Effect of Vibration on the Shear Strength of Impacted Bone Graft in Revision Hip Surgery

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Abstract

Aims: Studies on soil mechanics have established that when vibration is applied to an aggregate, it results in more efficient alignment of particles and reduces the energy required to impact the aggregate. Our aim was to develop a method of applying vibration to the bone impaction process and assess its impact on the mechanical properties of the impacted graft.

Methods: *Phase 1.* Eighty bovine femoral heads were milled using the Noviomagus bone mill. The graft was then washed using a pulsed lavage normal saline system over a sieve tower. A vibration impaction device was developed which housed two 15V DC motors with eccentric weights attached inside a metal cylinder. A weight was dropped onto this from a set height 72 times so as to replicate the bone impaction process. A range of frequencies of vibration were tested, as measured using an accelerometer housed in the vibration chamber.

Each shear test was then repeated at four different normal loads so as to generate a family of stress-strain curves. The Mohr-Coulomb failure envelope from which the shear strength and interlocking values are derived was plotted for each test.

Phase 2. Experiments were repeated with the addition of blood so as to replicate a saturated environment as is encountered during operative conditions.

Results

Phase 1. Graft impacted with the addition of vibration at all frequencies of vibration showed improved shear strength when compared to impaction without vibration. Vibration at sixty Hertz was displayed the largest effect and was found to be significant.

Phase 2. Graft impacted with the addition of vibration in a saturated aggregate displayed lower shear strengths for all normal compressive loads than that of impaction without vibration.

Conclusions

Civil engineering principles hold true for the impaction bone grafting procedure. In a dry aggregate the addition of vibration may be beneficial to the mechanical properties of the impacted graft. In our system the optimal frequency of vibration was 60 Hz. Under saturated conditions the addition of vibration is detrimental the shear strength of the aggregate. This may be explained by the process of liquefaction.

Introduction

In the setting of total hip replacements, polyethylene wear and osteolysis can lead to extremely large irregularly shaped bony defects. This presents a major challenge in revision hip surgery. Impaction bone grafting has the potential to restore lost bone stock. This makes the procedure especially appealing in the young and middle aged group patients where subsequent revision arthroplasty procedures are envisaged. The technique was first popularised for the treatment of acetabular bone loss in total hip arthroplasty surgery by Sloof et al. in 1984.[1] It was later modified by Gie et al., in 1993 for femoral side revisions. [2]

The underlying mechanism of failure of the graft construct is primary micro-movement which leads to mechanical instability and graft resorption. [3] The initial implant stability and long term outcome of whether or not the graft will incorporate into living host bone is very much determined by the initial mechanical properties of the graft aggregate. Variables which may lead to the creation of a more stable graft bed include: larger sized bone graft particles,[4] [5] [6] aggregates which are washed and well graded, [7] higher impaction forces, [8] [9] [10] the use of cement,[11] [12] [13] excluding cartilage remnants, [14] and the addition of bone graft extenders.[15] [16] [17]

Boland recently added vibration to the bone graft impaction process and showed that a femoral prosthesis inserted with vibration undergoes less subsidence and is more rotationally stable when compared to standard impaction methods. [18] On the acetabular side the mechanism of failure is through shearing of the impacted aggregate. The shear strength of a material is the maximum shear stress that it can resist before failure.[19] It is well understood by civil engineers that a compacted aggregate that is most resistant to shear utilizes vibration during the impaction process. There has however been no work carried out to date in this area with regards to impacted bone graft. The aim of this study was to determine whether the principle of applying vibration to impacted bone graft enhanced the mechanical properties of the construct in acetabular side revision surgery. In addition we hoped to quantify an optimum frequency of vibration to use during this process and also to explore differences under dry and saturated conditions.

