Mechanical testing of impaction bone grafting in the tibia

INITIAL STABILITY AND DESIGN OF THE STEM

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Clinical experience of impaction bone grafting for revision knee arthroplasty is limited, with initial stability of the tibial tray emerging as a major concern. The length of the stem and its diameter have been altered to improve stability. Our aim was to investigate the effect of the type of stem, support of the rim and graft impaction on early stability of the tray.

We developed a system for impaction grafting of trays which we used with morsellised bone in artificial tibiae. Trays with short, long thick or long thin stems were implanted, with or without support of the rim. They were cyclically loaded while measuring relative movement.

Long-stemmed trays migrated 4.5 times less than short-stemmed trays, regardless of diameter. Those with support migrated 2.8 times less than those without. The migration of short-stemmed trays correlated inversely with the density of the impacted groups. That of impaction-grafted tibial trays was in the range reported for uncemented primary trays. Movements of short-stemmed trays without cortical support were largest and sensitive to the degree of compaction of the graft. If support of the rim was sufficient or a long stem was used, impacted morsellised bone graft achieved adequate initial stability.

The use of impacted morsellised bone graft to restore bone stock in revision total hip replacement (THR) has been extensively reported. Results from mechanical studies and long-term clinical, histological, and radiological studies show it to be an excellent method.

The same results are not necessarily achieved in revision total knee replacement (TKR). The biomechanics of TKR are entirely different. One particular aspect is the importance of early mechanical stability. Although migration of the stem after impaction grafting in the hip has been reported, it does not seem to pose a clinical problem. Knee prostheses need stable components to ensure correct tension in the ligaments and a lack of stability has significant clinical consequences. In addition, large cyclical movements between the tray and impacted bone may cause resorption of the graft and a relatively high degree of stability is essential for ingrowth and restoration of bone stock to occur.

Within the limited clinical experience of impaction bone grafting in revision knee surgery, lack of stability has emerged as a primary concern. In 1996, Ullmark and Hovelius published the first description of the technique. They essentially adopted the Slooff-Ling concept of a short-stemmed primary implant, totally surrounded by graft and cemented in situ. Since this first description, a few relatively small clinical studies have reported good short-term results. However, a four-year histological study cast doubt on the use of the technique in the proximal tibia and concluded that sufficient initial stability of tibial trays could not be attained. In vitro studies on the hip suggested that the migration of impaction-grafted femoral stems correlated strongly with the degree of impaction. It was unclear whether the same applied to the use of impacted morsellised graft in the knee, but insufficient impaction of the graft could be a factor explaining this apparent lack of stability. As a result of the histological data, long, diaphyseal press-fit stems have been used. Although they may ensure greater initial stability, they bypass the graft, unloading it and causing stress shielding. Unfortunately, this obviates one of the major advantages of morsellised graft, namely its early incorporation when compared with large structural grafts. Two recent publications have described a compromise, namely the use of long thin stems. Three concepts of fixation of the stem for the tibial tray have thus emerged.

The role of the stem in the stability of the tibial component is unclear. Stern, Wills and...
Gilbert concluded from an in vitro study that stems did not enhance the initial fixation of primary trays and might increase toggling movements. This conclusion is in line with that of Lee, Volz and Sheridan. Their tests on a foam model showed that stems did not improve the early stability of tibial trays if bone with high density was stimulated. However, in foam simulating poor bone, stems did improve the stability of the tray. The mechanical properties of impacted morsellised bone differ from those of normal cancellous bone, with close to zero tensile stiffness and strength. It is, therefore, difficult to predict the effect that the design of the stem may have on the initial mechanical ability of impaction-grafted tibial components. Moreover, the loosening process of tibial trays often generates large cortical defects. These defects may compromise the support to the tray normally provided by the cortical rim. The design of the stem may be particularly important in these cases of poor support of the rim.

In the light of the many uncertainties related to initial stability, we have undertaken an in vitro study to investigate the effect of the design of the stem, the support at the rim and impaction of the graft on the early stability of the tibial tray. The four specific questions which we addressed were: 1) do longer stems improve stability, 2) does the diameter of long stems influence stability, 3) does poor support of the rim compromise stability and 4) does the degree of impaction of the graft influence the stability of short-stemmed trays?

