotomy in the contralateral hip. Including those that underwent Chiari osteotomy, the eight patients with bilateral involvement did not complain of severe pain in the contralateral hips. In the other 19 patients with DDH, the contralateral hips were intact.

The operative approach was posterolateral in all hips. Various types of implant were used: 18 patients had cementless metal-cancellous implants (S + G; Lübeck, Germany) and 12 had cemented implants (Japan Medical Material; Osaka, Japan, and Osteonics; Allendale, NJ, USA).

One patient died 15 years after surgery due to complications unrelated to the surgery or diseases of the lower extremities. Data for this patient at final follow up (14 years post-surgery) is included in this study.

The Japanese Orthopaedic Association (JOA) hip score was used for clinical evaluation of arthroplasty at follow up. This hip score is based on a 100-point scale; 40 points for pain, 20 points for range of motion, 20 points for walking ability, and 20 points for activities of daily living [11].

All patients had AP and lateral radiographs of the hip immediately after surgery and at final follow up for assessment of implant loosening. Femoral components were considered unstable if subsidence of >3 mm was noted or if component alignment had changed. Acetabular components were considered unstable if a circumferential radiolucent line of >2 mm width was noted or if changes were seen in inclination or anteversion [10]. Patients also had weight-bearing full-length AP radiographs of lower extremities during knee extension both, pre-operatively and at final follow up. We evaluated both the grade of knee (tibiofemoral) OA and the alignment of lower extremities on a single radiograph.

For grading of knee OA, we used a modified Kellgren–Lawrence (KL) scale because the original KL scale tends to emphasize osteophyte formation, while joint space narrowing may be more relevant for the purposes of this investigation (0, normal; 1, questionable osteophytes and or questionable joint space narrowing; 2, definite osteophytes with possible joint space narrowing or definite mild joint space narrowing with or without osteophytes; 3, definite moderate joint space narrowing; 4, severe joint space narrowing) [1, 6]. OA grades for both medial and lateral compartments of the knee were assessed using this grading system. Modified KL scores ≥2 at follow up, and increases of 1 grade or more during follow up were defined as indicating OA progression.

We defined an alignment parameter in order to assess the extent of mechanical axis shifting. A line connecting the center of the femoral head and the midpoint of the ankle (mechanical axis) was drawn. Another line connecting both the most medial and lateral points of the tibial plateau was then drawn. The distance between the most medial point of the tibial plateau and the point where the two lines cross was obtained. The ratio (%) of this distance against the

Table 1 Patient data ($n = 30$), including status of contralateral hip and previous surgery to contralateral hip

Case	Age	Gender	Disease	Side of total hip arthroplasty	Follow up (year)	JOA score at follow up	Status of contralateral hip	Previous surgery to contralateral hip
1	51	F	DDH	Right	19	80	Advanced OA due to DDH	
2	55	F	DDH	Left	18	79	Advanced OA due to DDH	Chiari osteotomy
3	65	F	DDH	Right	18	92	Normal	
4	73	F	DDH	Left	16	80	Advanced OA due to DDH	
5	49	F	DDH	Right	16	98	Normal	
6	50	F	DDH	Left	16	88	Normal	
7	57	F	DDH	Left	16	96	Normal	
8	56	F	DDH	Left	16	100	Normal	
9	63	F	DDH	Right	15	90	Normal	Chiari osteotomy
10	49	F	DDH	Left	15	92	Normal	Chiari osteotomy
11	41	F	DDH	Right	15	97	Normal	Chiari osteotomy
12	53	F	DDH	Right	15	97	Normal	
13	60	F	DDH	Right	15	98	Normal	
14	60	F	DDH	Left	14	86	Advanced OA due to DDH	
15	53	F	DDH	Left	14	76	Advanced OA due to DDH	
16	61	F	DDH	Right	14	92	Normal	
17	67	F	ON	Right	13	73	Normal	
18	40	F	DDH	Left	13	83	Advanced OA due to DDH	Chiari osteotomy
19	55	F	DDH	Left	13	83	Advanced OA due to DDH	
20	65	F	DDH	Right	12	88	Normal	
21	62	F	DDH	Right	12	96	Normal	
22	61	F	DDH	Left	12	84	Normal	
23	48	F	DDH	Left	11	92	Normal	
24	48	F	DDH	Left	11	87	Normal	
25	58	F	DDH	Right	11	79	Normal	
26	53	F	PVS	Left	10	94	Normal	
27	54	F	DDH	Left	10	98	Normal	
28	52	F	DDH	Left	10	77	Advanced OA due to DDH	Chiari osteotomy
29	67	F	ON	Left	10	98	Normal	
30	59	F	DDH	Right	10	98	Normal	

