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Chapter 7

Accuracy of Computer Navigated Patellar Tracking in Total Knee Arthroplasty. The influence of velocity of movement and marker occlusion on validity

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submitted

■ Abstract

Objectives

Complications after total knee arthroplasty (TKA) often involve the patellofemoral joint. Computer assisted surgery has been advocated to address these problems intra-operatively, in order to have the possibility to correct directly during surgery. This study measured the changes of the virtual patellofemoralkneekinematics during different velocities of an flexion-extension cycle (FE-EF) to validate tracking on a CAOS system.

Methods

An experimental knee set-up was used, which allowed single axis tibiofemoral and patella movement. The patellar kinematics was measured during active EF and FE motions at different velocities. Measurements obtained during flexion-extension movements were modeled using second-order polynomials based on least squares estimation in order to estimate means per time cycle. One way analysis of variance by ranks was performed using (non-parametric) Kruskal–Wallis test.

Results

The patellar motion was significantly different between the different EF-FE motion velocities. The measurements per time cycle were highly reproducible and excellent model fits were obtained; $R^2 > 0.95$ in all cases and $R^2 > 0.99$ for 90% of cases.

One way analysis of variance by ranks for the values at 20, 45 and 70 degrees of flexion showed significant differences per F and E motion at the different velocities. It is also shown that the positions in flexion and extension differ in a timecyclus and this difference gets larger at higher velocities.

Conclusions

The pattern of patellar tracking as presented during CAOS was influenced by the velocity of movement during a EF-FE cycle. One should be aware of this phenomenon when using this patella tracking system.

■ Introduction

Anterior knee pain following knee arthroplasty (TKA) is a common complaint, and is often related to abnormal tracking behaviour of the patellofemoral joint (maltracking).[1,2] Several factors influence patellar tracking, including prosthetic design, surgical technique and placement of the components.

Patellofemoral complications are a major cause of poor function in the prosthetic knee. There is good experimental and clinical evidence that poor femoral component rotational alignment can adversely affect patellar tracking and kinematics Intra-operative monitoring and evaluation of the patellar tracking during total knee arthroplasty gives intraoperative feedback to the surgeon on potential (mal)alignment of the kneeprosthesis. The patello femoral motion is a six degree-of-freedom motion, with translations along and rotations about an axis. Four of these motions can be related to the clinical shift, tilt, flexion, and rotation of the patella. In knee arthroplasty these patellar movements are the end result of the kneeprosthesis position. If the rotation of either the femoral or tibial component is too far off, the end result will be an dislocating patella. By adding the patellar component position and its movement within a CAOS system, might give the surgeon feedback on the ultimate component position. More subtle corrections in patellar maltracking (e.g. change of rotation of the tibial component) will be possible by soft tissue releases if visualized by CAOS compared to the normally considered "rule-of-no-thumb". The latter indicating intraoperative good patellar tracking while flexing the knee without pushing the patella in place. It is obvious that this method can only judge gross patellar maltracking (i.e. dislocation) and not subtle differences in patellar maltracking.

Computer assisted orthopaedic surgery (CAOS) systems are potentially valuable in giving intraoperatieve feed back on this patellar tracking to surgeons. Thus adjustments to patella position with respect to femoral and tibial component (or vice versa) might give an optimal patellar tracking. Futhermore since data are stored in the CAOS system, offline analysis is possible with subsequent evaluations of associations between clinical symptoms and dynamic patellar tracking. However, before such analyses can be performed, the validity of intra-operative patellar tracking during TKA surgery has to be evaluated. As was shown earlier, validity of CAOS systems is determined by the CAOS software as well as by the operator (i.e. surgeon).[3]

The aim of this study was to evaluate the validity of the patellar tracking software which is present in a CAOS system.

■ Materials and Methods

The patellofemoral and tibiofemoral joint kinematics are inter-related via the femoral component after TKA. Thus, an alteration of one factor alters the kinematics of the other joint.[4,5] Therefore, a phantom knee model was used in an experimental setup, in which a femoral and tibial sawbone were connected to each other with a hinge (figure 1), The clinical situation is confused by the variable relationship between the tibiofemoral and patellofemoral articulations thus only a single plane (extension and flexion) movement was allowed in the experimental set-up. In order to evaluate only the effect of a flexion and extension motion on patellar tracking motions the femoral and tibial sawbone were attached with a hinge. Thus the knee joint could only make motions in the sagittal plane (i.e. flexion and extension). The patellar sawbone was connected to the femur with a hinge, thus only movement in again a single, sagital plane was possible.