**Materials and Methods**

Artificial cortical shells of proximal tibiae were produced from resin (SL170; 3D Systems Europe Ltd, Hemel Hempstead, UK) using a stereolithographic process. The geometry of the cortex was designed to reproduce the anatomy of the proximal tibia and to allow a small tray to sink within the rim of the full thickness of the tray (6 mm). The cured resin had a tensile modulus of 3.7 to 4.2 GPa and a flexural modulus of 2.9 to 3.0 GPa, approximately one-third of the stiffness of tibial cortical bone. The dimensional accuracy of the artificial tibia depended on the size of the specimen, and varied from 4% for 10 mm parts to 0.5% for 200 mm parts.

Fresh-frozen femoral heads, harvested at primary THR and stored at -80°C, were morsellised using a bone mill (Noviomagus; SMT, Nijmegen, The Netherlands) which produced bone particles with an effective diameter of 3.0 mm and a uniformity of 1.8.

In order to investigate the influence of support of the rim on the stability of the tray, two sizes of tibial tray were used (both PFC Sigma Knee System; Johnson & Johnson/DePuy, Leeds, UK). The first was a small tray (size 2), which fitted within the cortical rim. It received no support from the rim and was therefore supported only by impacted graft. The second was a large tray (size 4) which was supported by the cortical rim along its entire edge. In order to investigate the influence of design of the stem, the trays were fitted with one of three different stems as follows: 13 mm diameter by 30 mm long (short stem), 12 mm diameter by 75 mm long (long thin stem) and 20 mm diameter by 75 mm long (long thick stem). The diameter of the long thick stem was chosen to achieve a close diaphyseal fit within the cortex. In total, six stem/tray combinations were investigated.

**Operative technique.** Preliminary testing and evaluation were carried out to develop specific instrumentation and a standardised technique to ensure reproducible, consistent impaction of the graft. According to this technique, a cement restrictor was inserted into the medullary canal of each tibial model, to a depth which left a gap of minimum width of 2 cm between the restrictor and the distal tip of the intended stem. Next, a central guide wire was fixed to a cement restrictor. Morsellised bone graft was introduced and impacted in a stepwise manner to produce a firm distal bed for the graft (this step was not used with the long thick stems). The graft was impacted up to a predetermined level, after which the guide wire was removed. The final tamp of the short stem left space for a cement mantle 2 mm thick around the stem. The final tamp of the two long stems did not leave space for a cement mantle around the stem. Bone cement (CMW3; CMW/De Puy, Blackpool, UK) was prepared. The short-stemmed implants were fully cemented, whereas the two long-stemmed designs were only cemented proximally. Finally, the tibial component was implanted and held firmly in place until the cement had cured. The implanted models were left at room temperature for 24 hours to allow the cement to polymerise fully before being frozen at -22°C for a minimum of 24 hours. For the short stem, eight specimens were prepared (four with rim support and four without) and for the two long stems, four specimens each were prepared (two with rim support and two without). Therefore, 16 specimens in total were prepared.

In order to establish the relationship between impaction and migration of the graft, dual-energy x-ray absorptiometry (DEXA) scans of the implanted short-stemmed specimens were made (Hologic QDR 1000; Hologic, Waltham, Massachusetts). We used the ‘high-density detection’ analysis protocol to calculate the bone mineral density of the impacted graft (the polymer artificial tibiae were radiolucent). These scans therefore produced a quantitative measure of the degree of impaction of the graft.

**Mechanical testing.** Before mechanical testing, specimens were thawed overnight at room temperature. An aluminium frame containing six linear displacement transducers with spring-return (S8FLP10A; Sakae, Kawasaki City, Japan) were fixed to the proximal tibia, such that the tip of each transducer was in contact with the tibial tray. Three transducers were located proximally recording movement in the distal direction, two posteriorly measuring in the anterior direction and one medially measuring in the lateral direction (Fig. 1). This allowed measurement of the relative movement between the tibia and the tray in all six degrees of freedom. Specimens were mounted on a 5 KN servo-hydraulic testing machine (ESH Testing Ltd, Brierley Hill, UK) using a hydraulic testing machine (ESH Testing Ltd, Brierley Hill, UK). Specimens were mounted on a 5 KN servo-hydraulic testing machine (ESH Testing Ltd, Brierley Hill, UK).
and loaded cyclically at a frequency of 1 Hz. A series of three load cases was applied. The first two were normal forces, directed posteriorly along the tibial axis, one acting on the centre of the medial tibial condyle and one on the lateral. The third load case was a shear force directed anteriorly and acting on the centre of the posterior side of the tray. One hundred cycles of each load case were applied per series, each time superimposed on a static pre-load of 10 N. In the first series, the peak normal load was 500 N and the peak shear force 100 N. This ratio of normal and shear was chosen to mimic that measured by Taylor et al.\textsuperscript{24} For each consecutive series, peak normal loads were increased with 500 N and peak shear loads with 100 N up to a maximum normal load of 2500 N and shear load of 500 N, approximately three times normal body weight. This load was larger than the peak load measured telemetrically.\textsuperscript{24} Data on movement from the displacement transducers and on force from the load cell of the testing machine were digitised and stored in a PC for further analysis.

