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Meritev gibanja kolena z industrijskim robotom - avtomatska kompenzacija gravitacije prijemala

Measuring knee movement using an industrial robot – gravity compensation for the automatic gripper

Damir Omrčen - Bojan Nemec

Poškodbe kolenskih vezi pri športnikih so dokaj pogoste. Za uspešno operacijo vezi je potrebno čim natančnejše poznavanje kolena ter kolenskih vezi. V tem prispevku so opisani postopki določitve geometrijskega modela gibanja kolena. Merjenje gibanja kolena smo izvedli z industrijskim robotom. Uporabili smo robota RIKO 106 s šestimi prostostnimi stopnjami, ki je voden s silo. Površine sklepov smo posneli z uporabo koordinatnega merilnika. Na podlagi meritev smo izdelali geometrijski model na osebnem računalniku s programskim paketom Matlab.

Med merjenjem robot upogiba koleno v določeni smeri, ne sme pa vplivati na naravno gibanje kolena. Zato moramo minimizirati sile in navore, ki jih ustvari robot v kolenskem sklepu. V ta namen je treba kompenzirati tudi vplive gravitacije prijemala ter vplive merilnih odmikov zaznavala sile/navora. Med meritvijo krmilimo sile v kolenskem sklepu, zaznavalo sil pa je nameščeno v prijemalki robota, zato je treba izmerjene sile prevesti v koordinatni sistem kolenskega sklepa.

V prispevku je natančneje opisan avtomatski postopek za kompenzacijo teže prijemala in določitve merilnih odmikov. Opisana pa sta tudi postopka za preslikavo sil/navorov v kolenski sklep in postopek za določitev vrha orodja, kar potrebujemo pri meritvi.

(Ključne besede: modeli kolena, prijemala, kompenzacija gravitacije, roboti medicinski, določitev vrha orodja)

Injuries to the knee ligaments are very common among althetes. Therefore, a thorough understanding of the knee and the knee ligaments is necessary for successful surgical operations on the ligaments. This paper describes procedures for determining of the geometrical model of the knee's movement. The movement of the knee was measured with a RIKO 106, force-controlled, six-degrees-of-freedom industrial robot. The surface of the knee joint was scanned with a coordinate-measuring machine and a geometrical model of the knee was developed on a PC. For the modelling we used a computer program called Matlab.

The robot should only bend the knee in a specified direction, and should not affect the natural movement of the knee. Therefore, we had to minimize the forces and torques in the knee joint that are caused by the robot. In order to do this, we had to compensate for the influence of gravity on the gripper and the sensor offsets. During the measurement we had to control the forces/torques in the knee joint. As the force/torque sensor was attached on the robot tip the measured forces/torque had to be mapped to the knee joint.

This paper more exactly addresses the automatic procedure for the gripper-weight compensation and the offset determination. It also explains the algorithm of the transformation of the forces/torques to the knee-joint coordinate system and the automatic determination of the tool's centre point.

(Keywords: knee models, grippers, gravity compensation, medical robots, tool centre point)

0 UVOD

Poškodbe kolenskih vezi pri športnikih so dokaj pogoste. Devetdeset odstotkov vseh poškodb kolenskih vezi so poškodbe sprednje križne vezi (SKV) ter medialne kolateralne vezi (MKV) [1]. Poškodbe MKV se največkrat zacelijo same brez kirurškega

0 INTRODUCTION

Injuries to the knee ligaments are very common among athletes. Of all knee ligament injuries, 90 % are injuries to the anterior cruciate ligament (ACL) and the medial collateral ligament (MCL) [1]. The MCL heals without intervention; the ACL requires a posega [2]. Pri poškodbah SKV pa je potreben kirurški poseg [2]. Eden glavnih problemov pri vsaditvi nadomestka SKV je, kako določiti primerno mesto za vsadek. Tega ne moremo vsaditi na mestu, kjer je poškodovani SKV. Primerna so tista mesta, kjer ostane dolžina nadomestka SKV med gibanjem enaka. Zato je za uspešno operacijo vezi potrebno čim natančnejše poznavanje kolena ter kolenskih vezi. V zadnjem času poteka vrsta raziskav na to temo ([2] do [6]). Mnogo raziskav poteka v smeri merjenja sil ter raztezkov v vezeh [4], kar je pripeljalo do sklepa, da se vezi kljub dokaj velikim silam le malo raztegujejo. Nekateri raziskovalci so se usmerili v raziskovanje kinematike kolena ([5] in [6]). S tem želijo ugotoviti natančno gibanje površin sklepov v kolenu. Poznavanje natančnega gibanja bo pripomoglo k boljšemu razumevanju kolena in posledično k uspešnim operacijam kolenskih vezi.

Ta prispevek opisuje uporabo industrijskega robota za testiranje *in vitro* kadaverskega kolena. Uporabljen je robot RIKO 106 s šestimi prostostnimi stopnjami, ki je voden s silo. Z robotom smo zelo natančno izmerili kinematiko neobremenjenega kolena. Na vrhu robota je nameščeno univerzalno zaznavalo sil in navorov, ki je zmožno merjenja treh sil in treh navorov. Za zagotavljanje želenih sil in navorov, ki jih ustvari robot v kolenskem sklepu, smo uporabili hibridno krmilno shemo. Sile, ki jih merimo z zaznavalom, moramo preslikati v kolenski sklep. Kompenzirati je treba tudi gravitacijo prijemala, saj teža prijemala povzroči, da sile v sklepu niso enake nič. Tudi merilni odmiki zaznavala sile vnašajo pogreške v meritev in jih moramo prav tako kompenzirati. Preslikava sil/navorov v kolenski sklep ter kompenzacija mase ter odmikov omogočajo večje sklenjenozančno ojačanje. S tem zmanjšamo pogreške pri sledenju želene sile/navora.

Površine sklepov smo posneli z uporabo koordinatnega merilnika MicroScribe. Dobljene podatke smo obdelali s programskim paketom Matlab, v katerem je bila izpeljana tudi grafična predstavitev gibanja kolena.

1 METODE

Namen postopka je ugotavljanje natančnega gibanja neobremenjenega kolena (slika 1). Gibanje je sestavljeno iz vrtenja ter premika in ga ne moremo zapisati s preprostimi matematičnimi funkcijami. Zato predlagamo eksperimentalno določitev gibanja z uporabo industrijskega robota s šestimi prostostnimi stopnjami, ki pa mora biti voden s silo.