Materials and methods

Preparation of Bone Graft

Eighty bovine femoral heads were obtained from the local abattoir (Ballymooeny Meats, Clane, Co. Kildare). The femoral heads were then thawed in warm 0.9% saline solution for 30 minutes. All soft tissue, cartilage and cystic areas were removed with a rongeur. The femoral heads were cut into quarters with a saw and then milled using the Noviomagus Bone Mill (Nijmegan, The Netherlands). The coarse milling drum which is designed to produce large bone chips for acetabular and proximal femoral impaction grafting was used. The samples were then washed of fat, marrow and blood using a pulsed lavage 0.9% normal saline jet over a sieve tower. This sieve tower consisted of a 2mm sieve over a 300 micron sieve. The contents of the two sieves were combined and mixed in a single container to reduce the variation between different femoral heads. [20] The bone graft was divided into samples weighing 350grams. All samples were kept in airtight, re-sealable plastic bags and frozen at -20 degrees between testing.

Vibration impaction device

The bone graft to be tested was impacted into the shear test rig using an impactor designed and built in Mechanical Engineering Department in Dublin City University. It consists of a 5.95kg drop weight drop, a trajectory guide and a vibration chamber (figure 1a). The vibration chamber houses two 15V DC motors (MFA/Como Drills, Kent, U.K.) with eccentric weights attached to their axels (figure 1b). The current to these motors was varied to achieve the desired frequencies of vibration of the base plate which was in contact with the bone graft. Data on the frequency of vibration of the chamber was gathered by means of a cubic piezoelectric accelerometer (Bruel & Kjaer, Skodsborgvej, Denmark) housed within the chamber which fed data to a computer running LabVIEW 8.1 software (National Instruments, Austin, Texas, U.S.A.). Frequencies of vibration tested in phase 1 were: no vibration, 20, 40 and 60 Hz. In phase two testing, no vibration and 60Hz were compared.

Shear testing

Phase 1 – dry aggregate

Each 350g bone graft sample was impacted in four sequential layers of 87.5g using the vibration impactor device. 5ml. of heparinised bovine blood was added to each layer resulting in a relatively dry aggregate. Each layer was impacted 18 times from the set height of 65mm. The energy applied to each test pellet was equivalent to one standard impaction procedure.[21] When vibration was used the base plate of the device was allowed to contact the bone graft for 70 seconds per layer; 20 seconds prior to the first impaction and one impaction approximately every 3 seconds thereafter.

The shear rig consists of a mobile upper ring and a stationary lower ring into which the bone graft is compacted. The inner diameter of the chamber was 105 mm. Once compaction was complete the shear rig and test pellet was transferred to the Hounsfield macro-mechanical testing machine (Redhill, Surrey, UK) and a normal downwards compressive load was applied to the graft layer (figure 2). The test sample was left to equilibrate for 15mins and the compressive load adjusted to allow for stress relaxation. The Hounsfield machine was set to shear at a constant strain of 3mm per minute and data collected on shear stress and shear strain for each sample tested. Test samples were then re-impacted and tested in the above sequence but at the higher value for normal compressive load (100, 200, 300 or 400KN). These stresses produce a family of curves within the lower range of normal human physiological stresses experienced by impacted graft in a typical revision hip replacement.[22] The Mohr-Coulomb failure envelope was plotted for each shear stress at 25mm strain, against the normal stress. [20, 24]

Phase 2 – saturated aggregate

The above methodology for dry aggregate testing was repeated with the exception of the following: the holes in the base plate of the shear rig were sealed with adhesive glue and 40ml of heparinised bovine blood was added to each layer.

Data analysis

The direct shear test imposes stress conditions on the impacted graft that force the failure plane to occur at a pre-determined location, between upper and lower shear rings. There are two stresses acting on this plane. The first of these is the downward normal compressive stress, σn, due to the applied vertical load (F_v). The second is the shearing stress; τ, which is due to the applied horizontal load (F_h) imparted by the Hounsfield to maintain a constant strain. These stresses are calculated as follows: $\sigma_n = F_v/A$ and $\tau = F_h/A$, where A is the cross sectional area of the specimen. These two stresses should satisfy Coulomb's equation:

$$\tau = (\tan\phi).(\sigma_n) + c$$

Where $\tau =$ shear strength, σ_n the normal downward stress, ϕ the angle of internal friction and c the interlocking between particles. It can be seen that Coulombs equation is in the form of a straight line graph i.e. $y = mx + c$ Where m is the gradient and c is the y intercept.