To assess the validity of the artificial tibiae for mechanical testing and to exclude tibial deformation between the tray and points of attachment of the transducer as a cause for artefacts within the recorded measurement of displacement, additional mechanical testing was performed. Inside two artificial cortical shells, rigid polyurethane foam was formed (mean density 0.1874 ± 0.004 SD gr/cm\textsuperscript{3} or 11.5 lb/ft\textsuperscript{3}), representing low-density cancellous bone. The two artificial tibiae were then prepared to receive a primary short-stemmed tray with support of the cortical rim, after which the implants were cemented in place. The measured permanent maximum displacement of the tray after 100 cycles of normal medial load at 1500 N was 47.8 μm and the cyclical maximum displacement was 23.0 μm. These values were close to the micromovement of 20 μm measured in a study of cemented fixation in cadaver tibiae which used almost identical loading conditions.\textsuperscript{25} In addition, the movements were an order of magnitude smaller than the displacements of the impaction-grafted trays. Hence, even if deformation of the tibial model produced all of the displacement in these control tests its effect was insignificant in the overall results.

Analysis of data. From the data on movement of the tray, permanent maximum total displacement after 100 cycles and cyclical maximum total displacement, averaged over the final ten cycles, were calculated separately for each load case and load series. The maximum total displacement was the total displacement between the tray and model tibia at the position where relative movement was maximal. The maximum total displacement was comparable to the maximum total point movement, measured in radiostereophotogrammetric analysis studies of migration of the tray.\textsuperscript{26} The maximum total displacement generated during cyclical loading can be divided into a permanent and a cyclical portion. The cyclical maximum total displacement is the difference between displacement at load peak and at pre-load level. The permanent maximum total displacement was the remaining displacement after 100 cycles of load, compared with the starting position. From the DEXA scans, the density of the graft bone was determined in three regions of interest of 7 x 7 mm, medially and laterally below the tray and below the tip of the prosthesis.

Statistical analysis. Two-way ANOVA was used to analyse the differences in maximum total movement, with the type of stem and the size of tray as independent factors. The Tukey-Kramer post hoc test was used to test for differences of significance between individual types of stem in case of a significant effect of the type of stem. Multiple regression analysis was used to analyse the relationship between the impacted density of the graft and total displacement of the short-stemmed trays, with support of the rim and density of the graft as independent predictors. For all analyses, a probability of p = 0.05 was assumed to indicate statistical significance. Data on migration needed to be log-transformed in order to ensure equal variances, a prerequisite for ANOVA. All the results are given as the mean ± SEM after back-transformation. All statistical analyses were performed using NCSS version 2001 (NCSS Statistical Software, Kaysville, USA).

Results
All the specimens except two survived the complete loading protocol up to normal loads of 2500 N without gross subsidence. The two specimens which failed at loads of 2000 and 2500 N were short-stemmed trays without support of the rim. In both cases, the movements were very large and
we therefore decided to stop the preliminary tests. The statistical analysis was based on the movements at loads of 1500 N, because the movements of some short-stemmed trays without support of the rim at higher levels of load exceeded the capacity of the displacement transducer. In addition, this value allowed direct comparison to be made with previous studies (see Table V). When comparing movement caused by the three variations of load, we found that invariably normal loading of the medial condyle gave the largest movements. Hence, we present the results for this load variation, which is the worst-case scenario.

A general pattern was found of small cyclical movements, superimposed on a larger permanent movement. The mean permanent maximum total displacement curves for each of the six stem-tray combinations showed that the first cycle gave a large displacement, after which further migration occurred at a decreasing rate (Fig. 2).