F female, *DDH* developmental dysplasia of the hip, *ON* osteonecrosis of the hip, *PVS* pigmented villonodullar synovitis

entire width of the tibial plateau was measured, and was defined as the alignment ratio (AR). High ARs indicate that the mechanical axis passed through a more lateral point of the knee joint (Fig. 1).

In addition, as a factor that may affect alignment, femoral offset at follow up was measured. Offset was defined as the perpendicular distance between the long axis of the femur and the center of the femoral head. We calculated the ratio (%) of femoral offset on the THA side against the non-THA side in order to avoid errors caused by variances in radiograph magnification among subjects. We defined this as the offset ratio (OR) (Fig. 2). Because it is difficult to identify the center of the femoral head in cases of pathologic hip, the center of the femoral head was considered to be the center of the hip joint, according to the method of Kandemir et al. [9] for measurement of AR and OR in patients with DDH. This method of measurement was applied to eight hips (contralateral to THA), in which the femoral heads do not appear spherical. Each parameter was measured for both the THA and non-THA sides, and laterality was assessed.

Statistical methods

Statistical analysis was performed using Stat View 4.58 software. A non-paired t test was used to compare ARs and ORs between the two groups (THA and non-THA sides). Similarly, Mann Whitney's test was used to compare modified KL scales, and χ^2-test was used to compare progression of knee OA and the THA side. Correlations between the two parameters (modified KL scales and ARs, and modified

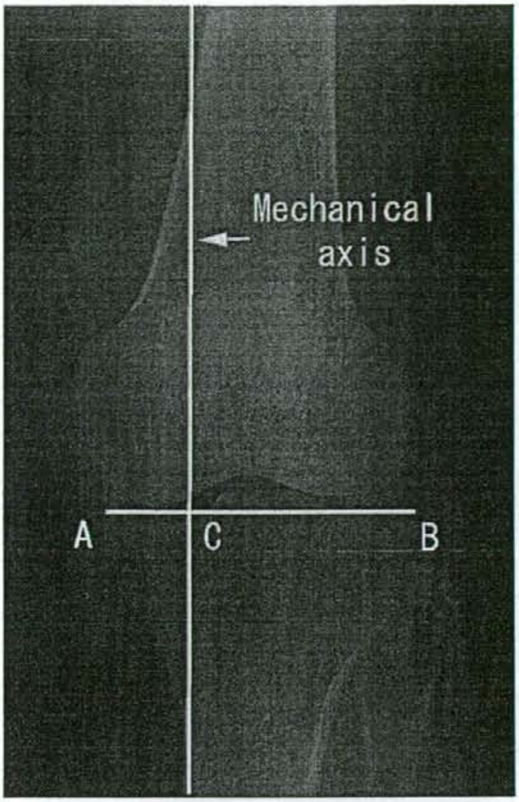

Fig. 1 Alignment ratio (*AR*) was defined as AC/AB (%). **a** Most medial point of the tibial plateau, **b** most lateral point of the tibial plateau, **c** intersection where mechanical axis and line AB cross

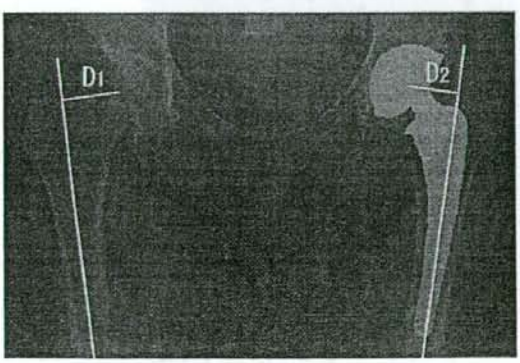

Fig. 2 Offset ratio was defined as D2/D1 (%)

KL scales and ORs) were analyzed by Spearman's rank correlation test. In all tests, P values of <0.05 were considered significant.