There are two unknown quantities (c and ϕ) in Coulombs equation. It is possible to solve for these values using simultaneous equations if two values for each of normal stress and shear stress are obtained through testing samples under the same conditions. An alternate method is to plot on a set of axes the mean values of τ (shear stress) versus σn (normal stress) from several experiments. Regression analysis is then performed to produce a line of best fit which is known as the Mohr Coulomb Failure envelope. The slope of this line may then be calculated. i.e. $\tan^{-1} dy/dx$. This angle represents the angle of internal friction, ϕ. The τ-axis intercept of this Mohr Coulomb failure envelope represents c, the interlocking value between particles in kPa.[23]

Statistical Analysis

Grouped linear regression analysis was performed to compare shear strengths at different frequencies of vibration. P values <0.05 were considered statistically significant.

Results

Phase 1 – Dry aggregate testing

Results of shear testing of each sample at four different normal compressive loads are displayed graphically as a family of stress versus strain curves.

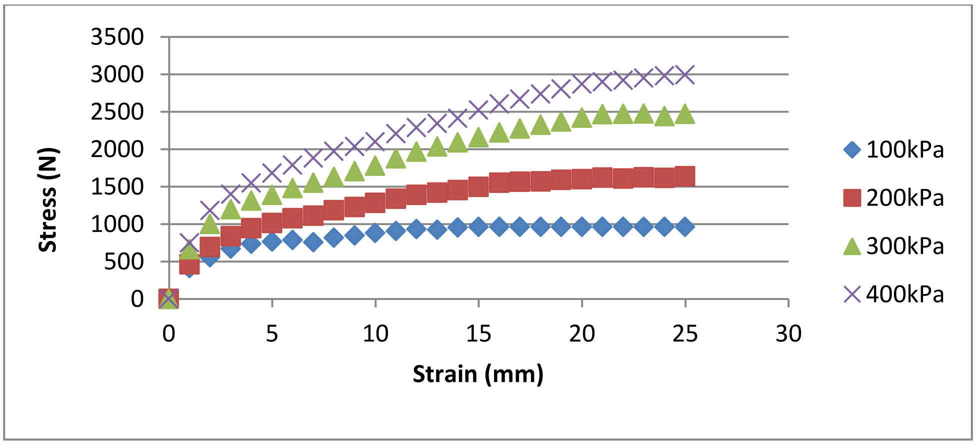

Figure 3 Stress versus strain curves for sample 1, tested without vibration, dry aggregate.

