CONTACT AREA, PRESSURE DISTRIBUTION, AND MECHANICAL STABILITY IN EXTERNAL ARTHRODESIS OF THE ANKLE JOINT

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Abstract

The ankle joint is often affected by arthritis, giving a joint that is painful, stiff, and restricts movement. This can result in a huge loss of mobility for the sufferer. Unlike replacement of the hip, the replacement of a diseased ankle joint is not as straightforward and the outcomes do not reach the same success levels. The preferred surgical choice is arthrodesis, a procedure whereby the two bones forming the joint are fused together to eliminate the joint and hence pain. The success of the procedure is dependent upon several factors, two of the most significant being the levels of contact area and pressure achieved during the compression period, during which bone growth occurs across the two bones being compressed together. These factors influence joint stability and micromotion at the bone to bone interface during this growth phase.

This study investigates the levels of contact areas and pressures that can be achieved for different arthodesis variables. These variables include the joint shape, which can be curved or flat, and the position of the compression pin within the talus, namely anteriorly or centrally positioned with reference to the talar dome. Influence of the Achilles tendon in joint stability is also investigated.

A test rig was developed allowing load/deflection curves to be determined for various configurations of these variables. Models representing the bones under consideration, together with pressure sensitive film, allowed measurement of contact areas and pressures within the joint under compression, achieved using pins and instrumented compression rods.

Results indicate there is little significant variation in contact area and pressure for the different shaped joint cuts, however, if the talar pin is placed in a more anterior position then the contact area can be improved over a centrally positioned pin. Anterior pin placement also gives increased resistance to motion and mechanical stability. It has been established that the athrodesis construct is especially weak in terms of rotation about the tibial axis, and the results from this study indicate that through the use of a curved joint shape the resistance to this motion can be improved greatly.

1. INTRODUCTION

The ankle is a joint that is often adversely affected by arthritis, resulting in a painful joint with limited mobility. One of the standard procedures for alleviating this pain is arthrodesis of the ankle, which involves fusing together the two major bones that form the ankle joint.

A number of techniques are available in order to perform this procedure, the first recorded technique having been documented by Albert in 1882 [1]. These various techniques include the use of internal screw methods and external compression using pins. Whilst these techniques have been documented and successfully performed for many years, there has been little investigation into the biomechanical factors that determine their success rate and their potential effect upon the joint during the initial bone growth phase.

This study investigated the effect of two variables upon the external arthrodesis structure. The particular fusion technique considered obtained compression at the joint site by inserting one horizontal pin through the talus and another horizontal through the distal tibia, and using compression clamps to force the two pins, and hence the joint, together. In 1951 Sir John Charnley proposed that optimum ankle fusion could be attained by cutting opposing bones in a flat shape, and that by positioning the talar pin in an anterior position, the Achilles tendon force would result in an even anterior-posterior compression force distribution [2]. Recent variations on this theme have sought to address the weakness of such a technique, especially when subject to axial rotation loads, by cutting the bones in a curved shape (i.e. attempting to retain approximate original joint shape) [3,4]. This study investigated the effect of pin position and joint shape upon the pressure distribution attained within the joint and its resistance to motion, both factors being critical to successful fusion, as any motion at the joint site will damage any potential bone growth taking place across it.

The vast majority of biomechanical studies in this field have compared the success of various arthrodesis techniques against one another [5,6], with only more recent studies investigating the effects of different physical variables available during the procedure [4]. This study used a combination of internal joint pressure measurement, together with bending and torque deflections at the joint site to determine the likely effect upon joint stability of these variables. The use of finite element models to evaluate the stability of arthrodesis constructs has only recently been applied to internal compression arthrodesis techniques only [7].

The use of pressure sensitive film to determine pressure levels within joints has been well documented in relation to biomechanical studies [8], and this technique was used to determine pressure levels within the joint under compression.

2. Materials and methods

A 3D CAD system was used to develop models of the talus and distal tibia to be constructed from CT scan data obtained of an adult male. These models were resected within the CAD environment to generate suitable flat and curved shaped models of both bones using appropriate surgical advice. Positions of compression pin holes were also mapped onto these computer models. Data from these models was then output and a CNC machining system used to reproduce approximations of these models as physical entities, as illustrated in Figure 1.