Results

Total hip arthroplasty was performed on the right side in 13 patients and on the left side in 17 patients. The difference in number of hips between each side was not significant ($P = 0.44$). All THAs were radiographically stable at follow up. Mean JOA hip score at follow up was 89 (SD 8), and mean pain score was 39 (SD 2), thus suggesting that hip pain was almost completely relieved by successful THA. Contralateral hips, including those with advanced-stage arthritis at baseline, remained asymptomatic at follow up.

Modified KL scale results are summarized in Table 2. There were no significant differences with respect to distribution of modified KL scales between the THA and the non-THA sides at baseline in both the medial and lateral compartments (medial, $P = 0.14$; lateral, $P > 0.99$). All subjects had normal knees or low-grade knee OA (modified KL scale 0, 1 and 2) in medial compartments on both the THA and non-THA sides at baseline. Baseline ARs on the THA and non-THA sides were 43.6 (SD 17.0) and 40.3 (SD 17.9), respectively, and did not significantly differ ($P = 0.48$).

At follow up, distribution of modified KL scales in the medial compartment revealed significantly more severe knee OA on the non-THA side than on the THA side ($P = 0.044$), while severity in the lateral compartment did not significantly differ ($P = 0.12$) between each side. With regard to medial tibiofemoral OA, 11 patients (33%) showed progression on the non-THA side, while 3 (10%) showed progression on the THA side. This difference was significant ($P = 0.033$). One subject even showed an improved modified KL score in the medial compartment on the THA side. OA progression in the lateral compartment

Table 2 Modified Kellgren–Lawrence scales

Modified Kellgren–Lawrence scale	Preoperative (No. (%))		Follow up (No. (%))	
	Non-THA side	THA side	Non-THA side	THA side
The medial compartment of the knee				
0	13 (43)	7 (23)	4 (13)	7 (23)
1	14 (47)	19 (63)	14 (47)	18 (60)
2	3 (10)	4 (13)	7 (23)	4 (13)
3	0 (0)	0 (0)	5 (17)	1 (3)
4	0 (0)	0 (0)	0 (0)	0 (0)
The lateral compartment of the knee				
0	27 (90)	25 (42)	27 (90)	22 (73)
1	0 (0)	4 (13)	0 (0)	5 (17)
2	2 (7)	0 (0)	3 (10)	1 (3)
3	1 (3)	1 (3)	0 (0)	2 (7)
4	0 (0)	0 (0)	0 (0)	0 (0)

was seen only on the THA side in two patients at follow up, but this laterality was insignificant ($P = 0.47$).

Mean AR on the THA side at follow up was 48.7 (SD 19.9) and was significantly higher than on the non-THA side (38.8 (SD 17.0)) ($P = 0.026$), indicating that the mechanical axes passed through a more medial point of the knee on the non-THA side relative to the THA side. Mean OR at follow up was 89.3 (SD 24.5), and thus the offset on the THA side was significantly shorter than that on the non-THA side ($P < 0.001$).

Correlation analysis among modified KL scale, AR and OR at follow up revealed that severity of lateral tibiofemoral OA (modified KL scale) correlated significantly with AR on the THA side ($P = 0.0059$, $r = 0.60$). No other significant correlations were observed among these parameters.

Discussion

The present article may be the first to describe the long-term radiographic changes emerging in the knee after THA. In addition, as pre-existing knee OA status was similar on each side, we were able to preferentially assess the effects of THA on the course of knee OA, which is the strength of this study.