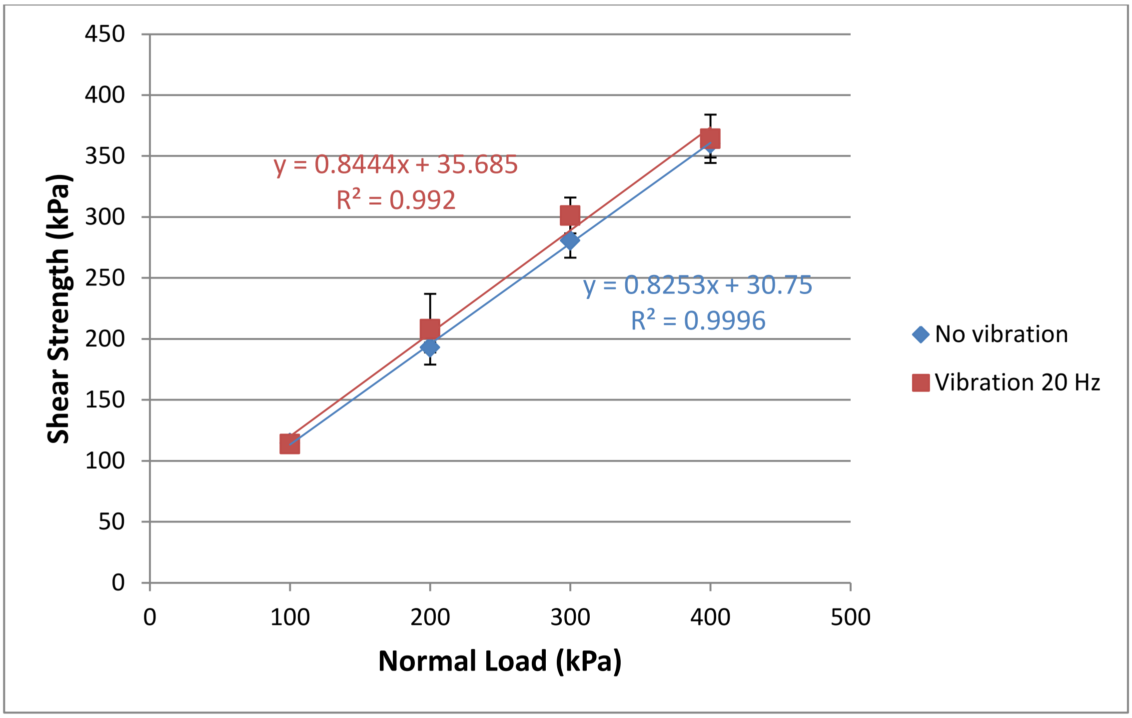

Figure 4 Shear strength envelopes comparing impaction with vibration at 20Hz to impaction without vibration in a dry aggregate.