The type of stem and support of the rim significantly influenced the permanent maximal total displacement (2-way ANOVA; p = 0.002) (Fig. 3, Table I). The mean maximum movement of the short-stemmed tray was 4.5 times that of the two long-stemmed designs, a significant difference (Table I). Maximum movements of the trays without support of the rim were 2.6 times greater than those with support of the rim (Table I). The type of stem and support of the rim also significantly affected cyclical maximal movement (2-way ANOVA; p = 0.02) (Fig. 4, Table II). The short-stemmed trays had cyclical micromovements which were twice as large as those of the long thin-stemmed trays, with the long thick-stemmed trays between these extremes.
stemmed trays tended to toggle more, whereas the thick-stemmed trays tended to piston more (Table III).

The mean bone mineral density under the short-stemmed trays varied from 1.1 gr/cm$^2$ to 1.5 gr/cm$^2$, depending on support of the rim and the site (Table IV). Proximal graft laterally and medially was impacted to a consistent density, with a coefficient of variation below 10%. Graft under the stem was impacted less consistently, in particular for trays without support of the rim in which the coefficient of variation was 25% (Table IV). The density of the graft under the stem proved to be a strong and significant predictor of maximum total displacement of the tray ($r = -0.90$ when adjusted for the influence of the rim support, $p = 0.005$) (Fig. 5).

Discussion

Regardless of their diameter, longer stems reduced permanent movement of the tray by almost 80%. Poor support of the rim increased movements of the tray by a factor of 2.6 and cyclical movement by a factor of 1.7, making short-stemmed trays vulnerable in particular. Hence, length of the stem and the support of the rim influence the stability of the tray, but the diameter of the longer stem had no significant influence. We also found that the density of the impacted graft strongly predicted the migration of short-stemmed trays, suggesting that these trays were sensitive to the degree of impaction of the graft achieved by the surgeon.

Our findings have shown that longer stems reduced permanent displacement of the tray by 77% and cyclical displacement by a mean of 40%. Permanent and cyclical displacements are both important. Permanent displacement relates to the general maintenance of the position of the tray. Large changes in position disturb the soft-tissue balance and lead to a poor clinical result. Cyclical displacement relates to the prospects for the formation of new bone which improve with smaller movements. The results suggest that both aspects benefit from longer stems.

The beneficial effect of a longer stem on the stability of the tray in our study contrasts with that reported by Stern et al.21 In their study, uncemented and cemented trays without stems and with stems of 40 and 75 mm were implanted in cadaver bones and their stability was assessed. The length of the stem had no influence on the stability of cemented trays, but that of cementless trays decreased with increasing length of stem. Stern et al21 hypothesised that the negative effect of longer stems might be due to the fact that the stem had only limited contact with the inner cortical bone surface. Such limited contact would be insufficient to prevent toggling or rocking, but sufficient to prevent settling of the prosthesis into place. In impaction grafting the bone is prepared to fit the stem, which may explain why long-stemmed trays showed superior stability in our study. The beneficial effect of a longer stem on the stability of the tray in our study is, however, in line with two studies on the fixation of uncemented trays,27,28 albeit that the benefit of a longer stem in these studies was smaller than in our study.

Table III. Mean percentage (± SEM) of cyclical maximal migration due to toggling of the tray during last ten cycles of medial loading at 1500 N

<table>
<thead>
<tr>
<th>Stem type</th>
<th>Mean percentage movement from toggling (SEM)</th>
</tr>
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<tbody>
<tr>
<td>Short</td>
<td>1.69 (0.06)</td>
</tr>
<tr>
<td>Long thin</td>
<td>0.58 (0.07)</td>
</tr>
<tr>
<td>Long thick</td>
<td>0.38 (0.08)</td>
</tr>
<tr>
<td>Rim support</td>
<td></td>
</tr>
<tr>
<td>Yes</td>
<td>0.56 (0.06)</td>
</tr>
<tr>
<td>No</td>
<td>0.61 (0.06)</td>
</tr>
</tbody>
</table>

Table IV. Mean bone densities (gr/cm$^2$; ±SD) and the coefficient of variation (COV, SD/mean) for short-stemmed trays. The standard deviations were not equal (modified-Levene test, $p = 0.003$), with significantly more variation in density under the tip of the non-supported trays

<table>
<thead>
<tr>
<th>Location</th>
<th>Rim support</th>
<th>No rim support</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bone density</td>
<td>COV</td>
</tr>
<tr>
<td>Medial</td>
<td>1.09 ± 0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Lateral</td>
<td>1.10 ± 0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Tip</td>
<td>1.12 ± 0.12</td>
<td>0.12</td>
</tr>
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</table>
This difference may be a consequence of the mechanical properties of the impacted graft. Impacted bone has little or no strength in tension, which implies that it has little resistance to lift-off. A longer stem will give extra leverage to resist toggling and rocking which make up a large portion of movements of the tray.