Medial tibiofemoral OA on the non-THA side was more likely to deteriorate than that on the THA side in patients undergoing unilateral THA. Although we were unable to find any previous reports regarding long-term follow up of knee OA focusing on changes in each compartment of the tibiofemoral joint, there are some reports describing the natural course of OA of the whole knee joint. Spector et al. described the natural course of knee OA using the KL scale and found that 33% of patients deteriorated over an average of 11 years [20]. Sahlström et al. [16] showed that among 132 normal knees or those with less than 50% joint space narrowing, 57 knees (42%) showed progression of OA for 20 years. The frequency of OA progression on the non-THA side in the present study agreed with these results, while progression on the THA side was obviously less frequent. The present results, along with previous epidemiologic reports, support the notion that the knee on the THA side is less vulnerable to OA progression when compared with the natural course.

The lower frequency of medial knee OA progression on the THA side might be attributed to altered offset. It is generally recognized that high load, shifts in mechanical axes and status of OA at baseline are major risk factors for knee OA progression [5, 13, 19, 21]. In the present study, the status of pre-existing knee OA was similar on each side. In addition, there was a significant correlation between severity of lateral tibiofemoral OA and mechanical axes on the THA side. Furthermore, one subject even showed an improved modified KL score in the medial compartment on this side. These findings support the notion that reduced offset and resultant lateral shifts in mechanical axes on the THA side, might be associated with less vulnerability to medial knee OA progression. This conclusion was not inconsistent with previous reports by Shakoor et al. [17, 18], which showed that the medial compartment load of the knee was significantly higher in the contralateral knee relative to the treated side after unilateral THA, and that patients undergoing unilateral THA were more likely to have TKA on the contralateral rather than on the ipsilateral side.

We should interpret the present results with caution. First, subjects with advanced knee OA (modified KL scale >2) were not included at baseline. Previous epidemiologic studies regarding the natural course of knee OA showed that advanced knee OA is more likely to deteriorate than mild knee OA [3, 16]. Therefore, in patients undergoing THA with advanced knee OA at baseline, the course of knee OA may be worse when compared with the present results. Second, the majority of our patients were DDH cases. Because the baseline status of the knees was similar on both the THA and the non-THA sides, we believe that we were able clarify the effects of alignment shift in patients undergoing THA, regardless of disease. However, further investigation is needed to confirm whether the results of the present study are applicable to other patient groups.

In conclusion, we investigated the long-term course of knee OA after THA. The course of medial knee OA progression in patients with unilateral THA differed between the contralateral and ipsilateral sides. Medial knee OA on the THA side was less likely to deteriorate than on the non-THA side. This may be related to lateral shifts in mechanical axes due to the reduced offset of conventional femoral prostheses.

References

1. Altman RD, Fries JF, Bloch DA, Carstens J, Cooke TD, Genant H, Gofton P, Groth H, Mcshane DJ, Murphy WA, Sharp JT, Spitz P, Williams CA, Wolfe F (1987) Radiographic assessment of progression in osteoarthritis. Arthritis Rheum 30:1214–1225
2. Bourne RB, Rorabeck CH, Patterson JJ, Guerin J (2001) Tapered titanium cementless total hip replacements: a 10- to 13-year follow up study. Clin Orthop 393:112–120
3. Cerejo R, Dunlop DD, Cahue S, Channin D, Song J, Sharma L (2002) The influence of alignment on risk of knee osteoarthritis progression according to baseline stage of disease. Arhtiritis Rheum 46:2632–2636
4. Du H, Chen SL, Bao CD, Wang XD, Lu Y, Gu YY, Xu JR, Chai WM, Chen J, Nakamura H, Nishioka K (2005) Prevalence and risk factors of knee osteoarthritis in Huang-Pu District, Shanghai, China. Rheumatol Int 25:585–590
5. Englund M, Lohmander LS (2004) Risk factors for symptomatic knee osteoarthritis fifteen to twenty-two years after meniscectomy. Arthritis Rheum 50:2811–2819