Golenica je trdno pritrjena na mizo, stegnenica pa je preko zaznavala sile pritrjena na vrh robota (sl. 2). Naloga robota je, da upogiba koleno od izravnanega položaja (0 °) do 110 °, pri tem morajo biti sile in navori v sklepu enaki nič. Za vodenje robota s silo je uporabljena klasična hibridna krmilna shema sila-lega.

reconstruction. One of the main problems when implanting the ACL graft is how to determine a convenient place for the graft. Unfortunately, we cannot implant the graft in a place where an injured ACL is located. Convenient places are those where the length of the ACL graft remains constant during motion. Therefore, a through understanding of the knee and the knee ligaments is necessary for a successful surgical operation. A lot of research has been done on this topic recently ([2] to [6]). An analysis of the forces and the extensions in ligaments [4] led to the conclusion that ligaments extend just a little under high forces. Some researchers studied knee kinematics ([5] and [6]) and they determined the exact motion of the knee-joint surfaces. However, knowing the exact motion of the knee would contribute to a better understanding of the human knee and would result in more effective surgical operations on knee ligaments.

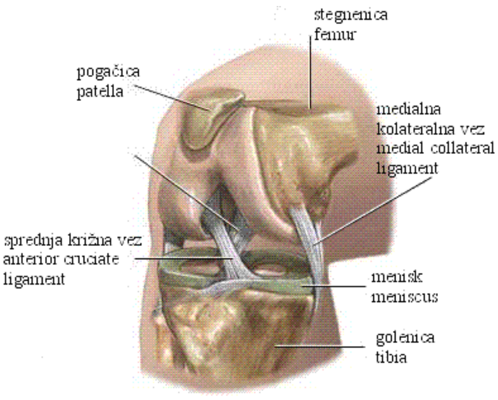
This paper describes the use of an industrial robot for *in vitro* tests on a cadaveric knee. We used a RIKO 106, force-controlled, six-degrees-of-freedom industrial robot to measure the exact kinematics of an unloaded knee. The robot tip was equipped with a universal force/torque sensor, which is capable of measuring three forces and three torques. To keep the desired forces and torques in the knee joint caused by the robot a hybrid force-position control method was used. The measured forces/torques had to be transformed to the knee-joint coordinate system. Additionally, we had to compensate for gravitational forces due to the gripper and the sensor offsets. The transformation of force/torque to the knee-joint coordinate system and the compensation of the gripper weight and offset allowed us to achieve a bigger closed-loop gain. This reduced the force/torque tracking errors.

We used the Matlab computer program for visualization, and the surface of the knee joint was scanned with the coordinate-measuring machine.

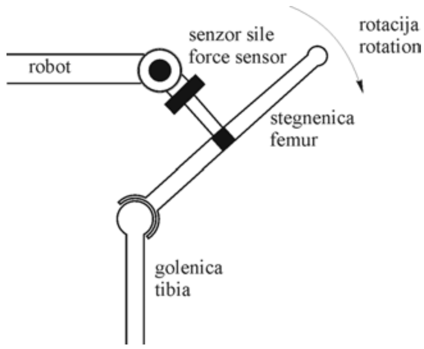
1 METHODS

Our aim was to determine the exact motion of the unloaded knee (Figure 1). This motion is a combination of rotation and translation and it cannot be expressed with simple analytical functions. We decided to determine the motion experimentally using a force-controlled robot with six degrees of freedom.

As shown in Figure 2 the tibia was attached to the table and the femur was attached to the force sensor on the robot tip. The robot had to move the knee from the straightened position (0 °) to 110 ° and during the motion the forces and torques had to be kept as small as possible. To achieve this we applied the well-known hybrid force-position control method.



Sl. 1. *Človeško koleno*
Fig. 1. *Human knee*



Sl. 2. *Vpetje golenice in stegnenice*
Fig. 2. *Attachment of the tibia and femur*

Ker teža prijemala vpliva na meritev sile, jo moramo kompenzirati pred začetkom meritve. Nato golenico trdno pritrdimo na mizo. Na golenico in stegnenico pritrdimo po tri kalibracijske točke. Z orodjem na vrhu robota izmerimo tri kalibracijske točke na golenici in jih zapišemo v koordinatnem sistemu baze robota. Prijemalo robota pripeljemo do stegnenice in jo pritrdimo. Meritev poteka tako, da koleno najprej upognemo za 7 °, nato minimiziramo sile in navore v kolenu ter izmerimo lego kolena. Postopek ponavljamo, dokler ne upognemo kolena od povsem izravnane do skrajne želene lege. Pri upogibu kolena vodimo robota hitrostno v smeri upogibanja kolena, v preostalih petih smereh pa poteka krmiljenje sile. Pri minimizaciji sil in navorov preklopimo na krmiljenje sil in navorov v vseh smereh.

Po končani meritvi gibanja izmerimo še pozicije kalibracijskih točk na stegnenici glede na vrh robota. Iz teh podatkov in iz konfiguracij robota izračunamo položaje kalibracijskih točk med gibanjem kolena. Nato se lotimo meritve geometrijske oblike kolena.

Pred merjenjem geometrijske oblike površine sklepa najprej odstranimo vse tkivo ter vezi. Nato izmerimo koordinate mreže točk na površinah sklepov ter na prijemališčih SKV. Te točke so izražene v koordinatnem sistemu koordinatnega merilnika in jih moramo prenesti v koordinatni sistem baze robota, za to potrebujemo kalibracijske točke na golenici in stegnenici. S koordinatnim merilnikom izmerimo tudi koordinate kalibracijskih točk. Ta izračun poteka v programskem paketu Matlab, v katerem je realizirana tudi grafična predstavitev gibanja.

1.1 Preslikava sil/navorov iz koordinatnega sistema (k.s.) zaznavala sile v k.s. kolenskega sklepa

S na sliki 3 prikazuje koordinatni sistem senzorja sil, **K** pa koordinatni sistem, ki je v središču kolenskega sklepa. Koordinatna sistema sta med seboj vzporedna in premaknjena za vektor ***p***. Zveza med silami ***F*** in navori ***M*** v obeh

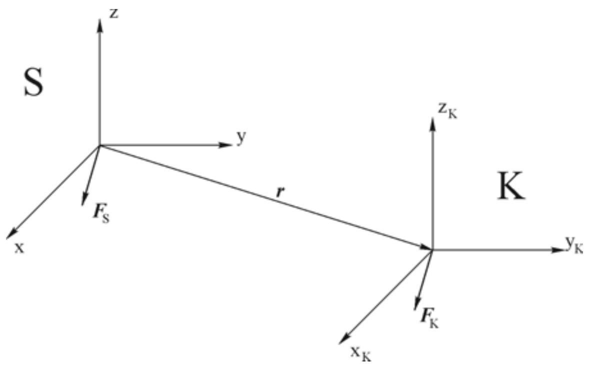
As the gripper's weight influences the force measurement it had to be compensated before the tibia was attached to the table. Next we had to determine the positions of the three calibration points that were fixed on the tibia. With the tool on the robot tip we measured the coordinates of the three calibration points in the robot-base coordinate system. Next, we had to move the gripper to the femur and attach thefemur to the gripper. Then, the robot bent the knee by 7 °. The next step was to minimize the forces and torques in the knee joint and to measure the position of the knee. The bending phase and force-minimizing phase were repeated until the knee reached the desired position (110 °). In the bending phase the robot was velocity controlled in the direction of the knee rotation and in all other directions it was force controlled. In the force-minimization phase the forces were controlled in all directions.