The patellar tendon was simulated with a length of non-elastic rope, thus coupling the motions of the patella to the motions of the tibia. The femur was fixed with the most-posterior parts of the femoral condyles horizontal. The component of the quadriceps was loaded with hanging weights using cables and pulleys with a total of 5N, according to the physiological directions of the quadriceps muscles relative to the femoral axis. From the upper pole of the patella, a second non-elastic rope was aligned with the center of the hip by a pulley wheel and loaded with a 0.5 kg weight, hanging downwards, thus imitating the quadriceps pull. The two hinges eliminated medio-lateral and tilting motions of the patella (figure 2). Thus, only rotation of the patella around the ‘epicondylar axis’ during flexion and extension was possible.

Data from the patellar tracking, which were analysed off line from the CAOS system, were: the patellar medio-lateral shift and, the medio-lateral tilt during the FE motion of the knee, and the off-circle distance with respect to the EF-FE velocity and knee flexion. All tracking results are also saved in a.text-file created by the software module.

The file contained information at certain points in time during testing of:

- Flexion: TF flexion in degrees.
- Shift: Medial-lateral patella shift in mm.
- yRot: Tilt, rotation around patella AP direction in degrees.
- zRot: Internal/External patella rotation in degrees.
- OffCircleDistance: Distance between patella and initial patella circle in mm.

The patellar tracking functionality of the CAOS system of Brainlab (BrainLAB CT Free Vector Vision navigation system, Version 1.6, BrainLAB, Heimstetten, Germany) was used throughout the experiments. This system was used according to the manufacturer's manual, it requires the use of two marker-trees next to the patellar tracking marker tree, which are attached to the femur and the tibia using a two-pin fixation device. For the registration of the patellar motion a third marker-tree is attached to the anterior surface of the patella (figure 1). Each marker-tree has three retro-reflective (passive) markers. All three marker trees are registered within the CAOS system and matched to the dimensionsof the phantom knee model during a registration process by manually indicating landmarks at the femur, tibia, and patellar saw bones. This matching process is guided through the Brainlab software according to a guided visual flow at the CAOS screen. To this purpose, the femoral head has to pivot in a ball and socket construction to determine the centre of rotation of the hip joint. This point is used for the virtual reconstruction of limb axes. After registration, the femur was fixed in a neutral horizontal position.

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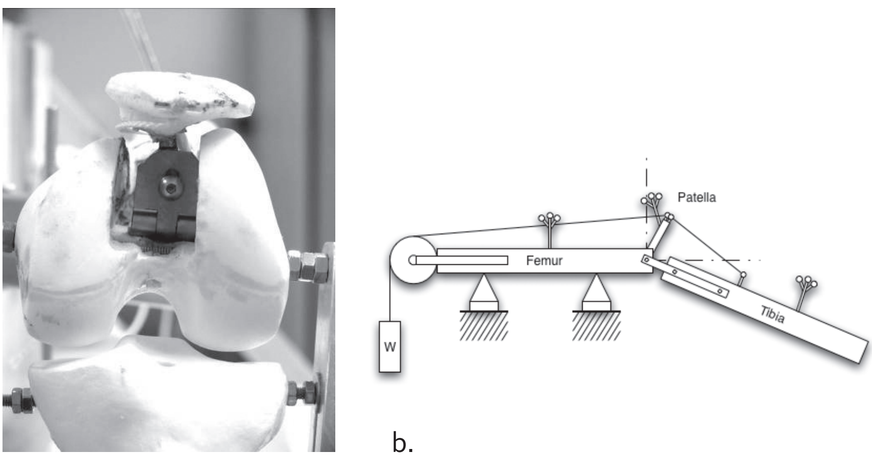

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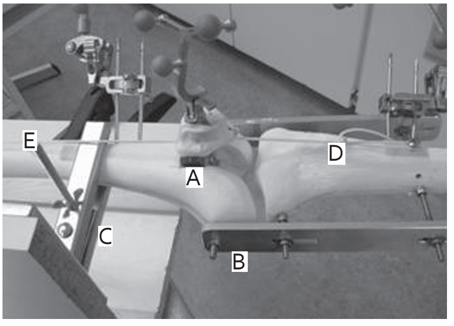

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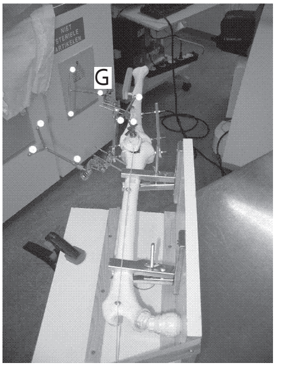


Figure 1. showing the model of the knee used to evaluate the patella tracking navigation module.