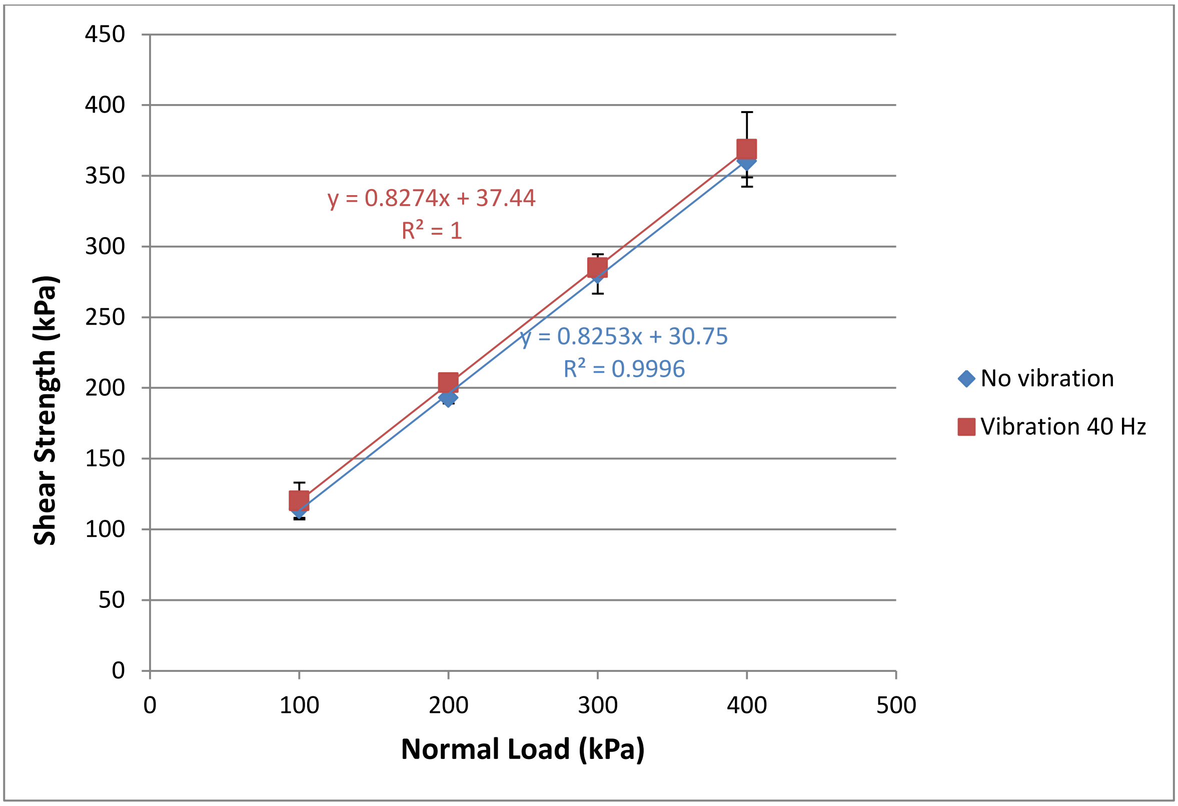

Figure 5 Shear strength envelopes comparing impaction with vibration at 40Hz to impaction without vibration in a dry aggregate.

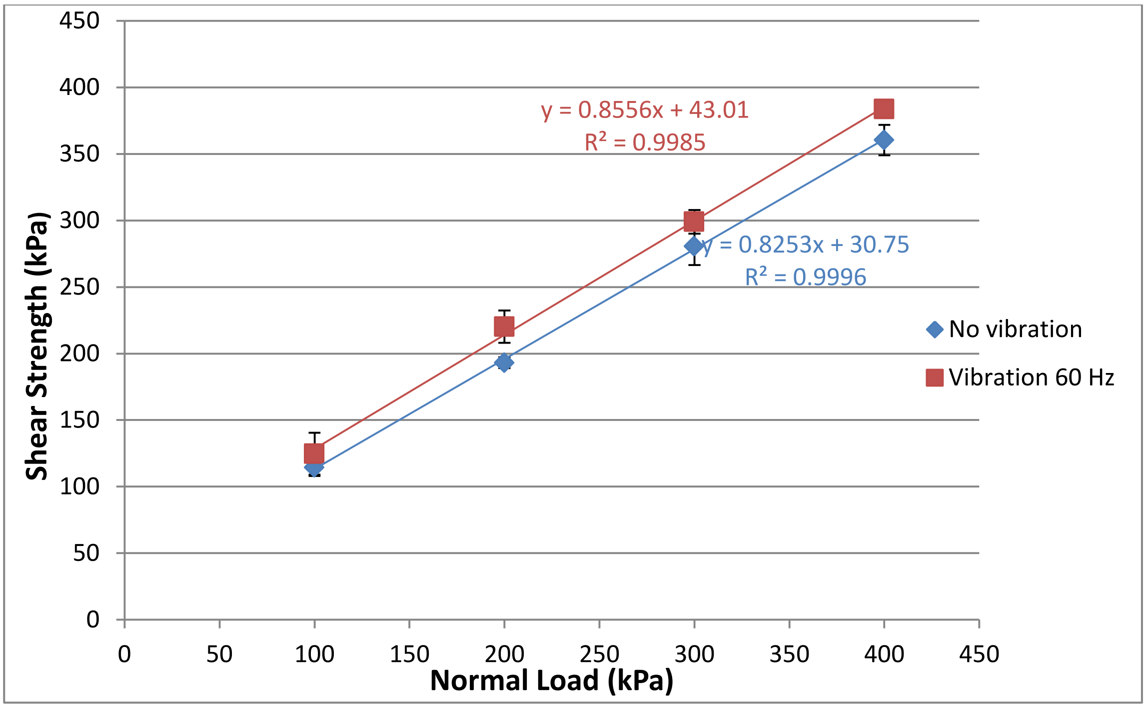

Figure 6 Shear strength envelopes comparing impaction with vibration at 60 Hertz to impaction without vibration in a dry aggregate.

