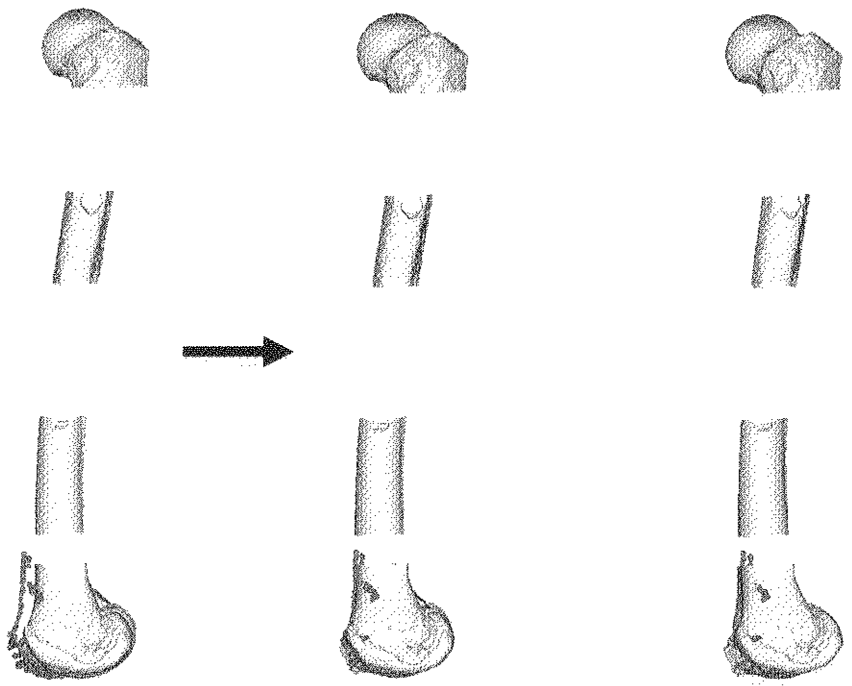
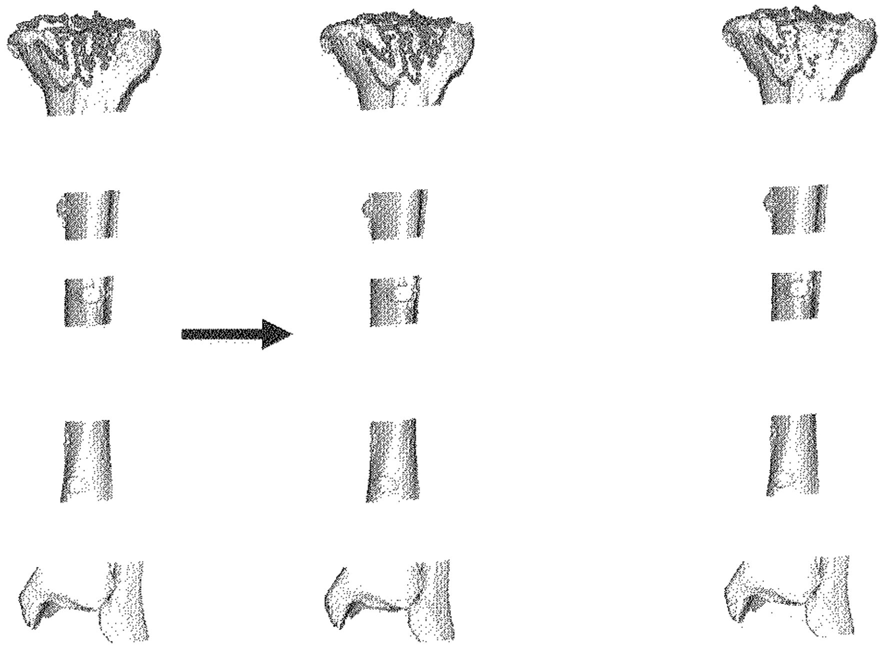
Femur (Side view)