1a: detailed AP view of bended knee showing the hinge on which the patella is attached
1b: schematic view of the model
1c.d: model in full extension from lateral and AP view showing the separate parts:
A: Patella fixed at a hinge
B: External tibial hinge
C: Femur clamp
D: Patellar tendon
E: Quadriceps
F: Hip joint
G: Lateral malleolus

The knee was moved into two cycles of flexion–extension, against the extending moment of the quadriceps tension, using a rod held transversely against the anterior surface of the distal tibia.

Data collected during knee extension and flexion were saved in the Brainlab system for analysis.

For patellar lateral translation (or shift), the position in extension of the knee was designated as 0 mm. Lateral patellar tilt was defined as a rotation about the longitudinal axis of the patella (figure 2) with positive values indicating that the lateral patella approached the femur. Positive patellar lateral rotation means that the distal patella moved laterally relative to its centre.

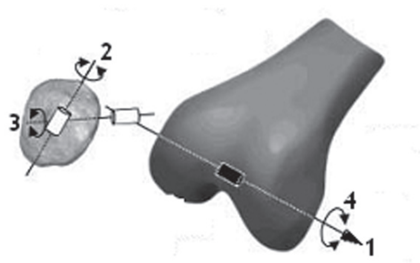


Figure 2. Patellar motion. A three cylinder open-chain-representation of the PF-joint. 1: Shift 2: Tilt 3: Rotation 4: Flexion. Because of the hinge, only patella motion in flexion/extension was possible.

In order to validate the (virtual) data produced by the patella tracking software of the CAOS system, matching was performed with the actual movements of the patella and knee in the sagittal plane. Data of patellar tracking were recorded by the COAS system during extension / flexion (EF) and reverse motion of the knee. Data were analysed off-line from the research module in the BrainLab CAOS.

Three effects were studied: First the effect of the extension / flexion (EF) and reverse movement (FE) on virtual patellar tracking. Each flexion motion ranged from 0º extension to 90º of knee flexion and vice versa and was repeated 10 times. Secondly, the influence of the velocity of flexion and extension movement was evaluated by applying a range of different flexion / extension cycle times: 60, 30, 10, and 2 seconds to this knee motion. Thus, a total of 4 series of 10 flexion-extension (FE) motion measurements of the knee were collected.

Finally, the influence of partial occlusion of the marker trees on patellar tracking visualisation was evaluated. The effect of marker occlusion on patellar tracking registration was tested by separately occluding the marker-tree of the femur, patella and tibia. Each of the three marker trees were occluded once during one cycle of EF and FE in 10 seconds.

■ Statistical analysis

Patella position data (medio-lateral shift, off circle distance, tilt etc.) were recorded from the FE and EF curves, for analysis maximum values at predetermined intervals of flexion angles (i.e. 0, 10, 20, 30, 45, 60, 70, 90 degrees) were used. These values correspond to knee flexion angles used in patellar motion.

Measurements obtained during individual flexion-extension movements were modeled using second-order polynomials based on least squares estimation in order to estimate means per time cycle (5 repeats per time cycle). The measurements per time cycle were highly reproducible and excellent model fits were obtained; $R^2 > 0.95$ in all cases and $R^2 > 0.99$ for 90% of cases. One way analysis of variance by ranks was performed using the (non-parametric) Kruskal – Wallis test for flexion values of 20, 45 and 70 degrees.

■ Results

Overall there is a curved motion visible of the "hinged" patella during the extension-flexion-extension motion of the hinged knee joint. There was a difference in motion pattern seen between a slow (60 sec) and fast (2 sec) speed flexion motion. A fast motion caused a far more visible difference between the path followed during flexion motion and the way back during the extension motion. The motion patterns are shown in figure 3. The maximum difference of the measured patella position during the flexion versus the extension motion are shown in table 1a,b.

Patellar motion				
Degr of flexion	Shift (mm)	Tilt (mm)	Rotation (mm)	Circle distance (mm)
0	0.2	0.3	0.4	0.2
10	2	7	2	2
20	4	8	5	6
30	5	10	7	8
40	6	13	10	10
50	6	10	11	10
60	5	7	10	7
70	5	5	10	5
80	4	3	5	4
90	2	1	3	2

a.

Knee	Patellar motion			
Degr of flexion	Shift (mm)	Tilt (mm)	Rotation (mm)	Circle distance (mm)
0	0.3	0.1	0.2	0.3
10	0.3	0.6	0.4	0.4
20	0.5	0.8	0.5	0.6
30	0.7	0.9	0.6	0.7
40	0.8	0.9	0.6	0.8
50	1.0	0.9	0.7	0.9
60	0.8	0.8	0.8	0.9
70	0.7	0.7	0.7	0.8
80	0.5	0.5	0.6	0.6
90	0.1	0.3	0.4	0.5

b.