After the measurement cycle we had to measure the coordinates of the calibration points on the femur in the robot-tip coordinate system. These data and the robot configurations data were used to calculate the positions of the calibration points during the knee motion. After the motion measurement the knee geometry had to be determined.

Before scanning the surface of the knee we had to remove all tissues and ligaments. The coordinate-measuring machine was used to measure the coordinates of points on the knee's surface and on the ACL grip. These coordinates were then transformed to the robot-base coordinate system. For this reason calibration points on the femur and tibia were needed, and these were also measured with the coordinate-measuring machine. The calculations and visualisation were made with the Matlab program.

1.1 Transformation of force/torque from the force sensor coordinate system (c.s.) to the knee joint c.s.

Figure 3 shows the coordinate system connected to the force sensor **S** and the coordinate system connected to the centre of the knee joint **K**. These two coordinate systems should be parallel to each other and translated. The vector ***p*** is the translation



Sl. 3. *Preslikava sil/navorov iz koordinatnega sistema zaznavala **S** v koordinatni sistem kolena **K***
Fig. 3. *Force/torque transformation from the force sensor coordinate system **S** to the knee c. s. **K***

koordinatnih sistemih **S** in **K** je:

between their origins. The relation between the forces ***F*** and the torques ***M*** in the coordinate system **S** and **K** are described by the following equations:

$$\boldsymbol{F}_\mathbf{K} = \boldsymbol{F}_\mathbf{S} \quad (1)$$

$$\boldsymbol{M}_\mathbf{K} = \boldsymbol{M}_\mathbf{S} - \boldsymbol{p} \times \boldsymbol{F}_\mathbf{S} = \boldsymbol{M}_\mathbf{S} - \hat{\boldsymbol{p}}\boldsymbol{F}_\mathbf{S} \quad (2).$$

kjer se $(.)_\mathbf{S}$ in $(.)_\mathbf{K}$ nanašata na izbrani koordinatni sistem, ***p***^ pa je operator vektorskega zmnožka, povezan z vekorjem ***p***:

where $(.)_\mathbf{S}$ and $(.)_\mathbf{K}$ denote the particular coordinate system and ***p***^ is the cross-product operator associated with vector ***p***:

$$\hat{\boldsymbol{p}} = \begin{bmatrix} 0 & -p_z & p_y \\ p_z & 0 & -p_x \\ -p_y & p_x & 0 \end{bmatrix} \quad (3).$$

Oznake $(.)_x$, $(.)_y$ ter $(.)_z$ se v članku nanašajo na *x*, *y* ter *z* (.) komponente vektorja.

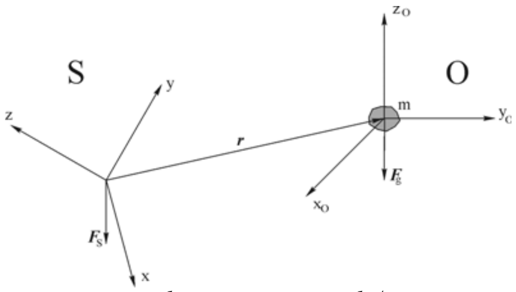
The notation $(.)_x$, $(.)_y$ and $(.)_z$ stands for the x, y and z components of vector (.), respectively.

1.2 Avtomatska kompenzacija gravitacije

Pri neobremenjenem zaznavalu želimo, da so izmerjene sile/navori enaki nič, kar pa zaradi mase prijemala in zaznavala ni res. Te sile/navore moramo kompenzirati. Masa ter težišče prijemala in zaznavala sta znana le redko. Izračun pa je mnogokrat prezapleten in ni primeren za praktične uporabe. Zato predlagamo določitev kompenzacijskih sil/navorov z meritvami. S predlaganim postopkom določimo maso in težišče prijemala in zaznavala ter tudi merilna odstopanja zaznavala.

1.2 Automatic compensation for gravity

In the case of an unloaded sensor the measured forces/torques should be equal to zero; however, due to the weight of the gripper and the sensor this is not the case and these forces/torques have to be compensated. The centre of gravity and the weight of the gripper and the sensor are rarely known. We could calculate the weight and the centre of gravity, which requires an exact knowledge of the geometry and materials; however, this calculation is often too complex and is not suitable for practical application. We propose to determine the compensation forces with measurements. Using this procedure we can determine the centre of gravity and the weight of the gripper and the sensor and also the sensor offset.



Sl. 4. *Vpliv mase prijemala m na meritev sile/navora v zaznavalu **S***
Fig. 4. *Influence of the gripper weight on the measurement of force/torque by sensor **S***

R naj pomeni robotovo rotacijsko matriko med k.s. **S** in k.s. okolja **W**, ***r*** pa je vektor med njunima izhodiščema. Kompenzacijsko silo/navor izračunamo:

Let **R** be the robot rotational matrix between the sensor c.s. **S** and the world c.s. **W** and ***r*** is the vector between their origins. Then the compensation force/torque can be calculated as:

$$\boldsymbol{F}_{comp} = \mathbf{R}\boldsymbol{F}_g = \begin{bmatrix} \boldsymbol{n} & \boldsymbol{o} & \boldsymbol{a} \end{bmatrix} \boldsymbol{F}_g = \begin{bmatrix} \boldsymbol{n} & \boldsymbol{o} & \boldsymbol{a} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ F_{g_z} \end{bmatrix} = \boldsymbol{a} F_{g_z} \qquad (4)$$

$$\boldsymbol{M}_{comp} = \boldsymbol{r} \times \boldsymbol{F}_{comp} = -\hat{\boldsymbol{F}}_{comp}\boldsymbol{r} \qquad (5),$$

kjer so vektorji ***n, o, a*** komponente matrike **R**. $\boldsymbol{F}_g$ pomeni silo gravitacije, $\boldsymbol{F}_{comp}$ in $\boldsymbol{M}_{comp}$ pa kompenzacijsko silo in navor. $\boldsymbol{F}^{\wedge}_{comp}$ je operator vektorskega zmnožka glede na vekor $\boldsymbol{F}_{comp}$

where vectors ***n, o, a*** are the components of the matrix **R**. $\boldsymbol{F}_g$ denote the gravitational force and $\boldsymbol{F}_{comp}$ and $\boldsymbol{M}_{comp}$ are the compensational force and torque and $\boldsymbol{F}^{\wedge}_{comp}$ is the cross-product operator associated with the vector $\boldsymbol{F}_{comp}$

$$\hat{\boldsymbol{F}}_{comp} = \begin{bmatrix} 0 & -F_{comp_z} & F_{comp_y} \\ F_{comp_z} & 0 & -F_{comp_x} \\ -F_{comp_y} & F_{comp_x} & 0 \end{bmatrix} \qquad (6).$$