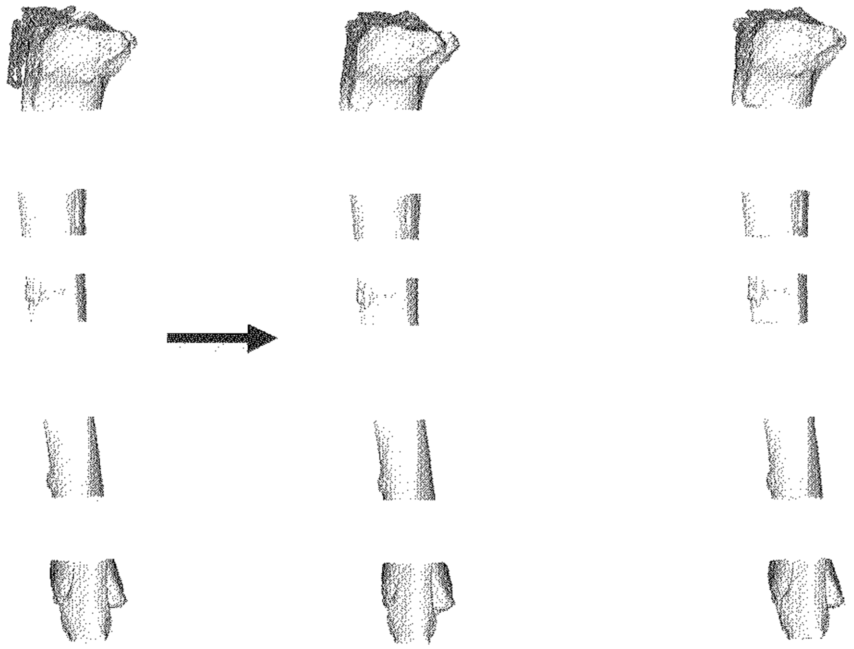
Surface registration Point matching registration

Tibia (Front view)



Surface registration Point matching registration

Tibia (Side view)



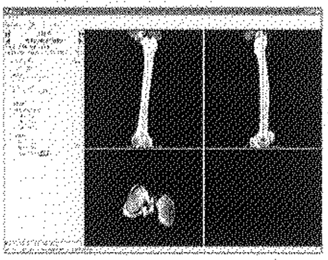
Surface registration　　Point matching registration

Coordinate system transformation

- The data to control the bone cutting machine tool is generated as follows: $^{F}_{A}T = {}^{B}_{A}T\,{}^{C}_{B}T\,{}^{D}_{C}T\,{}^{E}_{D}T\,{}^{F}_{E}T$
- $^{n}_{m}T$: Transformation from coordinate systems *m* to *n*.
- *A*: Local coordinate frame of the artificial joint, which is fixed to each cut surface: The cutting areas for the femur and tibia are described with reference to *A*.
- *B*: Artificial joint coordinate frame
- *C*: Preoperative planning coordinate frame: The position of the artificial knee joint, feature points and the shape of femur and tibia are presented with reference to *C*.
- *D*: Bone coordinate frame
- *E*: Static coordinate frame
- *F*: Bone cutting machine tool coordinate frame

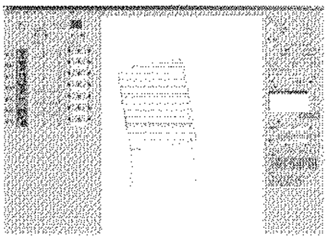
System construction

Software



(1) Extraction of bone surface
(2) Characteristic points
(3) Implant size
(4) Implant position

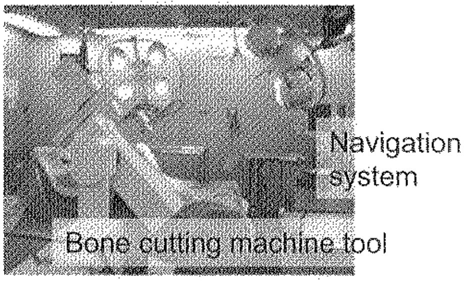
Preoperative planning system (CT-based)



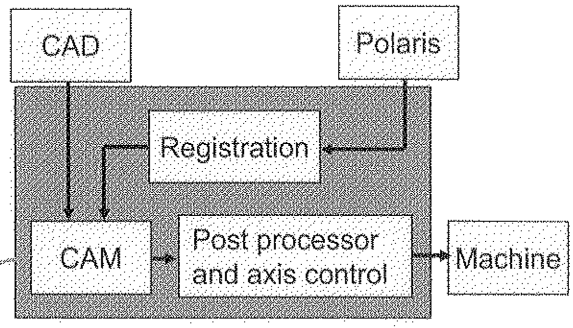
(1) Registration
(2) Tool path generation
(3) NC program generation