Table 1 a. Maximal difference in measured patella position during a fast (2 sec) flexion vs extension motion **b**. Maximal difference in measured patella position during a slow (60 sec) flexion vs extension motion

The patellar motion had an initial medial translation of 5.8mm ± 2 mm from 0º to 40º flexion ($P < 0.05$) followed by lateral translation of 5 ± 2 mm ($P < 0.001$) by 90º flexion. After TKA, the patella was 4 ± 3 mm ($P < 0.01$) more medial than in the native knee at 0º flexion. A significant difference was not shown between 5º and 60º. (Table 2)

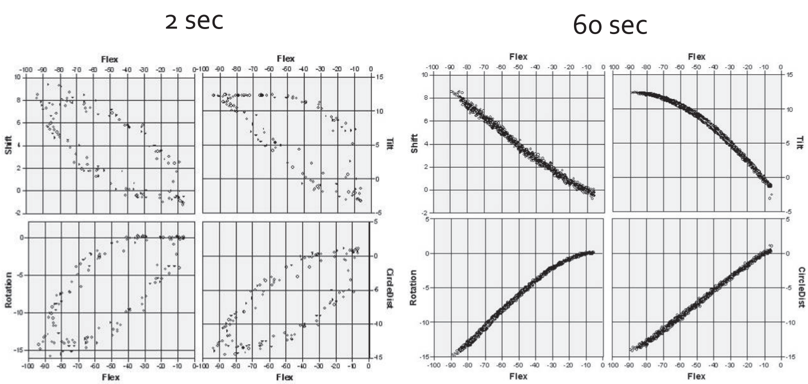


Figure 3. Registration of patellar position during flexion and extension at a extension-flexion and flexion-extension time of 2 and 60 seconds

