Optimized Thickness of Meniscal Component in Partial Knee Replacement Analysed with Computer Simulation

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Abstract. Computer simulation with programming and Matlab graphics was used to analyse effects of meniscal component thickness on lengths of ligament fibres in partially replaced human knee with uni-compartmental arthroplasty. A circular femoral, a flat tibial and a matching meniscal component were modelled in the sagittal plane with four intact ligaments represented as fibres that showed non-linear elastic behaviour. Shapes of the prosthetic components, attachments of the ligament fibres and their material properties were from anatomical studies in the literature. The components when placed on respective bones with surgical guidelines and an optimized thickness of the meniscal insert achieved nearly fixed lengths of ligament fibres during motion. Changes in thickness of the insert either stretched or slackened the fibres with variable effects during flexion of the joint. For example, a 2 mm thicker insert stretched a fibre of anterior cruciate ligament by 4.7% at 30° and 3.2% at 120° flexion. Such variations in component selection are probable due to surgical judgments. Stretched ligaments could increase joint stiffness, while slack ligaments could increase joint laxity – either of these effects has potential for affecting the joint kinematics. Computer models of the replaced knee validated with anatomical studies allow insight in the mechanics of the replaced knee and effects of surgical errors.

1. Introduction
Menisci are unique to the human knee and are known to play vital role in the normal function of the joint. They are understood to help in distribution of axial load at the tibiofemoral articulations, absorb shock and contribute to the joint stability. Meniscal injuries result in significant pain and functional limitations [1–4]. During partial or uni-compartmental knee replacement, articular surfaces as well as the meniscus of the affected compartment are replaced with artificial components [1–4]. Many such designs depend on intact ligaments for restoring the joint function. However, replaced components are suggested to have complex interaction with the ligaments in determining kinematics of the prosthetic knee [1–6]. Resulting alteration in the joint kinematics has potential for affecting transmission of forces and motion across the joint. Consequently, restoration of normal joint mechanics and function may get affected following replacement [1–6].

During surgery, as the prosthetic components are implanted, the ligaments are balanced such that they do not get either overstretched or loose as the bones rotate relative to each other [1]. However, such balancing acts are limited to specific joint positions and in the absence of any muscle action [1]. A careful selection of meniscal component with an appropriate thickness is normally achieved by trial and depends on personal judgment of the surgeon. The natural knee is functionally supported with four major ligaments, namely, lateral and medial collateral ligaments and, anterior and posterior cruciate ligaments [1]. Anatomical studies on cadaver knee have shown that incorrect thickness of the meniscal component...
has the potential of either loosening the ligaments with increased laxity of the joint, or tightening the ligaments with altered and restricted relative positions of the bones – either of these conditions can affect patient outcome [1–7]. For example, dislocation of the meniscal component is a post-surgery complication which might be related to slackness in ligaments [2–4]. Such effects are found to vary with the joint motion as determined by relative positions and orientations of the bones [4, 5–10]. Therefore, there is a need for detailed analysis in order to determine optimum component sizes and positions.

The aim of this computer simulation-based study is to analyse sagittal plane kinematics of a human knee with partial or uni-compartmental replacement containing a meniscal component that requires ligaments of the joint to be intact and functional with proper balancing of their lengths. The study focusses on ligament lengths as influenced by different thicknesses of the meniscal component analysed over a wide range of joint positions during flexion.

2. Methods
A partially replaced knee in the sagittal plane was modelled analytically with computer programming. Femoral articular surface was circular and tibial articular surface was flat as explained in references [1, 2]. A matching meniscal component was inserted in-between such that it matched with femoral circle above and tibial flat plateau below as elaborated in references [6, 11, 12]. Thickness of this component could be varied. Non-linear elastic strands represented ligaments that connected the femoral and tibial bones. Insertion positions of the ligament strands and their material properties were taken from previous anatomical studies [13–15]. Two cruciate and two collateral ligaments were considered [1, 2, 6, 13]. For a selected position of the tibial plateau and thickness of the meniscal component, femoral articular circle was positioned on the upper bone such that selected strands in the cruciate ligaments maintained their initial straight line lengths at 0 and 90 degree flexion of the joint, as normally practiced for this type of partial knee replacement surgery [1–3]. Effects of changing thickness of the meniscal component was then analysed for 1 and 2 mm thicker and 1 and 2 mm thinner component. Such variations in component selection are possible in practice due to surgical decisions and techniques [3].