Intraoperative CAM system

Hardware



System in an operation room

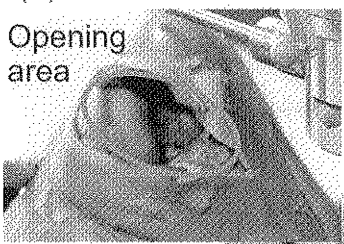


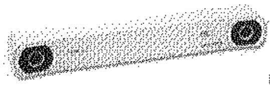
System configuration

Toolpath generation: Step1

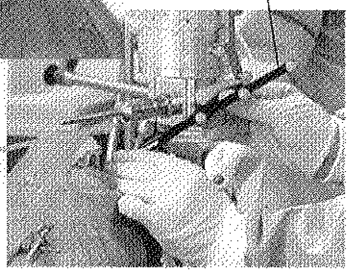
Modeling of knee joint

(1) Measurement of opening area

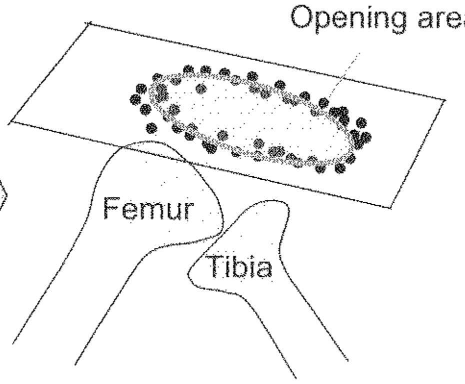




Probe with markers



With a 3-dimensional optical position sensor



The border of the area is measured as the points for the opening plane.

Regression analysis is used for measured data $\vec{p}_i\ (i=1,\ldots)$,

$$J(a,b,c)=\sum(z_i-ax_i-by_i-c)^2$$

$$\frac{\partial J}{\partial a}=0,\frac{\partial J}{\partial b}=0,\frac{\partial J}{\partial c}=0$$

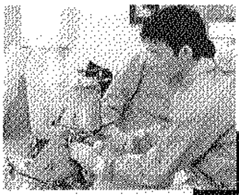
is calculated

A plane $z=ax+by+c$ is obtained.

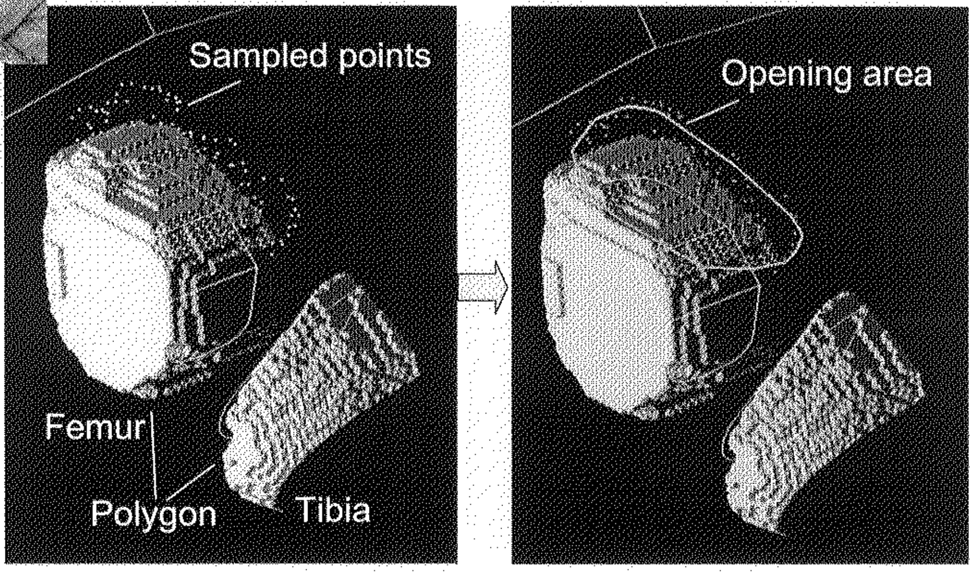
(2) Measurement of obstacles

Area which cutting tool should not contact (soft tissue, nerves, vessels, etc.) is measured and calculated.