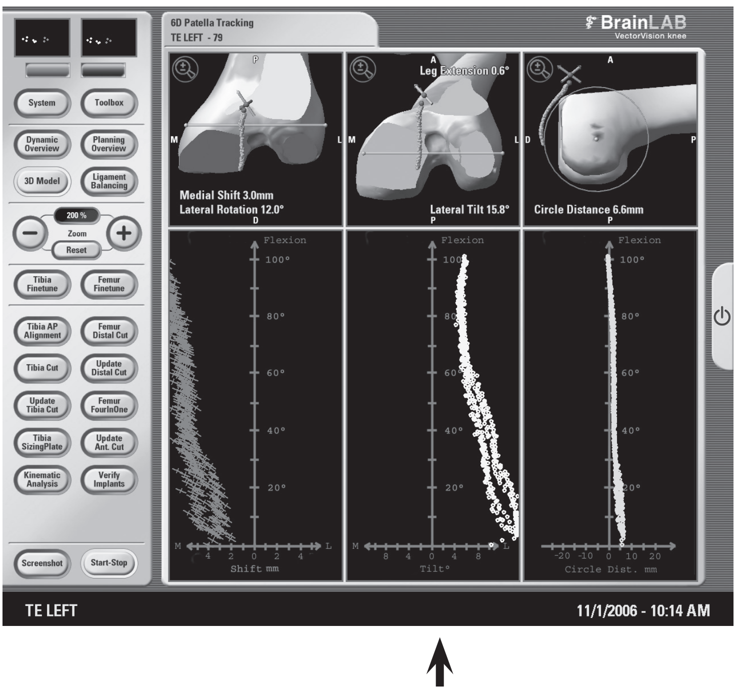
		Shift		y-Rotation		z-Rotation		Off circle	
Motion	Time cycle	During flexion (0° - 90°)	During extension (90° - 0°)	During flexion (0° - 90°)	During extension (90° - 0°)	During flexion (0° - 90°)	During extension (90° - 0°)	During flexion (0° - 90°)	During extension (90° - 0°)
At 20° flexion	2	-0.63 (0.16)	2.78 (0.67)	-1.35 (0.60)	7.00 (1.39)	0.28 (0.22)	-4.33 (1.13)	0.48 (0.26)	-5.43 (1.09)
	5	0.15 (0.04)	1.21 (0.08)	0.88 (0.18)	3.83 (0.09)	-0.59 (0.07)	-1.61 (0.08)	-0.91 (0.09)	-2.69 (0.10)
	10	0.26 (0.04)	1.03 (0.02)	1.27 (0.17)	3.28 (0.06)	-0.62 (0.09)	-1.32 (0.08)	-1.13 (0.10)	-2.28 (0.07)
	20	0.49 (0.07)	0.92 (0.07)	1.79 (0.13)	2.91 (0.07)	-0.71 (0.04)	-1.14 (0.05)	-1.36 (0.06)	-2.05 (0.06)
	30	0.54 (0.06)	0.86 (0.04)	1.92 (0.05)	2.81 (0.04)	-0.77 (0.15)	-1.06 (0.07)	-1.45 (0.01)	-1.92 (0.05)
	45	0.61 (0.03)	0.83 (0.03)	2.03 (0.06)	2.76 (0.02)	-0.84 (0.04)	-1.04 (0.05)	-1.51 (0.04)	-1.89 (0.03)
	60	0.67 (0.04)	0.85 (0.04)	2.11 (0.06)	2.66 (0.19)	-0.83 (0.04)	-1.04 (0.04)	-1.52 (0.02)	-1.85 (0.02)
p		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
At 45° flexion	2	0.73 (0.47)	6.02 (0.92)	3.26 (1.04)	11.04 (0.70)	-1.03 (0.67)	-10.15 (1.73)	-2.16 (0.84)	-10.47 (1.26)
	5	2.61 (0.14)	4.00 (0.13)	6.97 (0.18)	9.18 (0.12)	-3.99 (0.13)	-6.40 (0.29)	-5.33 (0.16)	-7.49 (0.27)
	10	2.77 (0.12)	3.71 (0.10)	7.26 (0.19)	8.87 (0.09)	-4.16 (0.18)	-5.80 (0.13)	-5.55 (0.15)	-7.00 (0.14)
	20	3.00 (0.08)	3.60 (0.08)	7.56 (0.05)	8.51 (0.08)	-4.36 (0.04)	-5.37 (0.13)	-5.81 (0.05)	-6.72 (0.11)
	30	3.04 (0.04)	3.49 (0.06)	7.66 (0.08)	8.50 (0.06)	-4.46 (0.20)	-5.21 (0.15)	-5.93 (0.04)	-6.57 (0.11)
	45	3.13 (0.06)	3.41 (0.04)	7.77 (0.07)	8.38 (0.06)	-4.63 (0.04)	-5.06 (0.07)	-6.00 (0.06)	-6.47 (0.06)
	60	3.16 (0.06)	3.40 (0.06)	7.82 (0.07)	9.29 (0.47)	-4.71 (0.09)	-5.15 (0.05)	-6.09 (0.04)	-6.53 (0.05)
p		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
At 70° flexion	2	3.61 (0.60)	8.14 (0.83)	8.05 (1.11)	12.75 (0.56)	-5.96 (1.27)	-13.91 (1.43)	-7.05 (1.13)	-13.51 (1.11)
	5	5.54 (0.18)	6.78 (0.10)	10.93 (0.26)	12.00 (0.11)	-9.27 (0.16)	-11.56 (0.16)	-9.90 (0.21)	-11.62 (0.21)
	10	5.72 (0.18)	6.56 (0.13)	11.02 (0.25)	11.93 (0.19)	-9.38 (0.25)	-11.04 (0.16)	-10.08 (0.19)	-11.30 (0.22)
	20	5.91 (0.11)	6.45 (0.12)	11.16 (0.10)	11.60 (0.09)	-9.65 (0.08)	-10.80 (0.20)	-10.37 (0.11)	-11.21 (0.19)
	30	5.92 (0.10)	6.40 (0.13)	11.22 (0.16)	11.78 (0.06)	-9.91 (0.23)	-10.76 (0.26)	-10.54 (0.06)	-11.15 (0.13)
	45	6.05 (0.13)	6.31 (0.15)	11.35 (0.18)	11.66 (0.17)	-10.24 (0.13)	-10.68 (0.22)	-10.68 (0.15)	-11.14 (0.05)
	60	6.09 (0.08)	6.30 (0.19)	11.35 (0.16)	11.52 (0.81)	-10.16 (0.22)	-10.70 (0.07)	-10.76 (0.09)	-11.21 (0.05)
p		< 0.001	< 0.001	0.001	0.001	< 0.001	< 0.001	0.001	0.001

Table 2. Relation between velocity and motion of the patella during flexion and extension cycle.