Figure 1 illustrates position of components on the femoral and tibial bones, shown at 0 degree and at 90 degree flexion as observed in the sagittal plane. Figure 2 shows the meniscal component which may be thicker or thinner than an optimum sized component that achieves nearly constant length for selected ligament fibres in multiple joint positions [1–3]. A thicker than optimum component pushes the bones farther apart, thus, stretching ligament fibres. A thinner than optimum component brings the bones closer, thus, slackening ligament fibres.

![Image](image-url)
Figure 2. The meniscal component illustrated with three thicknesses. Optimum sized thickness ‘\(x\)’ represents a surgeon’s choice that appears to keep the ligaments balanced. However, a thicker or a thinner choice of the component is also likely due to differences in judgement and adopted techniques.

Figure 3. The knee ligaments are illustrated as seen in the sagittal plane attached to the femoral and tibial bones as bundles of elastic fibres. Straight lines represent fibres that are ready to stretch, while curves represent fibres that are slack.

Figure 3. shows the four major ligaments of the knee in the sagittal plane as in [5, 6, 13]. Major knee motion of flexion in the sagittal plane is mainly controlled by the two cruciate ligaments [1, 2, 6]. In the model simulation, changes in lengths of the ligament fibres were calculated from their respective insertion points on the two bones as the joint was flexed from 0 to 120° flexion in 15° steps [13–15]. This exercise was repeated for the optimum sized thickness of the meniscal component as well as for 1mm and 2 mm thicker component and, 1mm and 2 mm thinner component.

3. Results and Analysis
Figure 4 shows percent variation of length of anterior fibre of the anterior cruciate ligament calculated over 0 – 120° flexion. The length changes were taken with respect to those achieved with the optimum sized meniscal component that helped in balancing the ligaments at 0 and 90° as shown in Figure 1. In the figure, a ligament fibre is shown to illustrate the balancing effect that requires such fibres to maintain their lengths. Results are presented here for the optimum sized as well as 1 and 2 mm thicker or thinner meniscal component. Fibres of each of the four ligaments showed similar pattern with changing meniscal thickness or with changing flexion angle. Changes over the flexion range were more pronounced for the cruciate ligaments in comparison to those for the collateral ligaments, not presented here. This agrees with anatomical and theoretical studies in the literature [7, 9, 13, 16].

For the optimum sized component, percent change in the fibre length was close to zero for any flexion position, suggesting that the replaced configuration did not stretch or slacken the fibre. A thicker component resulted in stretched fibre for each flexion position and for each thickness. On the contrary, a thinner component resulted in slack fibre for each flexion position and for each reduced thickness. This effect was more pronounced at low flexion angles and with wider difference in thickness from the optimum. For example, at 30° flexion, 1 and 2 mm thicker component resulted in stretched fibre by 2.3% and 4.7%, respectively. At the same flexion angle, 1 and 2 mm thinner component resulted in slack fibre with its length reduced by 2.6% and 5%, respectively.
Figure 4. Percent change in length of an anterior fibre of the anterior cruciate ligament are plotted over the flexion range with different thickness of the meniscal component.

Table 1. Comparison of results from current study of from related studies from literature. Average movement of optimum sized meniscal component is reported during 0 – 90° flexion

| Compared Study               | Average movement during 0 – 90° flexion (mm) |
|------------------------------|---------------------------------------------|
| Current study                | 8.0                                         |
| *In vitro* study (reference [2]) | 13.9                                        |
| *In vivo* study (reference [4]) | 5.5                                         |

Further comparison between the current and other studies given in Table 1 shows that during 0 – 90° flexion with the optimum sized component as illustrated in Figure 1, the model femur moved on the tibia by 8 mm. In comparison, experimental measurements on replaced knee with similar prosthetic components, an average 13.9 mm movement was reported in an *in vitro* study on cadaver knees reported in reference [2] and an average 5.5 mm movement was reported in an *in vivo* study from radiographs of similarly replaced knees reported in reference [4]. Such variations are possible due to person to person anatomical differences and due to surgical decisions.

4. Conclusion and Clinical Relevance

Computer simulation was used with anatomical input to study effects of variations in thickness of meniscal component on changes in lengths of ligament fibres. Though it is obvious that component thickness can affect lengths of ligament fibres, quantification of such effects could help in gaining insight in the resulting joint kinematics. The effects varied with component thickness as well as from one joint position to another.

In clinical relevance, stretched ligament fibres have a tendency to increase joint stiffness while slack fibres in a ligament have a tendency to increase joint laxity – either of these effects have potential of influencing the joint mechanics after prosthetic replacement. Clinical experience shows that in uni-compartmental knee replacement differences in surgical decisions and techniques could influence patient outcome.
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