Measurement of opening area



Sampling — Calculation of opening area



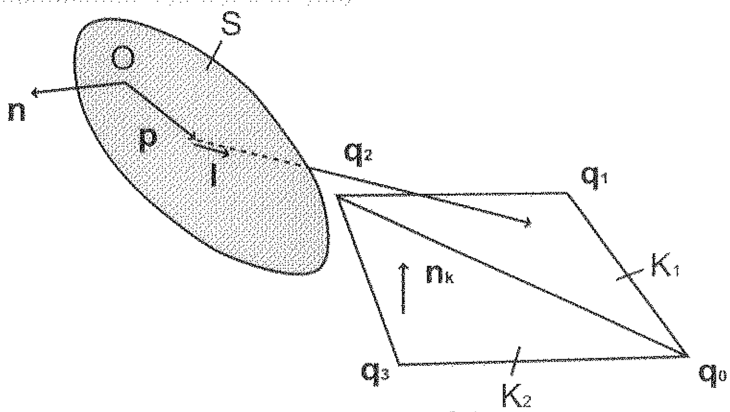
Toolpath generation: Step2(1)

Calculation of the initial cutting tool posture

- The machinable area is calculated at a given cutting tool attitude utilizing the cross detection of the cutting tool vector and the target plane.
- The resection plane is divided into the triangle patches *Ki*.
- Vertex vectors are set ***qi***.

Triangle patch *Ki* can be presented as

$$(1-u-v)\vec{q}_0 + u\vec{q}_1 + v\vec{q}_2$$
$$0 < u, v < 1$$



A local coordinate system *S* is set on the opening area.

$\vec{p} = (x \quad y \quad z)^{\mathrm{T}}$: offset vector from the origin

$\vec{l} = R(\theta,\phi)(0 \quad 0 \quad 1)^{\mathrm{T}}$: attitude vector

The cutting tool vector can be presented as

$\vec{p} + t \cdot \vec{l}$

Toolpath generation: Step2(2)

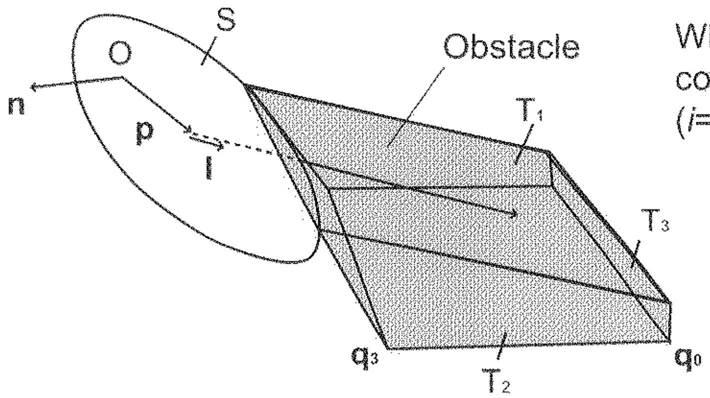
Calculation of the initial cutting tool posture

The following equation detects whether the patch is machinable:

$$\begin{pmatrix}-\vec{l} & (\vec{q}_1-\vec{q}_0) & (\vec{q}_2-\vec{q}_0)\end{pmatrix}\begin{pmatrix}t\\u\\v\end{pmatrix}=(\vec{p}-\vec{q}_0)$$

(Equation of Tomas Moller)

The detection is executed for all patches.



When it is machinable, the collision with interferences *Ti* (*i*=1, ...) is checked.

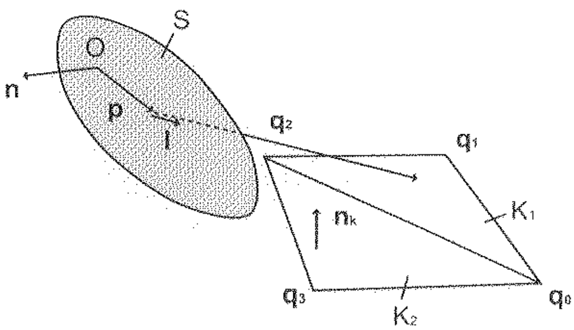
Toolpath generation: Step2(3)