Occlusion of one of the three marker trees showed that:

1. Occlusion of the tibial marker tree stopped recording of patellar tracking
2. Occlusion of the femoral markertree resulted in no changes in output of the patellar tracking data. After ending the occlusion, the patellar tracking recordings followed the original tracking pathways. However, when the position in the room of the test-setup was changed during the time that the femoral marker was occluded by moving the table on which the model stands on, the pathways shifted when the occlusion ended. (figure 4a)
3. Occlusion of the patella marker tree resulted in false data output as well: patella motion was visualised (i.e. resgitered) as a straight line during the range of motion. After the occlusion was ended, the registration was restored and followed the original pathways. (figure 4b)

a.



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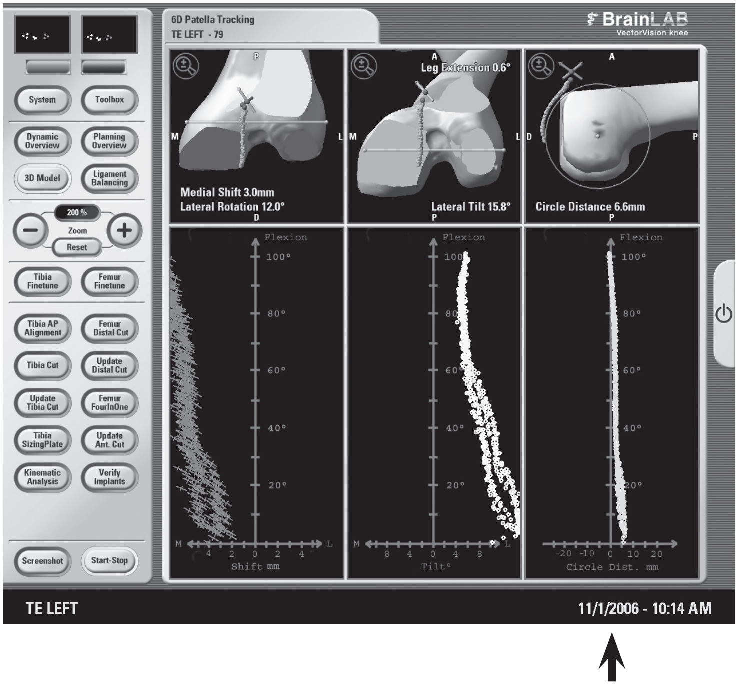

Figure 4. Print screen of the registration of the patella tracking during flexion-extension **a.** Occlusion femoral markertree shows shifted pathway (arrow) **b.** Occlusion patella marker tree shows straight line (arrow)

■ Discussion

This study showed that the velocity of movement within a flexion-extension cycle influenced the amount and degree of patellar tracking as registered and visualized on a CAOS screen: a low velocity resulted in an equal track during flexion and extension where a high velocity resulted in a significantly different path. The direction of motion (extension to flexion or flexion to extension) showed also that a different patellar pathway is seen between flexion and extension motion. Occlusion of one of the marker trees was also of influence on this patellar tracking pathway and resulted in erratic patellar pathways.

The use of navigation in TKA is of high interest. An additionally developed feature in the software at this moment is the patellar tracking module. A good patellar tracking is considered important for the success of TKA, since complications at the patellofemoral joint represent one of the main causes of failure and are the end result of malrotation of either the femoral or tibial or both components.[1,6,7] This indicates that further research concerning this compartment is of importance in order to evaluate the end result of a TKA.

The ideal in vivo patellar tracking in kneeprotheses has been studied, but a wide range of patellar tracking patterns are reported, probably reflecting the different study methods used. Only few have evaluated patellar tracking in vivo[4,8,9], and even then most have used static positions of flexion, thus making extrapolation of the dynamic range of motion difficult. Analysis of patellar tracking has been done by the use of many different techniques: from active or passive markers, a 2D or 3D images (CT, MRI)[10,11,12] to fluoroscopy, X-ray photogrammetry and recently CAS.[13,14,9]

The occurrence of outliers in our data can completely explained by the (partially) occlusion of marker trees during the phantom experiment. Erratic behaviour occurs as soon as one or more markers are occluded. Depending on which marker tree is partly occluded different outliers occur, all of which are highly undesirable.

Especially occlusion of the femur markertree caused recording of a false patella tracking pattern.

Obviously, the navigation system should give an indication of possible false data. In our case, simply beeping and excluding data points that were acquired during occlusion of one or more markers would be sufficient.

The sawbone experiment with two hinge, one between the femur and tibia and one between the femur and the patella showed a clear difference between the flexion and extension pathways at the higher FE motion speeds. This hysteresis was correlated with the FE velocity and became clearest at the fastest FE speed (2sec) (Figure 3). This resulted in a maximal difference in the medio-lateral translation of >6 mm and >10° difference on patellar tilt between the flexion and extension pathways. During a slow FE speed (60 seconds) the results given by the Vector Vision Brainlab system showed no difference in the flexion and extension pathways. These differences in flexion and extension pathways of the patella were seen in all three motions; mediolateral shift (red), tilt (yellow) and circular distance (blue).