6. Felson DT, Naimark A, Anderson J, Kazis L, Castelli W, Meenan RF (1987) The prevalence of knee osteoarthritis in the elderly. The Framingham osteoarthritis study. Arthritis Rheum 30:914–918
7. Frost HM (1994) Perspectives: a biomechanical model of the pathogenesis of arthroses. Anat Rec 240:19–31
8. Hassett G, Hart DJ, Doyle D, March L, Spector TD (2006) The relationship of progressive osteoarthritis of the knee and long-term progression of osteoarthritis of the hand, hip and lumbar spine. Ann Rheum Dis 65:623–628
9. Kandemir U, Yazici M, Alpaslan AM, Surat A (2002) Morphology of the knee in adult patients with neglected developmental dysplasia of the hip. J Bone Joint Surg 84A:2249–2257
10. Kawamura H, Dunbar MJ, Murray P, Bourne RB, Rorabeck CH (2001) The porous coated anatomic total hip replacement. A ten to fourteen-year follow-up study of a cementless total hip arthroplasty. J Bone Joint Surg 83A:1333–1338
11. Kawate K, Tanaka Y, Ohmura T, Hiyoshi N, Yajima H, Tomita Y, Takakura Y (2004) Twenty-five years follow up of patients who had valgus osteotomy for arthritic hips. Clin Orthop 426:151–158
12. McGrory BJ, Morrey BF, Cahalan TD, An KN, Cabanela ME (1995) Effect of femoral offset on range of motion and abductor muscle strength after total hip arthroplasty. J Bone Joint Surg 77B:865–869
13. Miyazaki T, Wada M, Kawahara H, Sato M, Baba H, Shimada S (2003) Dynamic load at baseline can predict radiographic disease progression in medial compartment knee OA. Ann Rheum Dis 61:617–622
14. Miki H, Sugano N, Hagio K, Nishii T, Kawakami H, Kakimoto A, Nakamura N, Yoshikawa H (2004) Recovery of walking speed and symmetrical movement of the pelvis and lower extremity joints after unilateral THA. J Biomech 37:443–455
15. Radin EL, Burr DB, Caterson B, Fyhrie D, Brown TD, Boyd RD (1991) Mechanical determinants of osteoarthrosis. Semin Arthritis Rheum 21:12–21
16. Sahlstrom A, Johnell O, Redlund-Johnell I (1997) The natural course of arthrosis of the knee. Clin Orthop 340:152–157
17. Shakoor N, Block JA, Shott S, Case JP (2002) Nonrandom evolution of end-stage osteoarthritis of the lower limbs. Arthritis Rheum 46:3185–3189
18. Shakoor N, Hurwitz DE, Block JA, Shott S, Case JP (2003) Asymmetric knee loading in advanced unilateral hip osteoarthritis. Arthritis Rheum 48:1556–1561
19. Sharma L, Song J, Felson DT, Cahue S, Shamiyeh E, Dunlop DD (2001) The role of knee alignment in disease progression and functional decline in knee osteoarthritis. JAMA 286:188–195
20. Spector TD, Dacre JE, Harris PA, Huskisson EC (1992) Radiological progression of osteoarthritis: an 11 year follow up study of the knee. Ann Rheum Dis 51:1107–1110
21. Tetsworth K, Paley D (1994) Malalignment and degenerative arthropathy. Orthop Clin North Am 25:367–377
22. Weidow J, Mars I, Karrholm J (2005) Medial and lateral osteoarthritis of the knee is related to variations of hip and pelvic anatomy. Osteoarthritis Cartil 13:471–477

Hip Motion Analysis Using Multi Phase (Virtual and Physical) Simulation of the Patient-specific Hip Joint Dynamics

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Abstract. In total hip arthroplasty (THA), the patient-specific bone geometry or the characteristics of the skeletal movement should be considered during treatment in order to prevent complications. In this paper, we propose a novel approach for the analysis of joints which combines the patient-specific virtual and physical simulation. The patient-specific anatomical structure and hip motion was obtained from CT and optical motion capture. The virtual simulation was conducted by integrating these data using virtual reality technique. The physical simulation was achieved by using plaster models of the patient's pelvis and femur and robotic manipulator. The plaster models were driven by two robotic manipulators to reproduce the hip motion. The accuracy of the robot movement was 0.245mm over the working area according to the validation by an optical tracking system. By combining this system with linear actuators that reproduce the muscle functions, patient-specific muscle function can be simulated, thereby helping clinicians to diagnose and make a treatment plan.