Calculation of the initial cutting tool posture

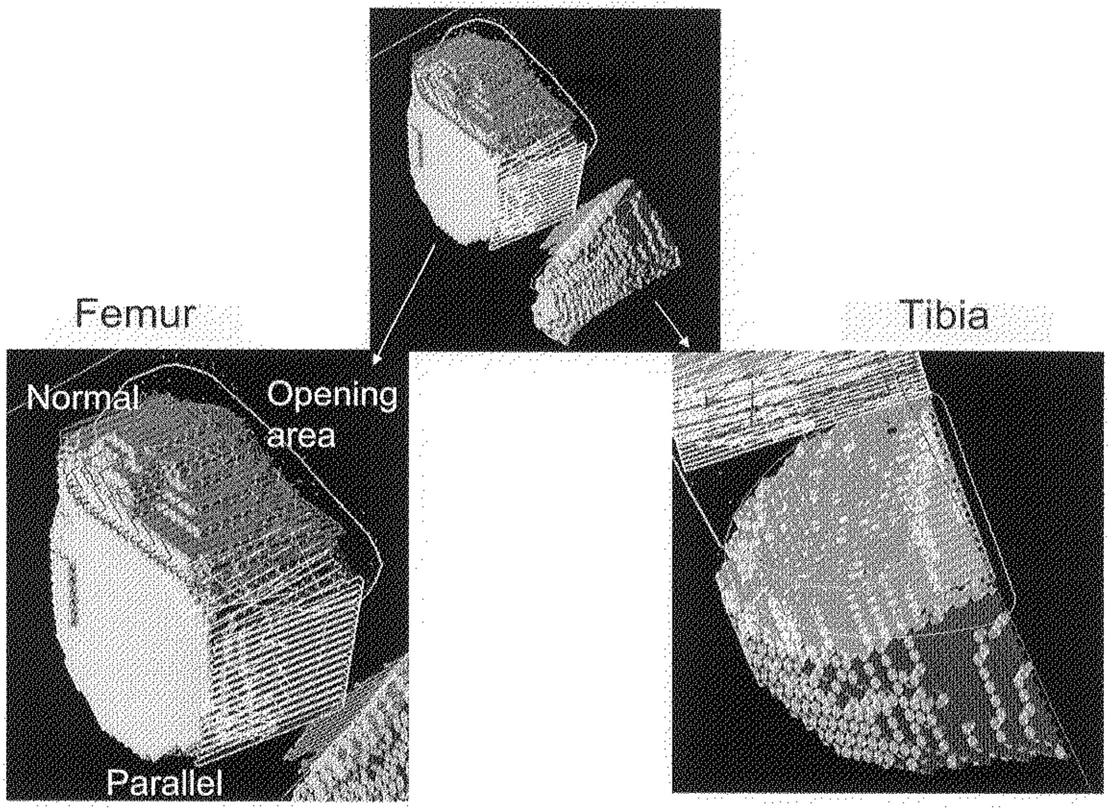
- The offset vector ***p*** is varied on the opening plane with the parameter of the tool attitude ***l***, and the machinable area is calculated on the triangle patch *Ki*.
- An attitude ***l*** to maximize the evaluation function is selected as the initial tool posture.

$$E(\vec{l},\vec{p}) = \begin{cases} 1 & \text{(without collision)} \\ 0 & \text{(with collision)} \end{cases}$$

$$J(\vec{l}) = \sum_{k_1}^{K_n} \int E(\vec{l},\vec{p})dxdy \quad x,y,\vec{p} \in S$$

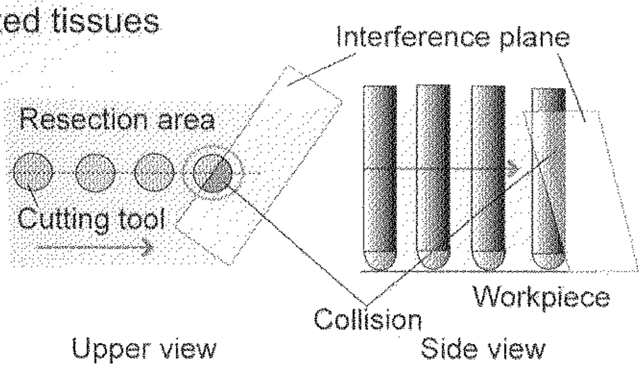


Calculation of cutter location

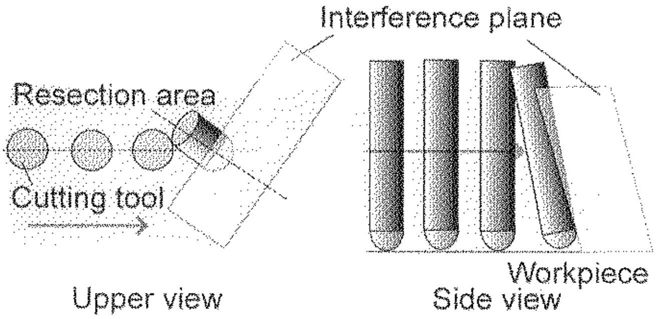


Collision avoidance

Interference with prohibited tissues are checked.