Težava pri merjenju s temi zaznavali je tudi merilni odmik. Kompenzirano silo/navor dobimo z:

The sensor offset is also a problem and has to be compensated:

$$\boldsymbol{F}_{\mathbf{S}} = \boldsymbol{F}_{meas} - \boldsymbol{F}_{comp} - \boldsymbol{F}_{off} \qquad (7)$$

$$\boldsymbol{M}_{\mathbf{S}} = \boldsymbol{M}_{meas} - \boldsymbol{M}_{comp} - \boldsymbol{M}_{off} \qquad (8).$$

kjer $\boldsymbol{F}_{meas}$, $\boldsymbol{M}_{meas}$, $\boldsymbol{F}_{off}$, $\boldsymbol{M}_{off}$ označujejo izmerjene sile/navore ter sile/navore merilnih odmikov.

Pri neobremenjenem zaznavalu je določitev merilnega odmika preprosta, mogoče je celo izvesti odštevanje že znotraj senzorja. Kadar pa je senzor obremenjen, merilnega odmika ne moremo tako lahko določiti.

Kadar je prijemalo neobremenjeno, želimo, da sta prava sila/navor $\boldsymbol{F}_S$ in $\boldsymbol{M}_S$ enaka 0, iz (7) in (8) izhaja:

where $\boldsymbol{F}_{meas}$, $\boldsymbol{M}_{meas}$, $\boldsymbol{F}_{off}$, $\boldsymbol{M}_{off}$ are the measured and offset force and torque, respectively.

In the case of an unloaded sensor the determination of the offset is simple. It is possible to subtract the offset within the sensor. When the sensor is under the load, the offset cannot be easily determined and subtracted.

In the case of the unloaded gripper the forces/torques $\boldsymbol{F}_S$ and $\boldsymbol{M}_S$ should be equal to zero. From (7) and (8) it follows that:

$$\boldsymbol{F}_{meas} = \boldsymbol{F}_{comp} + \boldsymbol{F}_{off} \qquad (9)$$

$$\boldsymbol{M}_{meas} = \boldsymbol{M}_{comp} + \boldsymbol{M}_{off} \qquad (10).$$

Za izračun $\boldsymbol{F}_{comp}$ ter $\boldsymbol{F}_{off}$ uporabimo dve meritvi sile iz dveh različnih usmeritev vrha, ti meritvi $(.)^{(1)}$ in $(.)^{(2)}$ združimo z uporabo (4) in (9):

For the calculation of $\boldsymbol{F}_{comp}$ and $\boldsymbol{F}_{off}$ we need two force measurements in two different orientations of the gripper. These two measurements $(.)^{(1)}$ and $(.)^{(2)}$ should be combined using (4) and (9):

$$\begin{bmatrix} \boldsymbol{F}^{(1)}_{meas} \\ \boldsymbol{F}^{(2)}_{meas} \end{bmatrix} = \begin{bmatrix} \boldsymbol{a}^{(1)} F_{g_z} + \boldsymbol{F}_{off} \\ \boldsymbol{a}^{(2)} F_{g_z} + \boldsymbol{F}_{off} \end{bmatrix} = \begin{bmatrix} \boldsymbol{a}^{(1)} & \mathbf{I} \\ \boldsymbol{a}^{(2)} & \mathbf{I} \end{bmatrix} \begin{bmatrix} F_{g_z} \\ \boldsymbol{F}_{off} \end{bmatrix} \qquad (11).$$

Sistem enačb je predoločen. Z uporabo nevidezne obratne vrednosti dobimo rešitev po metodi najmanjših kvadratov:

This system is overdeterminated. Using the pseudo-inverse gives the least-square solution:

$$\begin{bmatrix} F_{g_z} \\ \boldsymbol{F}_{off} \end{bmatrix} = \left(\begin{bmatrix} \boldsymbol{a}^{(1)} & \mathbf{I} \\ \boldsymbol{a}^{(2)} & \mathbf{I} \end{bmatrix}^T \begin{bmatrix} \boldsymbol{a}^{(1)} & \mathbf{I} \\ \boldsymbol{a}^{(2)} & \mathbf{I} \end{bmatrix} \right)^{-1} \begin{bmatrix} \boldsymbol{a}^{(1)} & \mathbf{I} \\ \boldsymbol{a}^{(2)} & \mathbf{I} \end{bmatrix}^T \begin{bmatrix} \boldsymbol{F}^{(1)}_{meas} \\ \boldsymbol{F}^{(2)}_{meas} \end{bmatrix} \qquad (12).$$

Določiti moramo še težišče prijemala ter merilne odmike navora. Pri tem potrebujemo tri meritve. Z uporabo (5) in (10) dobimo:

However, we still have to calculate the centre of gravity and the torque offset. For these calculations we need three measurements. Using (5) and (10) we get:

$$\begin{bmatrix} \boldsymbol{M}^{(1)}_{meas} \\ \boldsymbol{M}^{(2)}_{meas} \\ \boldsymbol{M}^{(3)}_{meas} \end{bmatrix} = \begin{bmatrix} \boldsymbol{M}^{(1)}_{comp} + \boldsymbol{M}_{off} \\ \boldsymbol{M}^{(2)}_{comp} + \boldsymbol{M}_{off} \\ \boldsymbol{M}^{(3)}_{comp} + \boldsymbol{M}_{off} \end{bmatrix} = \begin{bmatrix} -\hat{\boldsymbol{F}}^{(1)}_{comp} & \mathbf{I} \\ -\hat{\boldsymbol{F}}^{(2)}_{comp} & \mathbf{I} \\ -\hat{\boldsymbol{F}}^{(3)}_{comp} & \mathbf{I} \end{bmatrix} \begin{bmatrix} \boldsymbol{r} \\ \boldsymbol{M}_{off} \end{bmatrix} \qquad (13)$$

in zopet z uporabo psevdoinverza:

and using the pseudo-inverse yields:

$$\begin{bmatrix} \boldsymbol{r} \\ \boldsymbol{M}_{off} \end{bmatrix} = \left(\begin{bmatrix} -\hat{\boldsymbol{F}}_{comp}^{(1)} & \mathbf{I} \\ -\hat{\boldsymbol{F}}_{comp}^{(2)} & \mathbf{I} \\ -\hat{\boldsymbol{F}}_{comp}^{(3)} & \mathbf{I} \end{bmatrix}^T \begin{bmatrix} -\hat{\boldsymbol{F}}_{comp}^{(1)} & \mathbf{I} \\ -\hat{\boldsymbol{F}}_{comp}^{(2)} & \mathbf{I} \\ -\hat{\boldsymbol{F}}_{comp}^{(3)} & \mathbf{I} \end{bmatrix} \right)^{-1} \begin{bmatrix} -\hat{\boldsymbol{F}}_{comp}^{(1)} & \mathbf{I} \\ -\hat{\boldsymbol{F}}_{comp}^{(2)} & \mathbf{I} \\ -\hat{\boldsymbol{F}}_{comp}^{(3)} & \mathbf{I} \end{bmatrix}^T \begin{bmatrix} \boldsymbol{M}_{meas}^{(1)} \\ \boldsymbol{M}_{meas}^{(2)} \\ \boldsymbol{M}_{meas}^{(3)} \end{bmatrix} \qquad (14).$$

Obračanje matrike velikosti 6x6 je problem pri uporabi preprostih računalnikov, ki se uporabljajo za vodenje industrijskih robotov. Zato predlagamo postopek za zmanjšanje velikosti invertirane matrike. Zapišimo (13) v razširjeni obliki:

Inversion of a 6x6 matrix can be a problem when a simple computer is used for the robot control. We propose the following procedure for reducing the necessary arithmetic operations. Let us rewrite (13) in its expanded form:

$$\begin{bmatrix} \boldsymbol{M}_{meas}^{(1)} \\ \boldsymbol{M}_{meas}^{(2)} \\ \boldsymbol{M}_{meas}^{(3)} \end{bmatrix} = \begin{bmatrix} \boldsymbol{M}_{comp}^{(1)} + \boldsymbol{M}_{off} \\ \boldsymbol{M}_{comp}^{(2)} + \boldsymbol{M}_{off} \\ \boldsymbol{M}_{comp}^{(3)} + \boldsymbol{M}_{off} \end{bmatrix} = \begin{bmatrix} 0 & -F_{comp_z}^{(1)} & F_{comp_y}^{(1)} & 1 & 0 & 0 \\ F_{comp_z}^{(1)} & 0 & -F_{comp_x}^{(1)} & 0 & 1 & 0 \\ -F_{comp_y}^{(1)} & F_{comp_x}^{(1)} & 0 & 0 & 0 & 1 \\ \hline 0 & -F_{comp_z}^{(2)} & F_{comp_y}^{(2)} & 1 & 0 & 0 \\ F_{comp_z}^{(2)} & 0 & -F_{comp_x}^{(2)} & 0 & 1 & 0 \\ -F_{comp_y}^{(2)} & F_{comp_x}^{(2)} & 0 & 0 & 0 & 1 \\ \hline 0 & -F_{comp_z}^{(3)} & F_{comp_y}^{(3)} & 1 & 0 & 0 \\ F_{comp_z}^{(3)} & 0 & -F_{comp_x}^{(3)} & 0 & 1 & 0 \\ -F_{comp_y}^{(3)} & F_{comp_x}^{(3)} & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -r_x \\ -r_y \\ -r_z \\ M_{off_x} \\ M_{off_y} \\ M_{off_z} \end{bmatrix} \qquad (15).$$

V tej enačbi se pojavlja šest neznank in devet enačb, od katerih je le 6 linearno neodvisnih. Če odstranimo 3., 5. in 7. vrstico, se izkaže, da dobimo 6 linearno neodvisnih vrstic (enačb):

Note that there are six unknowns and nine equations, and only six of them are linearly independent. By removing the 3rd, 5th and the 7th rows (equation) we obtain six linearly independent equations:

$$\begin{bmatrix} M_{meas_x}^{(1)} \\ M_{meas_y}^{(1)} \\ M_{meas_x}^{(2)} \\ M_{meas_z}^{(2)} \\ M_{meas_y}^{(3)} \\ M_{meas_z}^{(3)} \end{bmatrix} = \begin{bmatrix} 0 & -F_{comp_z}^{(1)} & F_{comp_y}^{(1)} & 1 & 0 & 0 \\ F_{comp_z}^{(1)} & 0 & -F_{comp_x}^{(1)} & 0 & 1 & 0 \\ 0 & -F_{comp_z}^{(2)} & F_{comp_y}^{(2)} & 1 & 0 & 0 \\ -F_{comp_y}^{(2)} & F_{comp_x}^{(2)} & 0 & 0 & 0 & 1 \\ F_{comp_z}^{(3)} & 0 & -F_{comp_x}^{(3)} & 0 & 1 & 0 \\ -F_{comp_y}^{(3)} & F_{comp_x}^{(3)} & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -r_x \\ -r_y \\ -r_z \\ M_{off_x} \\ M_{off_y} \\ M_{off_z} \end{bmatrix} \qquad (16).$$

Za izračun $\boldsymbol{r}$ in $\boldsymbol{M}_{\mathrm{off}}$ je treba obrniti matriko velikosti 6x6. Postopek poenostavimo, če zamenjamo 3. in 4. vrstico iz enačbe (16) in dobimo:

For the calculation of $\boldsymbol{r}$ and $\boldsymbol{M}_{\mathrm{off}}$ we have to invert a 6x6 matrix. The calculation can be simplified if we swap the 3rd and the 4th rows in (16) as follows:

$$\begin{bmatrix} M_{meas_x}^{(1)} \\ M_{meas_y}^{(1)} \\ M_{meas_z}^{(2)} \\ \hline M_{meas_x}^{(2)} \\ M_{meas_y}^{(3)} \\ M_{meas_z}^{(3)} \end{bmatrix} = \left[\begin{array}{ccc|ccc} 0 & -F_{comp_z}^{(1)} & F_{comp_y}^{(1)} & 1 & 0 & 0 \\ F_{comp_z}^{(1)} & 0 & -F_{comp_x}^{(1)} & 0 & 1 & 0 \\ -F_{comp_y}^{(2)} & F_{comp_x}^{(2)} & 0 & 0 & 0 & 1 \\ \hline 0 & -F_{comp_z}^{(2)} & F_{comp_y}^{(2)} & 1 & 0 & 0 \\ F_{comp_z}^{(3)} & 0 & -F_{comp_x}^{(3)} & 0 & 1 & 0 \\ -F_{comp_y}^{(3)} & F_{comp_x}^{(3)} & 0 & 0 & 0 & 1 \end{array}\right] \begin{bmatrix} -r_x \\ -r_y \\ -r_z \\ \hline M_{off_x} \\ M_{off_y} \\ M_{off_z} \end{bmatrix} \qquad (17).$$