Keywords. total hip arthroplasty, virtual simulation, physical simulation

1. Introduction

Total hip arthroplasty (THA) is a surgical procedure in which the diseased parts of the hip joint are removed and replaced with new artificial ones. The main complications of this surgery are dislocation and loosening due to the wearing of the sliding surface. To

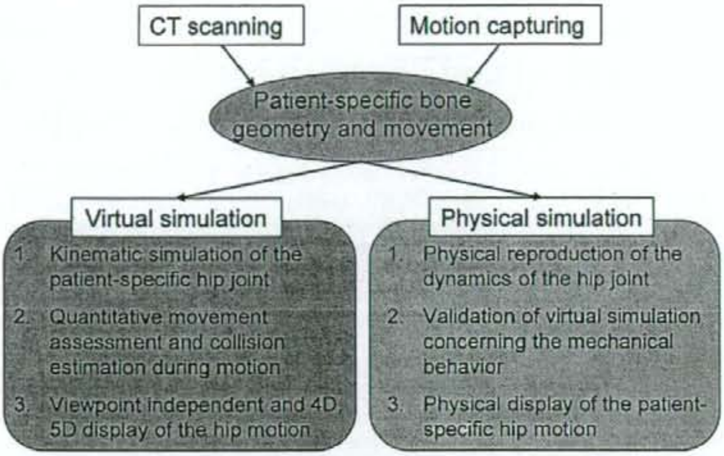

Fig. 1 Overview of the proposed system

prevent these complications, the patient-specific bone geometry or the characteristics of the skeletal movement should be considered during treatment. In recent studies [1][2], a patient-specific three-dimensional (3D) skeletal model prepared from computed tomography (CT) and motion capture data of the patient was used to simulate patient-specific skeletal motion. On the other hand, for analyzing the typical dynamics of joints, especially the knee joint, a few researchers have developed systems that reproduce previously recorded 6-degree-of-freedom kinematics using a robotic manipulator with the joint part of porcine carcasses or cadavers [3][4]. These systems were intended to be used for the analysis of the general characteristics of a dynamic state of the knee joint such as the tension in the anterior cruciate ligament, etc. However, because these systems used a porcine carcass or a cadaver, the motion of the individual was not available: therefore the simulation result has some limitations concerning the correspondence between the geometry and the movement.

In this paper, we propose a novel approach for the analysis of joints which combines the patient-specific virtual simulation we have been developing for patients after THA [2] and a newly developed physical simulation system. As described above, physical simulation in this research analyzes the dynamics of the joint such as forces acting on or within the joint. This physical simulation system consists of a 6-degree-of-freedom robotic manipulator and a plaster model of the patient-specific bone geometry. Analysis by this physical simulation reinforces the result of virtual simulation and also helps the patients to understand the motion of their hip joint.

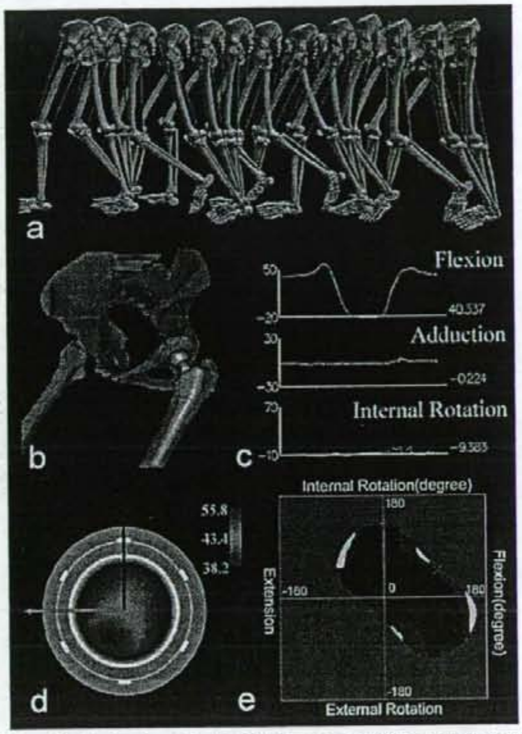

Fig. 2 Simulation using the virtual model. a, b: skeletal motion analysis; c: transition of the joint angle; d: distribution of the wearing part estimated by the simulation; e: estimated range of motion.