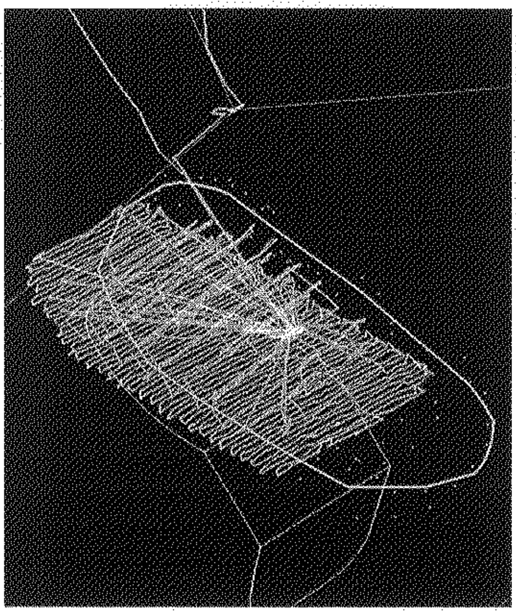
Strategy of avoidance



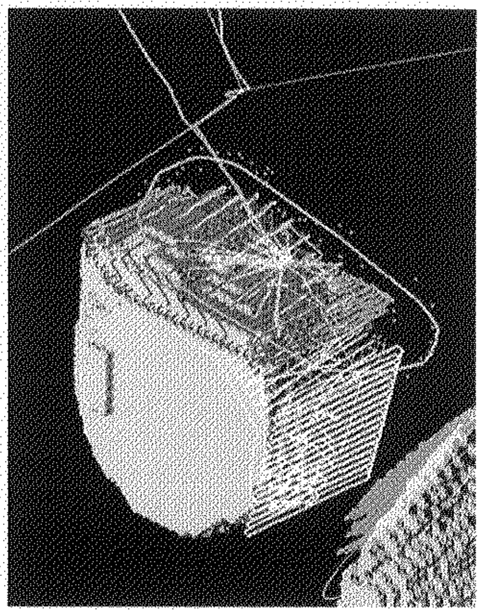
- Interference is avoided with a minimal change of the cutting tool attitude
- The avoidance direction is equal to the normal vector of the interference plane.

Toolpath generation: Step3

Trajectory



Cutter location and trajectory



Concept of toolpath generation

Requirements

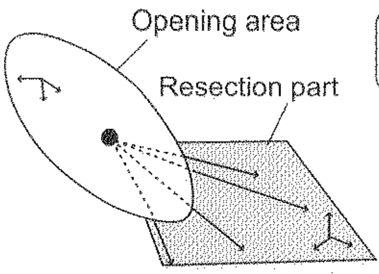
(1) Less invasiveness
(2) Accuracy
(3) Precision
(4) Safety