Phase 2 – Saturated aggregate

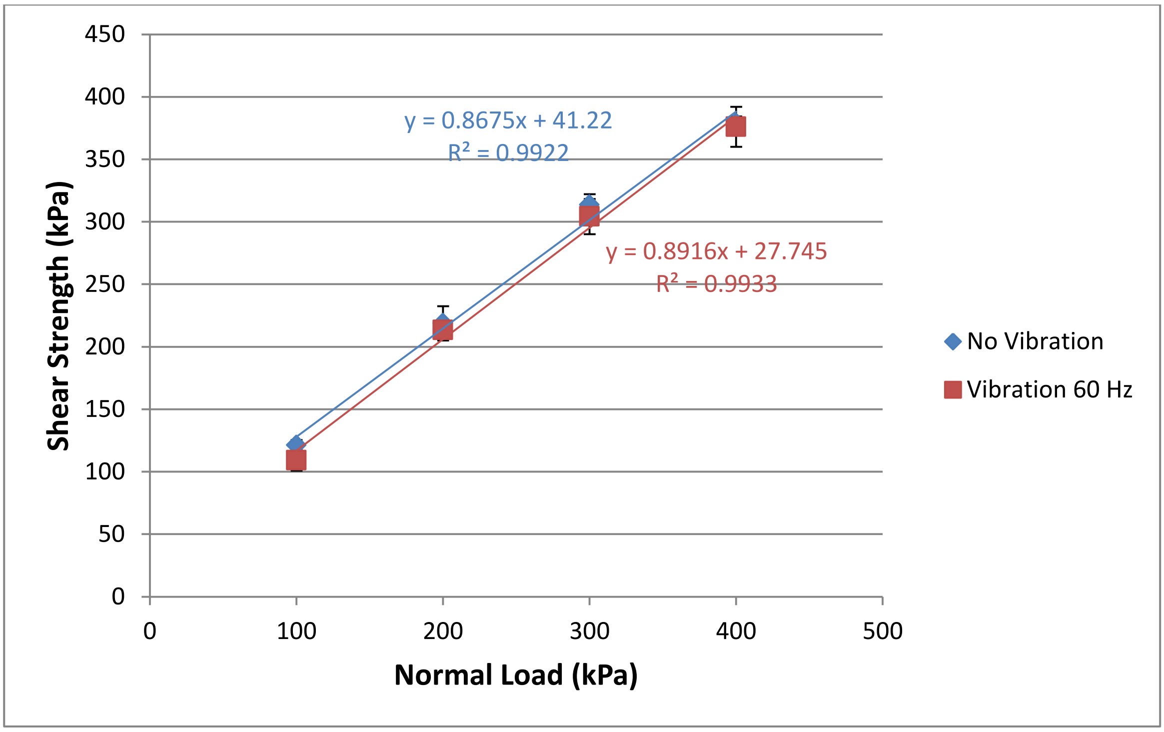

Figure 7 Shear strength envelopes comparing impaction with vibration at 60Hertz to impaction without vibration in saturated conditions.

Test Group	**Interlocking (kPa)**	**Angle of internal Friction ($\text{Tan}^{-1}dy/dx$)**	**Shear strength (kPa) at σ = 350 kPa**
Dry aggregate			
No vibration	30.75	39.51°	319.43
Vibration 20Hz	35.69	40.18°	331.23
Vibration 40Hz	37.44	39.61°	327.04
Vibration 60Hz	43.00	40.55°	342.47
Saturated aggregate			
No vibration	41.22	40.94°	344.84
Vibration 60Hz	27.74	41.72°	339.81

Table 1 Summary of shear test results

Discussion

Our results indicate that the addition of vibration to the impaction bone grafting procedure is beneficial to the mechanical properties of the impacted aggregate in a dry environment but is detrimental in a saturated environment. We feel that the environment encountered intraoperatively is most similar to that of phase two, the saturated environment and hence are opposed to the addition of this form of vibration in acetabular side revision surgery.