Having established the benefit of a longer stem, the next question is whether the diameter of the longer stem influences stability. Our results showed no significant influence of the diameter of the stem on maximum permanent and cyclical displacement of the tray. This suggests that the diameter of the stem is less critical than length. The lack of influence of the diameter of longer stems is in contrast with a study on the effect of the diameter of the stem on the stability of uncemented trays in young human cadaver bones.28 In the latter study, an inverse relationship between the diameter of the stem and the movement of the tray was found. One possible explanation for the difference between this and our study is the material which supports the tray, impacted graft versus cancellous bone. A further possible explanation is the role of the support of the cortical rim. Provided support of the rim was present, there was a tendency for thick-stemmed trays to move less, although the difference was not significant (Fig. 3). This is in line with the findings of Jazrawi et al.28 However, without support of the rim thick-stemmed trays tended to move more (Fig. 3). We speculate that impacting graft around thin long stems is easier, and that this graft gives more support to the tray when support of the rim is lacking. Although in our study the diameter of the stem did not influence the stability of the tray, it did affect the pattern of movement of the tray. Thick-stemmed trays pistoned more, whereas thin-stemmed trays toggled more. This difference is probably an effect of the tight fit of the thick stem inside the cortex in our experiments, which left little potential for toggling and rocking. Whether such a precise fit can always be obtained in practice is an open question. When the fit is less tight, the stability of thick-stemmed trays probably decreases because impacting a thin layer of graft around such thick stems to compensate for the poor fit is difficult.

Cortical support of revision trays is often compromised after loss of bone during the process of loosening. We therefore posed the question whether support of the rim influences the stability of the tray. Our results showed that lack of support increased permanent movement by a factor of 2.6 and cyclical movement by a factor of 1.7, suggesting that poor support strongly decreased stability. This increase of stability was found for each of the three types of stem. However, it should be kept in mind that the short-stemmed trays moved more than long-stemmed trays. Because poor support for the rim increases movement by a multiplication factor, its absolute effect on the stability of the short-stemmed trays is larger than that on long-stemmed trays. In other words, our results suggest that the stability of short-stemmed trays in particular is vulnerable to poor support of the rim. This suggestion is in line with the conclusions in a case report of a retrieved impaction-grafted revision.14 In that report, the proximal cortical bone of the tibia was restored by endosteal mesh before impaction of the graft, and after impaction a short-stemmed tibial tray was inserted. After four years, most of the graft had not incorporated and the central portion was necrotic, probably due to a lack of stability.14 Our results suggest that a longer stem would have performed better, in particular in this case of poor cortical support.

Because graft impaction is a difficult surgical procedure, our final question was whether the degree of impaction achieved influenced the stability of the tray. We limited this part of the investigation to short-stemmed trays because they are surrounded by a larger mass of graft and hence the influence of impaction is clearer. We found a strong correlation between the density of the distal graft region and permanent movement of the tray confirming that the degree of impaction is indeed an important factor. This conclusion is in line with earlier work which we performed on THR in which we found a strong inverse relationship between the density of the impacted distal graft region and movement of the stem of the hip prosthesis was found.13 The case of the best impacted graft showed how impaction even compensated for the lack of support of the rim (Fig. 5). Although large variations were found in the density of the distal graft region, the density of proximal medial and lateral graft region had a small coefficient of variation. The proximal region can easily be inspected during the procedure, which may explain its smaller variation. Assessing the degree of impaction at the tip region is difficult and this lack of feedback may account for insertion of the guide stem before adequate impaction at this region has been achieved.

Impaction of more distally located graft may also be more open to chance events, such as accidental falling of graft material under the stem which then needs to be impacted strongly to ensure sufficient space for the stem. The bone mineral density of impacted grafts in the proximal region was in the upper range under tibial trays measured using DEXA.29 The clinical DEXA values included the cortex, whereas the values in our study reflected impacted graft only. The density of the impacted graft is thus higher than the density of the proximal tibial cancellous bone and explains why these trays achieved levels of stability equivalent to those previously reported for primary uncemented TKRs (Table V).