⇩

Strategy

(1) Short incision length
(2) Less attitude change

Strategy 1: Incision length minimization

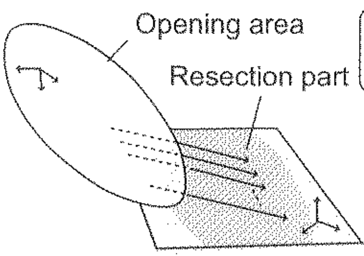


Short incision

⇩

Attitude of the cutting tool is changed actively

Strategy 2: Not changing the tool attitude



Less attitude change

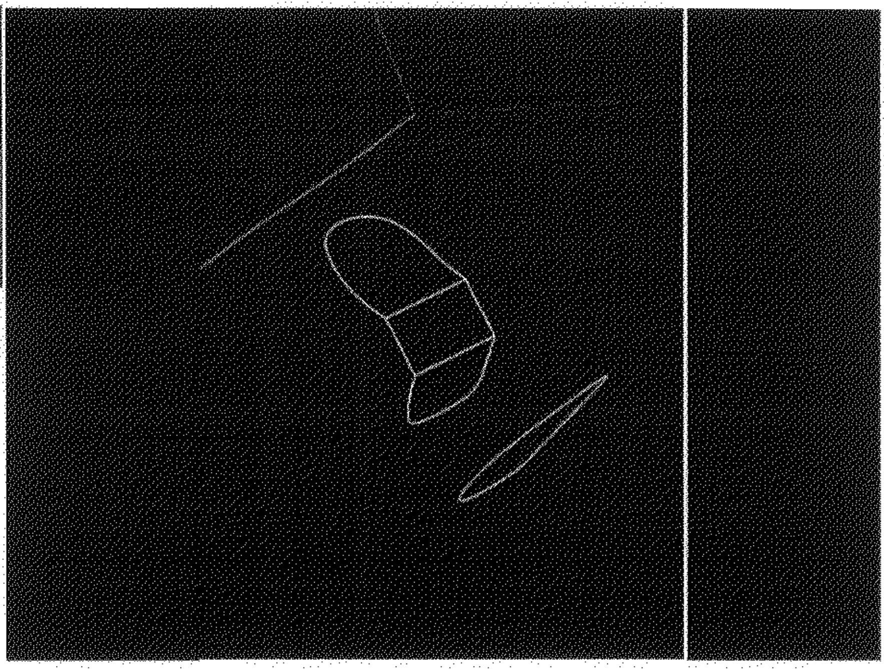
⇩

Easy to predict the attitude and position of the tool

Prototype of proposed method: video

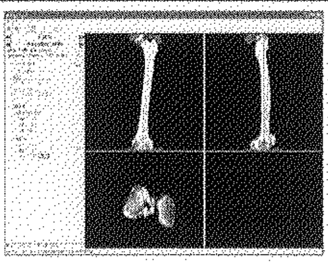
Setting plane of UKA

Flow of toolpath generation



Implementation: overview of the system

Software



(1) Extraction of bone surface
(2) Characteristic points
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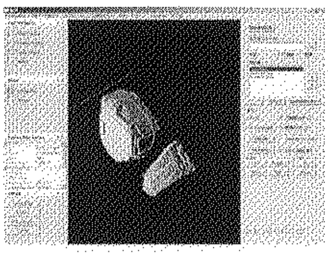
Preoperative planning system (CT-based)



(1) Registration
(2) Tool path generation
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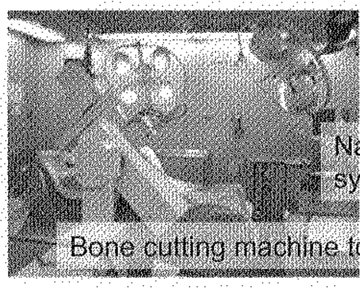
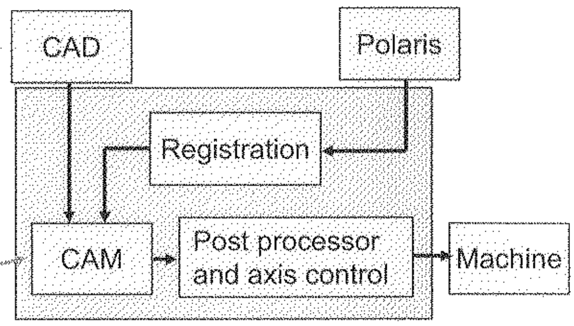
Intraoperative CAM system