In the literature different tracking patterns of the patella during flexion and extension are described (hysteresis).[15,16] However, we found that the patterns also differed considerably depending on the speed of our manually applied flexion and extension.

A general explanation for the difference in tracking patterns during flexion and extension at different velocities can be attributed to elastic hysteresis. An example of elastic hysteresis is a rubber band with weights attached to it: hung on a hook and weights attached at the end will lengthen the band. More weights will extend the band but unloading will shorten it less. This is because the band does not obey Hooke's law perfectly. An example of such a hysteresis loop is shown in figure 5. We used a cord of unknown elasticity in our model, but this material also shows this phenomenon. In vivo muscle (and tendon) lengthening in a movement cycle is higher than during shortening; one should be aware of this hysteresis when performing patella tracking measurements.

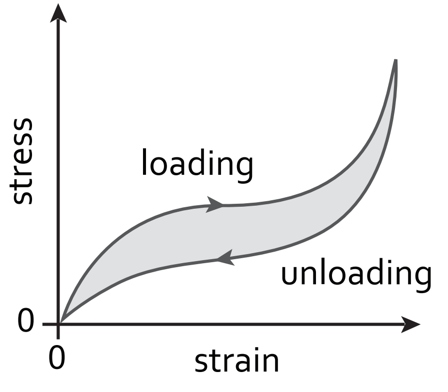

Figure 5. Example of an hysteresis loop.

A second possible explanation for hysteresis is that the positions of the marker trees are not measured simultaneously. If the patellar marker tree is sampled slightly later than the tibial and femoral maker tree, then hysteresis would occur. According to the manufacturer the software of the system calculated the tracking data with the patella location at one sample step back in time. This confirms our possible explanation and is supported by our measurements that the hysteresis increases with higher velocity times for the extension-flexion motion.

When further adjustments in the software are made and the patellar tracking module is valid and accurate during the registration, the discussion rises which method is most reliable to register 'normal' patellar tracking. Patellar tracking is influenced by several factors such as muscle loading, range and direction of knee motion, use of static or dynamic measurement techniques, and last but not least femoral component rotation[8,17] will all affect the results obtained. Strachan et al.[18] used this module to evaluate staged releases of the patella. The effect of the release is clearly visible but what the optimal patellar track should be is yet not known.

Belvedere et al.[13] used another navigation system to evaluate patellar tracking in vitro. They found approximately similar motion as reported in earlier studies[19,20].

Replication of the original patellofemoral motion in the intact knee was not fully accomplished in the replaced knee. However, the original patellofemoral motion could be influenced by osteoarthritis and secondary soft tissue contractures and therefore normal motion will not be captured either.

When normal patella tracking in future is defined, maybe showing individual differences, the navigation system might help in the decision whether to resurface the patella or not and where a patella component is ideally placed. However, tracking abnormalities of the patella are mostly resembling a malpositioned knee prosthesis.

There are strengths and limitations of this in vitro study which influence its clinical relevance. An important strength of this study is that it's shown that the use of a new tool/module should be tested before using in clinical practice to be able to know it's limitations and pitfalls.

One of the limitations is that the quadriceps components were loaded in physiological directions, however tibiofemoral rotation was not allowed in the hinged joint, in order to reduce variabilty on the patellar tracking motion pattern. Thus we could not study the effect of tibiofemoral rotation on patellar motion.

■ Conclusion

Overall, the new patellar tracking functionality in the navigation system appeared to be a relatively easy instrument to evaluate the patella kinematics before, during, and after total knee arthroplasty.

Apart from attachment of the patellar marker tree and a small amount of extra time for the patella tracking registration it needs no special preparation in navigated TKA.

However, the velocity of movement and partial marker tree occlusion gives a misinterpretation of absolute values of the patella movement. One should be aware of the hysteresis phenomenon when analyzing patellar tracking.

Overall, monitoring the patello-femoral kinematics gives the surgeon a more complete prediction of the performance of the final implant and it is therefore a valuable support in TKA. Patellofemoral complaints might be related to the patellar tracking. However, the technique to monitor tracking needs to be further developed before clinical symptoms can be related to it.