2. Methods

First, we scanned the patient's lower extremity using CT and constructed a patient-specific 3D bone geometry model. Then, we captured the motion of the patient during some daily activities. The details of the method for obtaining these patient-specific data were described in the previous paper [2]. These data were used as the input for both the virtual and physical simulation systems (Fig. 1). In the virtual simulation system, accurate joint motion, collisions between hard tissue around the hip joint, and the estimated muscle force induced by the surrounding muscles were calculated (Fig. 2).

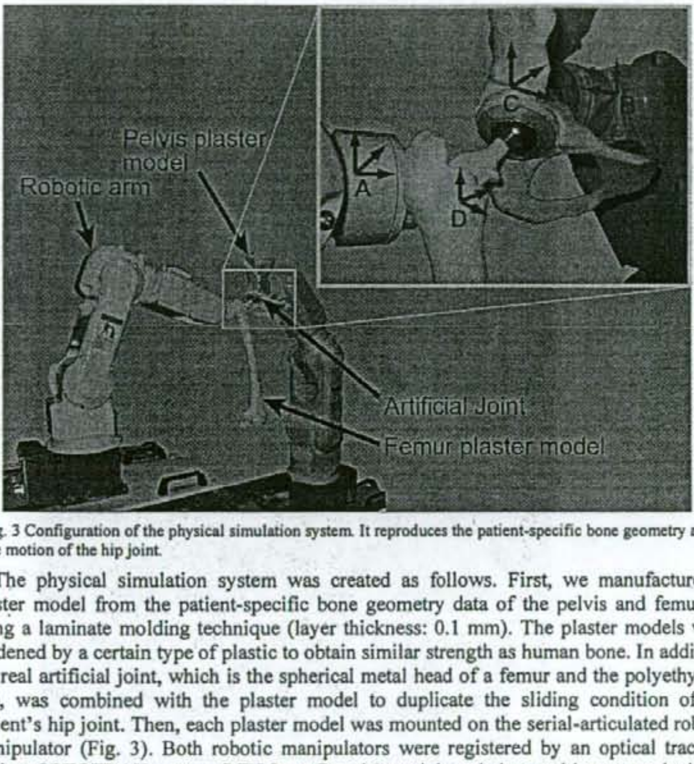

Fig. 3 Configuration of the physical simulation system. It reproduces the patient-specific bone geometry and the motion of the hip joint.

The physical simulation system was created as follows. First, we manufactured a plaster model from the patient-specific bone geometry data of the pelvis and femur by using a laminate molding technique (layer thickness: 0.1 mm). The plaster models were hardened by a certain type of plastic to obtain similar strength as human bone. In addition, the real artificial joint, which is the spherical metal head of a femur and the polyethylene cup, was combined with the plaster model to duplicate the sliding condition of the patient's hip joint. Then, each plaster model was mounted on the serial-articulated robotic manipulator (Fig. 3). Both robotic manipulators were registered by an optical tracking device, OPTOTRAK system (NDI Inc., Canada), and the relative position was calculated. Both robots were driven simultaneously by a single computer according to the patient's motion data to reproduce the relative motion between pelvis and femur.

Then, to validate the accuracy of the robot movement, the programmed movement of the robotic arm was validated using an optical tracking device. The robot with optical markers was driven throughout the working area (Fig. 4). The distance between the programmed and measured position was calculated as the error.

3. Results

Using the virtual and physical simulation system, the patient-specific movement of the skeletal structures was reproduced (Fig. 5). This helped the clinician in the analysis of the

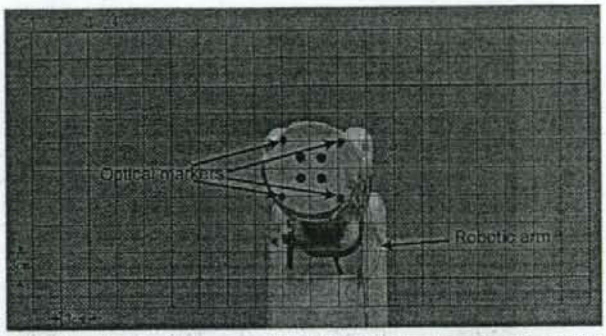

Fig. 4 Experiment for validating the accuracy of the robot manipulator. The red grid indicates the position that the experiment targeted.

joint structure and the dynamics of each patient's hip joint in detail, such as the contact force at the sliding surface or the characteristics of the movement. The root-mean-square error between the programmed and measured motion was 0.245 mm over the working area.