Zapišimo zgornjo enačbo drugače:

Rewriting the upper equation yields:

$$\begin{bmatrix} \boldsymbol{M}_a \\ \boldsymbol{M}_b \end{bmatrix} = \left[\begin{array}{c|c} \mathbf{F}_a & \mathbf{I} \\ \mathbf{F}_b & \mathbf{I} \end{array}\right] \begin{bmatrix} -\boldsymbol{r} \\ \boldsymbol{M}_{off} \end{bmatrix} = \begin{bmatrix} -\mathbf{F}_a \boldsymbol{r} + \boldsymbol{M}_{off} \\ -\mathbf{F}_b \boldsymbol{r} + \boldsymbol{M}_{off} \end{bmatrix} \qquad (18).$$

Izrazimo težišče in merilne odmike navorov:

The centre of gravity and the torque offset are calculated as:

$$\boldsymbol{r} = (\mathbf{F}_b - \mathbf{F}_a)^{-1} (\boldsymbol{M}_a - \boldsymbol{M}_b) \qquad (19)$$

$$\boldsymbol{M}_{off} = \boldsymbol{M}_a + \mathbf{F}_a \boldsymbol{r} \qquad (20).$$

Za izračun $\boldsymbol{r}$ je treba obrniti le matriko ($\mathbf{F}_b$ – $\mathbf{F}_a$), ki je velikosti 3x3, kar pa ne dela posebnih težav.

Sedaj, ko poznamo vpliv gravitacije ter merilnih odmikov, moramo ta dva prispevka od meritve odšteti, da dobimo pravo vrednost:

For the calculation of $\boldsymbol{r}$ we only have to invert the matrix ($\mathbf{F}_b$ – $\mathbf{F}_a$) which is of size 3x3.

For the calculation of the force/torque without the influence of gravity on the gripper and the offset we have to subtract the gravity and offset influence from measured force/torque:

$$\boldsymbol{F}_{\mathrm{S}} = \boldsymbol{F}_{meas} - \boldsymbol{F}_{off} - \boldsymbol{F}_{comp} \tag{21}$$

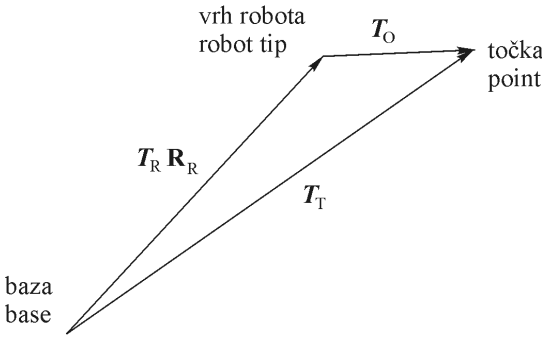
$$\boldsymbol{M}_{\mathrm{S}} = \boldsymbol{M}_{meas} - \boldsymbol{M}_{off} - \boldsymbol{M}_{comp} \quad (22).$$

1.3 Avtomatska določitev vrha orodja

Pri mnogih robotskih uporabah je treba določiti lego vrha orodja glede na vrh robota, prav tako potrebujemo znan vrh orodja za določitev koordinat kalibracijskih točk na golenici. To lego vrha lahko izračunamo ali pa izmerimo. Ker je meritev lahko dokaj nenatančna, predlagamo lažji in hitrejši postopek za avtomatsko določitev lege vrha.

1.3 Automatic determination of the tool's centre point

In many robot applications it is necessity to determine the position of the robot tool's centre point with respect to the robot tip. For the determination of the calibration points on the tibia we also need to know the position of the tool's centre point. This position can be measured or calculated. We propose a simple automatic procedure for the determination of the tool's centre point.



Sl. 5. *Prenos baznega koordinatnega izhodišča v določeno točko v prostoru*
Fig. 5. *Transfer from the robot base to a fixed point in space*

Z vrhom orodja se trikrat dotaknemo poljubne točke, vendar vsakokrat z drugo usmerjenostjo vrha robota. Pozicijo določene točke lahko izrazimo na dva načina (sl. 5):

With the tool tip we have to touch the same point in space every time using different orientations of the robot tip. The position of the point can be written in two ways:

$$\boldsymbol{T}_O + \mathbf{R}_R \boldsymbol{T}_R = \boldsymbol{T}_T \quad (23).$$

S $\boldsymbol{T}$ so označene translacije med posameznimi koordinatnimi sistemi, z $\mathbf{R}$ pa rotacije. $(.)_{\mathbf{R}}$ se nanaša na robotove transformacije, $(.)_O$ na transformacije orodja, $(.)_T$ pa na transformacije točke. Pozicija neke točke glede na bazo je sestavljena iz translacije robota $\boldsymbol{T}_R$ ter translacije orodja $\boldsymbol{T}_O$, ki je zarotirana za rotacijsko matriko robota $\mathbf{R}_R$. Pozicijo te iste točke pa lahko opišemo tudi s translacijo $\boldsymbol{T}_T$ od baze do točke.

V tej enačbi sta znani translacija in rotacija robota, transformacije točke ne poznamo, iščemo pa translacijo orodja $\boldsymbol{T}_O$. Za določitev neznank potrebujemo tri meritve $(.)^{(.)}$ – tri konfiguracije robota, tako da vrh orodja kaže v enako točko. Zapišimo sistem s tremi konfiguracijami v matrični obliki:

T denotes a translation between two coordinate systems, **R** denotes rotations between them and $(.)_R$ relates to the robot transformation, $(.)_O$ relates to the tool transformation and $(.)_T$ relates to the point transformation. The position of the point with respect to the base is calcualted from the robot translation $\boldsymbol{T}_R$ and the tool translation $\boldsymbol{T}_{\mathrm{O}}$, which is rotated with a robot rotational matrix $\mathbf{R}_R$. The position of the same point can be described as translation $\boldsymbol{T}_T$ from the base to the point.