Reference List

1. Katchburian MV, Bull AM, Shih YF, Heatley FW, Amis AA. Measurement of patellar tracking: assessment and analysis of the literature. Clin Orthop Relat Res 2003b;241--259.
2. Lachiewcz PF, Soileau ES. Patella maltracking in posterior--stabilized total knee arthroplasty. Clin Orthop Relat Res 2006 (452):155--158.
3. Linden, van der HMJ, Valstar ER, Molen, van der AJ, Nelissen RGHH. Transepicondylar axis accuracy in computer assisted knee surgery: a comparison of the CT--based measured axis versus the CAS--determined axis. Comput Aided Surg 2008 Jul:13(4):200-6.
4. Wilson NA, Press JM, Koh JL, Hendrix RW, Zhang LQ. In vivo noninvasive evaluation of abnormal patellar tracking during squatting in patients with patellofemoral pain. J Bone Joint Surg Am. 2009 Mar 1;91(3):558--66.
5. Lin F, Wilson NA, Makhsous M, Press JM, Koh JL, Nuber GW, Zhang LQ. In vivo patellar tracking induced by individual quadriceps components in individuals with patellofemoral pain. J Biomech. 2010 Jan 19;43(2):235--41. Epub 2009 Oct 29.
6. Bey MJ, Kline SK, Tashman S, Zauel R. Accuracy of biplane x--ray imaging combined with moedel--based tracking for measuring in--vivo patellofemoral joint motion. J Orthop Surg 2008(3) 38.
7. Scuderi GR. The stiff total knee arthroplasty: causality and solution. J Arthroplasty 2005 (20): 23--26.
8. Anglin C, Ho KC, Briard JL, Plaskos C, Nodwell E, Stindel E. In vivo patellar kinematics during total knee arthroplasty. Comput Aided Surg 2008; (13):377--391.
9. Sawaguchi N, Majima T, Ishigaki T, Mori N, Terashima T, Minami A. Mobile--bearing total knee arthroplasty improves patellar tracking and patellofemoral contact stress: in vivo measurements in the same patients. J Arthroplasty. 2010 Sep;25(6):920--5. Epub 2009 Sep 23.
10. Connolly KD, Ronsky JL, Westover LM, Küpper JC, Frayne R. Differences in patellofemoral contact mechanics associated with patellofemoral pain syndrome. J Biomech. 2009 Dec 11;42(16):2802--7. Epub 2009 Nov 3.
11. Nha KW, Papannagari R, Gill TJ, Van de Velde SK, Freiberg AA, Rubash HE, Li G. In vivo patellar tracking: clinical motions and patellofemoral indices. J Orthop Res. 2008 Aug;26(8):1067--74.
12. Fellows RA, Hill NA, Macintyre NJ, Harrison MM, Ellis RE, Wilson DR. Repeatability of a novel technique for in vivo measurement of three--dimensional patellar tracking using magnetic resonance imaging. J Magn Reson Imaging. 2005 Jul;22(1):145--53.
13. Belvedere C, Leardini A, Ensini A, Bianchi L, Catani F, Giannini S. Three--dimensional patellar motion at the natural knee during passive flexion/extension. An in vitro study. J Orthop Res. 2009 Nov;27(11):1426--31.
14. Heinert G, Kendoff D, Preiss S, Gehrke T, Sussmann P. Patellofemoral kinematics in mobile--bearing and fixed--bearing posterior stabilised total knee replacements: a cadaveric study. Knee Surg Sports Traumatol Arthrosc. 2011 Jun;19(6):967--72. Epub 2010 Nov 18.
15. Augustus E. Love . Treatise on the Mathematical Theory of Elasticity (Dover Books on Physics & Chemistry). New York: Dover Publications. ISBN 0--486--60174--9. 1927.

16. Hopkinson B, Williams GT. The Elastic Hysteresis of Steel. Proc Roy Soc. A 87: 502. doi:10.1098/rspa. 1912.0104. 1912.

17. Luring C, Perlick L, Bäthis H, Tingart M, Gri{a J. The effect of femoral component rotation on patellar tracking in total knee arthroplasty. Orthopedics. 2007 Nov;30(11):965--7.

18. Strachan RK, Merican AM, Devadasan B, Maheshwari R, Amis AA. A technique of staged lateral release to correct patellar tracking in total knee arthroplasty. J Arthroplasty. 2009 Aug;24(5):735--42.

19. Bull AM, Katchburian MV, Shih YF, Amis AA Standardisation of the description of patellofemoral motion and comparison between different techniques. Knee Surg Sports Traumatol Arthrosc. 2002 May;10(3):184-93.

20. Hefzy MS, Jackson WT, Saddemi SR, Hsieh YF. Effects of tibial rotations on patellar tracking and patellofemoral contact areas. J Biomed Eng. 1992 Jul;14(4):329-43.

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