Our study was a laboratory study designed to address specific clinical concerns regarding technique, selection of the implant and the resulting stability of impaction-grafted tibial trays. In keeping with any similar laboratory study, a number of assumptions and simplifications have been made. The first concerns mechanical loading. To load the trays, a combination of two unilateral axial loads and a (smaller) central shear load were chosen. The two unilateral loads were chosen because they would test the stability of the tray more severely than central loading. A fluoroscopic study of the PFC Sigma implant has shown that repeated
unilateral medial and unilateral lateral loads are commonly observed in patients. The absolute load and the ratio of shear to axial load which we have adopted mimic the levels recorded in vivo during walking. A combination of three loads simplifies load patterns in vivo.

A further limitation is our restriction to the measurement of short-term early stability only and the exclusion of the in vivo osseous response. We consider this limitation to be justified because the initial stability is thought to be the factor which dictates the in vivo response. A third limitation is our use of a synthetic tibial model instead of a cadaver tibia. Artificial bones have the advantage that they minimise the experimental noise from variations in geometry and properties, which can be considerable. We produced proximal tibiae stereolithographically to create a cortical shell into which a small tray could sink over its full thickness without touching the cortex. This allowed us to study the contribution of the support of the rim in isolation. An additional advantage of the stereolithographic process is the ability to reproduce tibial models with cortical defects, which may be important for future studies. Other investigators have also used synthetic models with a lower modulus to represent bone. The artificial cortical shell used in our study had no cancellous bone, and therefore the whole shell was filled with impacted graft. Clinically, in revision situations, some remaining cancellous bone would probably be present inside the cortical shell. The combined effect of a lower modulus of the cortex of the model and complete filling with impacted graft was probably to decrease the stability of the trays and exaggerate the differences between them. This therefore represents a relatively severe situation for revision. However, an effect on their relative ranking is unlikely. Although differences in loads make a direct comparison difficult, the amount of permanent and cyclical displacement in our study is in the same order as others found for uncemented primary implants (Table V).

Finally, our use of an undersized tray to model poor support of the rim means that the tray was only held up by impacted graft. This exaggerates the clinical situations in which restoration of the cortex would be attempted so that there might be some support for the tray. The amount of support offered by such restored cortices is unknown, and biomechanical studies to address this question would be useful. Our model can be seen as a worst-case scenario, and may well exaggerate the effect of poor support of the rim. Nevertheless, we think the qualitative influence which we found is realistic.

Our study shows that the stability of impaction-grafted short-stemmed trays is sensitive to poor support of the rim and surgical technique. Longer stems do not have this problem. The influence of the diameter of a long stem on the stability of the tray was negligible, which suggests that considerations other than stability should guide the choice of the diameter. One such consideration is the potential for creating new living bone stock, a specific attraction of impaction bone grafting. A thin stem would leave more space for graft, creating a situation closer to the primary case and facilitating improved bone stock if a later revision were to be needed. A further consideration would be the risk of stress shielding. Although we did not measure strains in our study, other studies have shown that thicker stems reduce proximal cortical strains, in particular in the absence of support of the rim. Stress shielding could cause a reduction in the quality of the bone and may also delay the osseointegration of the impacted bone. A final consideration is the pattern of movement. The thicker stem had a pistoning pattern, which may be more desirable than toggling. The latter may lead to unilateral subsidence, altering the overall mechanical alignment of the knee and accelerating a potential collapse into varus or valgus.

An issue which we have not discussed is the minimum level of stability required. The level of movement of impaction-grafted trays in our study is in the range of that of uncemented primary trays measured in other studies in vitro (Table V). For uncemented implants, bone ingrowth at the interface between the implant and the bone is the primary concern. Relative movement at the interface is considered to be a critical factor of ingrowth with cyclical movements of 150 µm hindering ingrowth into porous surfaces but still allowing bone apposition to hydroxyapatite surfaces. For impaction-grafted implants, movements may be more distributed through the mass of the graft, suggesting that larger cyclical movements may be well tolerated. Nevertheless, in all cases in which we pulled the implant from the tibial shell after testing we found some bone mixed with cement forming a coating on the implant, which during removal separated from the remaining mass of graft. This suggests that much of the relative movement is concentrated in a small zone within the graft and that values for micromovement observed for hydroxyapatite-
coated implants may also be valid for impaction-grafted trays. Assuming that this is indeed the case, cyclical movements of all stems supported by the rim in our experiments are probably sufficiently small to support bone ingrowth. However, when there is insufficient support only the thin-stemmed trays may produce adequate stability.

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References