The robot translations and rotations are known, however, we have to obtain the tool translation $\boldsymbol{T}_O$. Equation (23) has three equations and six unknowns. In order to solve eq. (23) we need three robot configurations $(.)^{(.)}$ when the tool centre point points to the same point in space with different orientations. Combining (23) for three measurements we obtain:

$$\begin{bmatrix} \mathbf{R}_R^{(1)} & -\mathbf{I} \\ \mathbf{R}_R^{(2)} & -\mathbf{I} \\ \mathbf{R}_R^{(3)} & -\mathbf{I} \end{bmatrix} \begin{bmatrix} \boldsymbol{T}_O \\ \boldsymbol{T}_T \end{bmatrix} = \begin{bmatrix} -\boldsymbol{T}_R^{(1)} \\ -\boldsymbol{T}_R^{(2)} \\ -\boldsymbol{T}_R^{(3)} \end{bmatrix} \tag{24}$$

Sistem je mogoče rešiti z uporabo navidezne obratne vrednosti:

This system could be solved using the pseudo-inverse:

$$\begin{bmatrix} \boldsymbol{T}_O \\ \boldsymbol{T}_T \end{bmatrix} = \left(\begin{bmatrix} \mathbf{R}_R^{(1)} & -\mathbf{I} \\ \mathbf{R}_R^{(2)} & -\mathbf{I} \\ \mathbf{R}_R^{(3)} & -\mathbf{I} \end{bmatrix}^T \begin{bmatrix} \mathbf{R}_R^{(1)} & -\mathbf{I} \\ \mathbf{R}_R^{(2)} & -\mathbf{I} \\ \mathbf{R}_R^{(3)} & -\mathbf{I} \end{bmatrix} \right)^{-1} \begin{bmatrix} \mathbf{R}_R^{(1)} & -\mathbf{I} \\ \mathbf{R}_R^{(2)} & -\mathbf{I} \\ \mathbf{R}_R^{(3)} & -\mathbf{I} \end{bmatrix}^T \begin{bmatrix} -\boldsymbol{T}_R^{(1)} \\ -\boldsymbol{T}_R^{(2)} \\ -\boldsymbol{T}_R^{(3)} \end{bmatrix} \tag{25}$$

Zaradi zmanjšanja velikosti obratne matrike uporabimo postopek, ki je bil opisan v prejšnjem poglavju:

However, we propose the same procedure as in the previous section, which results in an easier matrix inversion:

$$\left[\begin{array}{ccc|ccc} n_x^{(1)} & o_x^{(1)} & a_x^{(1)} & -1 & 0 & 0 \\ n_y^{(1)} & o_y^{(1)} & a_y^{(1)} & 0 & -1 & 0 \\ n_z^{(2)} & o_z^{(2)} & a_z^{(2)} & 0 & 0 & -1 \\ \hline n_x^{(2)} & o_x^{(2)} & a_x^{(2)} & -1 & 0 & 0 \\ n_y^{(3)} & o_y^{(3)} & a_y^{(3)} & 0 & -1 & 0 \\ n_z^{(3)} & o_z^{(3)} & a_z^{(3)} & 0 & 0 & -1 \end{array}\right] \begin{bmatrix} \boldsymbol{T}_O \\ \boldsymbol{T}_T \end{bmatrix} = - \left[\begin{array}{c} T_{R_x}^{(1)} \\ T_{R_y}^{(1)} \\ T_{R_z}^{(2)} \\ \hline T_{R_x}^{(2)} \\ T_{R_y}^{(3)} \\ T_{R_z}^{(3)} \end{array}\right] \tag{26}$$

Zaradi preprostejšega obračanja matrike, zapišemo sistem enačb:

Rewrite (26) into:

$$\begin{bmatrix} \mathbf{R}_{R_a} & -\mathbf{I} \\ \mathbf{R}_{R_b} & -\mathbf{I} \end{bmatrix} \begin{bmatrix} \boldsymbol{T}_O \\ \boldsymbol{T}_T \end{bmatrix} = - \begin{bmatrix} \boldsymbol{T}_{R_a} \\ \boldsymbol{T}_{R_b} \end{bmatrix} \tag{27}$$

in dobimo:

and finally we obtain

$$\boldsymbol{T}_O = (\mathbf{R}_{R_a} - \mathbf{R}_{R_b})^{-1} (\boldsymbol{T}_{R_b} - \boldsymbol{T}_{R_a}) \tag{28}$$

Z uporabo te preproste enačbe določimo pozicijo vrha orodja glede na vrh robota. Vrh orodja je treba trikrat čim natančneje pripeljati v določeno točko v prostoru. Natančnost določitve $\boldsymbol{T}_O$ je odvisna od natančnosti robota in natančnosti dotika točke. Brez težav pa lahko dosežemo natančnost pod 0,5 mm.

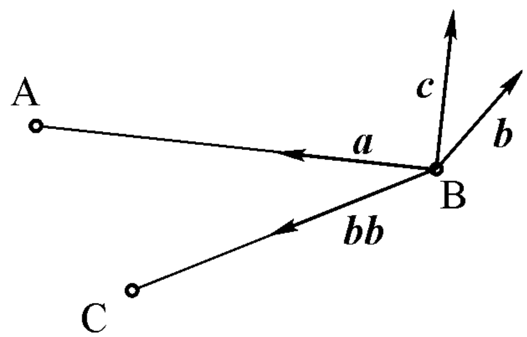
The position of the tool tip with respect to the robot tip is determined using this simple equation. We only need to move the robot tool to same point in space. The accuracy of $\boldsymbol{T}_O$ depends on the robot accuracy and the accuracy of the touch. The accuracy can be better that 0.5 mm.

1.4 Obdelava podatkov ter grafična predstavitev

Točke, ki smo jih izmerili na koordinatnem merilniku, moramo prenesti v koordinatni sistem robota. Za ta namen uporabimo po tri kalibracijske točke (A, B, C) na golenici in stegnenici. Iz teh treh točk najprej določimo rotacijsko matriko ravnine, ki poteka skozi te tri točke (slika 6).

1.4 Data calculating and graphical presentation

The points measured with the coordinate-measuring machine had to be transformed to the robot-base coordinate system. To do this three calibration points (A, B, C) on the tibia and femur are needed. Using these three points we define the rotational matrix of the plane, which contains these three points.



Sl. 6. *Določanje rotacijske matrike ravnine*
Fig. 6. *Defining of the plain rotational matrix*

Med točkama B in A ter B in C določimo enotina vektorja $\boldsymbol{j}$ ter $\boldsymbol{m}$. Normirani vektorski zmnožek med njima da normalo na ravnino ($\boldsymbol{l}$). Za določitev vrtilne matrike pa potrebujemo še en pravokotni vektor $\boldsymbol{k}$:

Between points B and A and between B and C we define the unit vectors $\boldsymbol{j}$ and $\boldsymbol{m}$, respectively. The normalized vector product between $\boldsymbol{j}$ and $\boldsymbol{m}$ gives us the plane normal $\boldsymbol{l}$. To define the rotational matrix we need one more prependicular vector $\boldsymbol{k}$:

$$\boldsymbol{j} = \frac{\overrightarrow{BA}}{\|\overrightarrow{BA}\|} \tag{29}$$

$$\boldsymbol{m} = \frac{\overrightarrow{BC}}{\|\overrightarrow{BC}\|} \tag{30}$$

$$\boldsymbol{l} = \frac{\boldsymbol{j} \times \boldsymbol{m}}{\|\boldsymbol{j} \times \boldsymbol{m}\|} \tag{31}$$

$$\boldsymbol{k} = \frac{\boldsymbol{j} \times \boldsymbol{l}}{\|\boldsymbol{j} \times \boldsymbol{l}\|} \tag{32}$$

$$\mathbf{R} = [\boldsymbol{j}|\boldsymbol{k}|\boldsymbol{l}]^T \qquad (33).$$

Kot translacijo vzamemo pozicijo točke B. Tako dobimo po dve rotacijski matriki ($\mathbf{R}$) ter dve translaciji ($\boldsymbol{T}$) za golenico in stegnenico, eno za meritev z robotom $(.)_R$ in drugo za meritev s koordinatnim merilnikom $(.)_{cm}$. Vse točke na površinah sklepov ($\boldsymbol{P}$), ki so izmerjene s koordinatnim merilnikom, prenesemo v koordinatni sistem robota:

The translation $\boldsymbol{T}$ is the position of the point B. So we have two rotational matrices ($\mathbf{R}$) and two translations ($\boldsymbol{T}$) for tibia and femur, one for robot $(.)_{\mathbf{R}}$ measurement and one for the coordinate-measuring $(.)_{cm}$ machine measurement. All the points on the knee surfaces ($\boldsymbol{P}$) that were measured with coordinate measuring machine had to be transformed to the robot-base coordinate system using:

$$\boldsymbol{P}_R = \mathbf{R}_R(\mathbf{R}_{cm}^{-1}(\boldsymbol{P}_{cm} - \boldsymbol{T}_{cm})) + \boldsymbol{T}_R \qquad (34).$$

Podatke smo preračunali s programskim paketom Matlab, v katerem je bil izveden tudi izris (slika 9).

The calculations and graphical presentation were made with the Matlab program (Figure 9).

2 REZULTATI

2 RESULTS

Meritve smo izvajali na prašičevem kolenu, ki je po zgradbi najbolj podobno človeškemu (sl. 7). Izvedli smo vrsto 10 meritev z zelo dobro ponovljivostjo. Sile ter navori v sklepu so bili znotraj 0,5 N oziroma 0,05 N m. Vzporedno z merivijo z robotom smo izvajali tudi testno merjenje s koordinatnim merilnikom MicroScribe, katerega natančnost je 0,01 mm. Meritev z robotom se je izkazala za dovolj natančno. S koordinatnim merilnikom smo pomerili tudi površine sklepov (sl. 8), in sicer na vsaki površini sklepa po 20 do 30 točk.

Grafična predstavitev je potekala v programskem paketu Matlab (sl. 9), pri katerem smo tudi računali dolžino l srednjega vlakna SKV (sl. 10).

The measurements were performed on a porcine knee, the structure of which is similar to a human knee (Figure 7). We performed a series of 10 measurements. Forces and torques in the knee joint were within 0.5 N and 0.05 N m, respectively. For control purposes we also measured the positions of control points with the MicroScribe coordinate-measuring machine. The accuracy of the MicroScribe machine is better than 0.01 mm. We checked the measurement accuracy of the robot with MicroScribe. The measuring accuracy of the robot was better than 0,5 mm. Using MicroScribe we also scanned the surface of the knee joint (Figure 8). On every surface we measured 20 to 30 points.

A graphical presentation of the knee movement was made with the Matlab program package (Figure 9), the length l of the ACL during the motion was also computed (Figure 10).

3 SKLEP

3 CONCLUSIONS

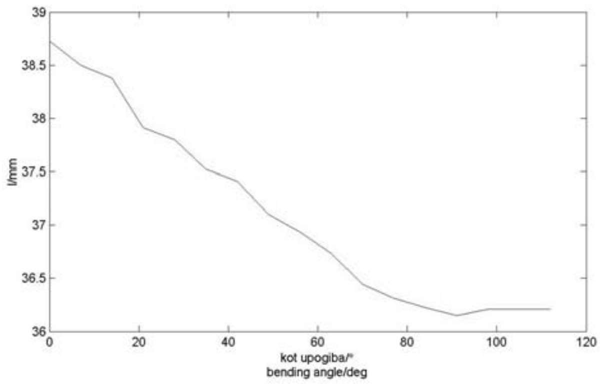
V prispevku smo obravnavali postopek za natančno določitev gibanja kolenskega sklepa. Pri tem smo uporabili industrijskega robota, ki je voden s silo. Zaradi tega je bilo treba kompenzirati vpliv

This paper describes procedures for a determination of the geometrical model of knee movement. The movement of the knee was measured with a force-controlled industrial robot. To do this we had to com-

Sl. 7. *Postopek meritve*
Fig. 7. *Measurement procedure*

Sl. 8. *Snemanje površine sklepa*
Fig. 8. *Scanning of knee surfaces*

Sl. 9. *Grafični prikaz površin kolena v Matlabu*
Fig. 9. *Graphical presentation of the knee surfaces in Matlab*



Sl. 10. *Prikaz dolžine SKV med gibanjem kolena*
Fig. 10. *Length of the ACL during knee movement*

gravitacije prijemala na zaznavalo sile/navora ter merilne odmike zaznavala.

Avtomatska kompenzacija gravitacije prijemala ter merilnih odmikov se je izkazala kot zelo uporabno orodje v robotiki. Postopek je preprost, hiter in dovolj natančen, tudi kadar imamo opravka z majhnimi silami/navori. V našem primeru kompenzacija zagotavlja majhne sile/navore v sklepu, s tem pa dosežemo boljšo stabilnost vodenja. Dodaten prispevek k stabilnosti je prinesla preslikava sil/navorov v sklep.

Razvili smo celovit sistem za meritev in prikaz gibanja kolen. Ta sistem bi bilo mogoče uporabiti v zdravstvene namene za prikaz gibanja kolena. S programom lahko izračunamo raztezke vezi, ki so pritrjene nekje na kosti, to pa je pri zamenjavi vezi ključnega pomena.

pensate the influence of gravity on the gripper and the sensor offsets.

The automatic gravity and offset compensation results in a very useful robotic tool. The procedure is very simple and sufficiently accurate, even when we are dealing with small forces and torques. In our case the compensation ensures small forces/torques in the knee joint and therefore a better control stability. An additional contribution to the stability is the transformation of the forces/torques from the force/torque sensor to the knee-joint coordinate system.

We developed a system for measuring and graphically presentating of human knees. This system can be used for medical purposes, for the animation of the knee movement. The most important thing in ligaments implantation is calculating the ligaments extension. This calculation can be performed with the developed system.

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