4. Conclusions

In this paper, we proposed a new approach for the analysis of joint motion and determined its feasibility. As described in previous research, physical simulation using the real joint object is extremely important for analyzing the forces acting on or within joints; however until now this has been achieved only for nonliving bodies. In the proposed system, even though only a few parts such as bones, artificial joints and motions were reproduced, it used data from living patients. For the application of these types of simulation to actual clinical settings for diagnosis, surgical planning or treatment planning, etc., the simulation of each patient's joint is inevitable. Furthermore, by combining this system with linear actuators that reproduce the muscle functions and a 6-axis force sensing device, patient-specific muscle function can be simulated accurately, thereby helping clinicians to select the optimal size of the artificial joint in preoperative planning and also predict postoperative complications such as dislocation or wearing at the sliding surface.

References

1. Y.Otake, K.Hagio, N.Suzuki, A.Hattori, N.Sugano, K.Yonenobu, T.Ochi: Four-dimensional Lower Extremity Model of the Patient after Total Hip Arthroplasty, Journal of Biomechanics, vol.38, pp.2397-405, 2005.

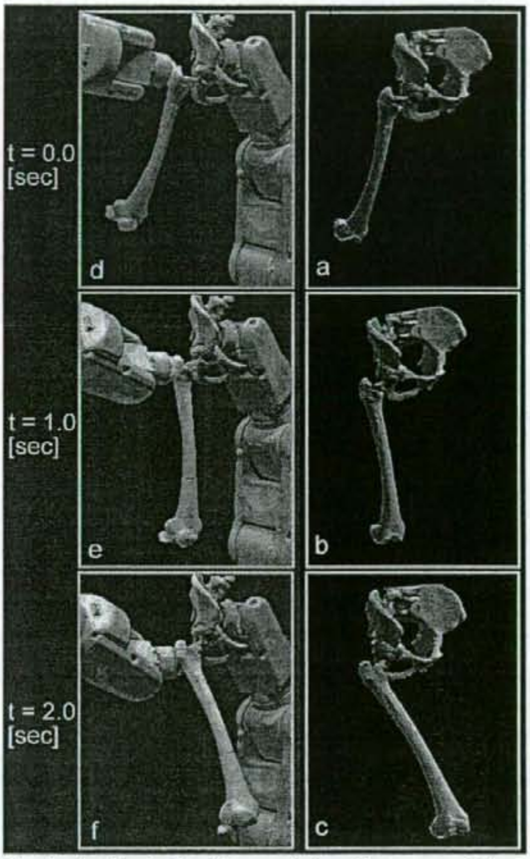

Fig. 5 Result of the virtual and physical simulation. a–c: display of the movement of the virtual model, d–f: motion of the plaster model and the robotic manipulator.

2. Y.Otake, N. Suzuki, A. Hattori, H. Miki, M. Yamamura, N.Nakamura, N. Sugano, K. Yonenobu, T. Ochi: Estimation of Dislocation after Total Hip Arthroplasty by 4-Dimensional Hip Motion Analysis, Studies In Health Technology and Informatics vol.111, pp.372-7, 2005.
3. Susan M. Moore, Maribeth Thomas, Savio L-Y. Woo, Mary T. Gabriel, Robert Kilger, Richard E. Debski: A novel methodology to reproduce previously recorded six-degree of freedom kinematics on the same diarthrodial joint, Journal of Biomechanics vol.39, pp. 1914-23, 2006.
4. Shon P. Darcy, Robert H. P. Kilger, Savio L-Y. Woo, Richard E. Debski: Estimation of ACL forces by reproducing knee kinematics between sets of knees: A novel non-invasive methodology, Journal of Biomechanics vol.39, pp. 2371-7, 2006.