According to soil mechanics, the inherent strenth of a an aggregate can be explained by the fact that each particle of soil has a number of points of contacts with its surronding particles. The weight of the soil on top of each particle causes a contact force to be produced which gives the soil its mechanical strength. The increase in shear strength in the dry aggregate bone testing can be explained by the fact that when particles are exposed to vibration within a confined space, they move into a tighter denser confiuration; this increases the number of point contacts between particles and hence increases the shear and compressive properties of the aggregate.

According to the Mohr Coulomb failure law, this improved alignment increases the particle interlocking ($\uparrow c$) and hence the shear strength ($\uparrow \tau$) as follows: $\uparrow \tau = \sigma \tan\varphi + \uparrow c$. [24] Results from phase one dry aggregate testing were consistent with this, showing a substantial increase in interlocking from 31kPa to 43kPa when vibration at 60Hz was employed. This finding is similar to the frequencies employed in road building techniques which are typically around 40Hz. [25]

Phase 2 testing produced contrasting results with a decrease in shear strength under saturated conditions. This was due to a large drop in the interlocking value from 41 to 28kPa when testing was conducted with the addition of vibration. One possible explanation for this is a phenomenon encountered in civil engineering called liquefaction. Liquefaction takes place in aggregates that have a high fluid content or are saturated. When the soil is subjected to rapidly applied laoding, the vibration causes the particles to want to move into a denser configuration. However, as the vibration also affects the fluid in the aggregate, this leads to an increase in the pore pressure between particles which forces the particles apart. In some instances there may be no contact between particles and the aggregate behaves more like a fluid than a solid. Hence the term liquefaction. When this occurs the shear strength and mechanical properties of the aggregate are decreased.[26] This phenomenon is the underlying reason for the devastation casued around areas of high soil water content that are suseptible to earthquake activity.

Bolland et al, modified a collarless tapered tamp (phantom) which is used in impaction grafting of femora, by drilling holes through its flanks. They subsequently attached a Woodpecker vibration device to the phantom and carried out vibration and impaction procedures on biomechanical models of the femur. They have shown that both the peak impaction loads experienced by the femur and the peak hoop strains transmitted to the femoral cortex were significantly reduced in the vibration procedure compared to the impaction procedure. In addition to this, the prostheses that were inserted using the vibration method of impaction were more stable. Their mean total axial subsidence and mean rotational subsidence (1.79mm and 0.57mm) was less than that of the standard impaction method (2.47mm and 0.66mm).[27] As the fluid volume in Bollands study was low, the beneficial effects on the mechanical properties observed are similar to our own findings in phase one testing. An increase in the pore fluid pressure was negated by the holes drilled in the phantom however it is questionable whether this would have the capacity to cope with the volumes produced by back bleeding from a reamed medullary canal intra-operatively.

An attempt to dry the graft before implantation may be made in an effort to decrease the pore fluid pressures generated however it is the back bleeding from cut bone surfaces that constiutes the main obstacle. Bone wax applied to the cut bone surfaces would decrease bleeding but may be detrimental to incorporation of the graft in the long term. Potential methods to decrease the blood volume in the operative field include the local administration of a vasoconstricting agent, anaesthetic induced hypotension or the use of a negative pressure intrusion (suction) device.[28]

A recent study used 3-dimensional micro-computed tomography to examine the effect of vibration and drainage on bone graft compaction and cement penetration in an in vitro femoral impaction bone grafting model. Three regions were analysed. In the proximal and middle regions it confirmed a significant increase in the proportion of bone graft with a reciprocal reduction in water and air in the vibration assisted group as compared to the control group. These findings are consistent with improved denser packing and compaction of the graft in the vibration-assisted group. There was no difference observed in the distal group. This may have resulted from a smaller surface area being acted on but also because an axial compressive force is imparted in this area rather than a radial compressive force.[29] Although an axial compressive force was used in our study, the observed differences may have resulted from the large surface area and volumes of graft impacted.

In conclusion the use of vibration in the impaction bone grafting process appears beneficial under dry conditions but may be detrimental the mechanical properties of the aggregate under saturated conditions. The observed differences appear to be related to changes in particle interlocking. The optimum frequency in our system was 60Hz.

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