Hardware

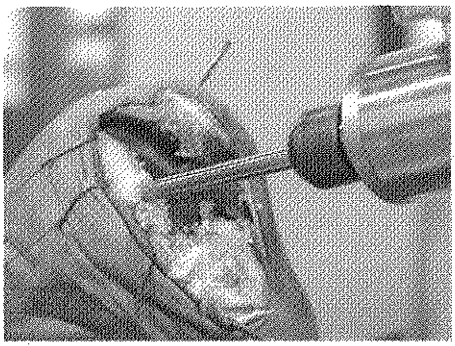


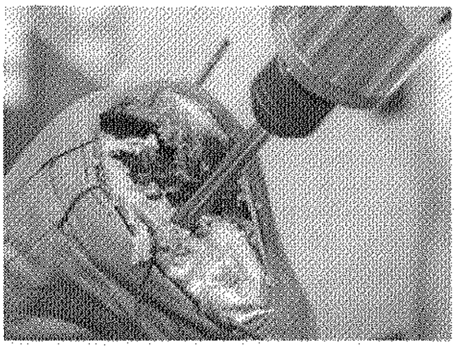
System in an operation room

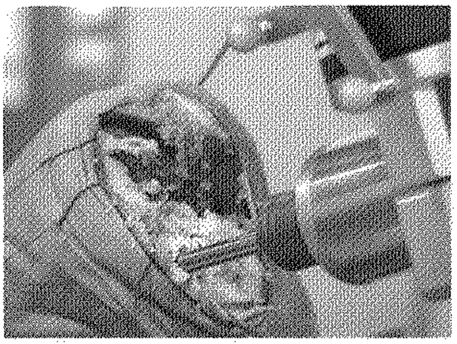


System configuration

Cutting experiment with a cadaver


Distal plane

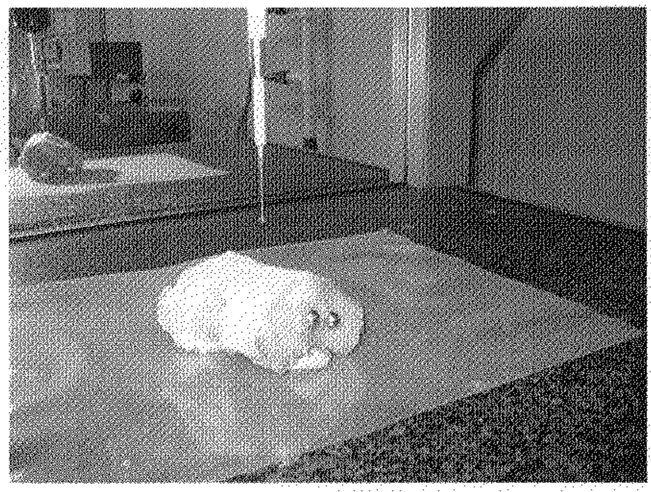

Posterior slope

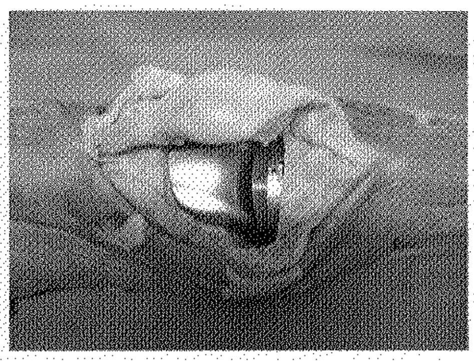

Posterior plane

Cutting Conditions:

Cutting speed: 125.6 m/min
Feed speed: 400 mm/min
Spindle speed: 5,000 rpm
Depth of cut: 3 mm
Cutting tool: end mill, biocompatible metal
Number of tooth: 4
Cutting tool diameter: 8 mm
Incision length: 100 mm

Measurement using a CMM





Experimental result: Analysis of cutting result

Angular error

Axis	Error (deg.)
Epicondyle axis	1.8
Load axis (normal to ③)	0.7

Position error of planes

Plane	Distance between local origin point and CAM calculated (mm)
Distal	0.847
Posterior	0.991

Angle error between adjacent planes

Evaluated plane	Planed (deg.)	Measured (deg.)	Error (deg.)
①−②	135.0	134.2	0.8
②−③	120.0	120.3	0.3

Conclusions

- A *medical CAD/CAM system* has been developed to assist a minimally invasive knee arthroplasty.
  - In particular, a method was proposed to measure the positions of soft tissues, and *to avoid any collision with these obstacles*.
  - The system has a feature to provide *safe operation* by not changing the posture of the bone cutting machine tool during the surgical operation.
- A multi-axis bone cutting machine tool with *safety, sterilization and irrigation capability* was implemented.
- *Minimally invasive cutting experiment* for a cadaver was performed using the developed system.
  - The angular error from the load axis of the femur was less than 2.0 deg.
  - The maximum angle error of adjacent planes was approximately 1.0 deg.
  - The position error of the planes was less than 1 mm.
  - The incision length was reduced to 100 mm.