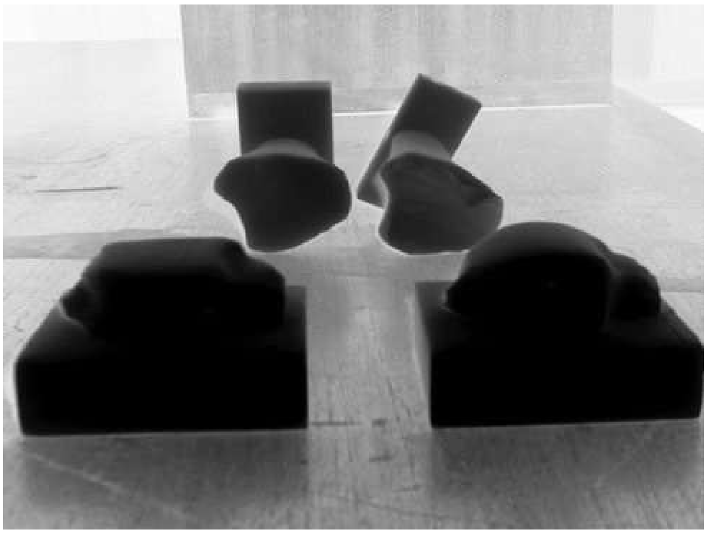

Figure 1: Physical Models

A test rig was developed that would allow the simulation of external arthrodesis. The talar model could be fitted into a component representing the foot, and the horizontal talar compression pin inserted through it. The model representing the distal tibia was mounted in a plate above this in the frame of the test rig. The contact between the lower tibial surface and the superior talus surface allowed the formation of the ankle joint to be simulated. Instrumented compression clamps were then used to apply known compressive loads to the joint, by compressing the talar model against the fixed tibial surface. Compression could also be applied at the rear of the foot component via an instrumented compression rod between the rear of the foot component and the upper frame of the test rig.

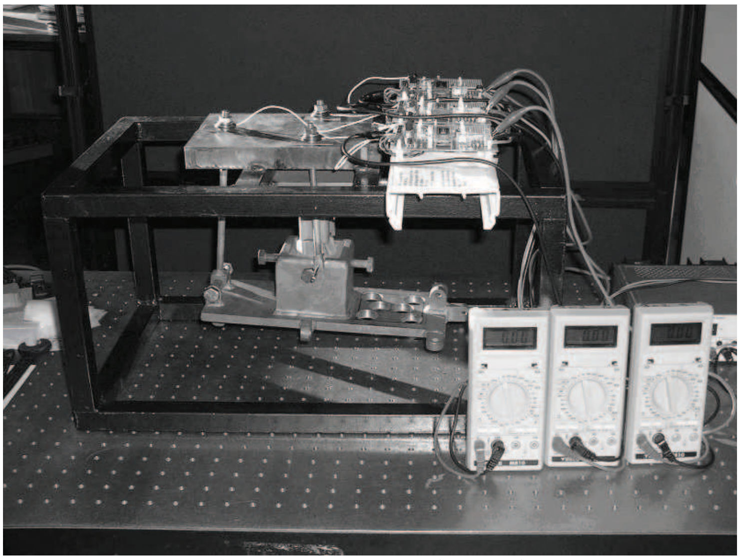

Figure 2: Instrumented Test Rig

Pressure sensitive film (a film that changes colour in relation to applied pressure) was inserted into the joint between the two models and the joint compressed to predetermined levels in order to record pressure distribution within the joint. This procedure was first performed for a flat joint shape with compression being achieved using an anteriorly positioned talar pin. The pressure sensitive film was then removed from the joint in its expended state for evaluation. The flat shaped model was then used again, with a centrally mounted talar pin. The process was then repeated using the curved shaped models, with the pin again being positioned in both the anterior and central positions. These studies were performed firstly without any Achilles tendon compression, and then repeated with the application of an Achilles tendon compressive load.

The pressure sensitive film that had been exerted to compression was scanned, converted to greyscale values and computer programs used that would count the number of pixels and their corresponding greyscale value in order to determine joint contact area and average pressure. Known calibration charts were used to quantify these figures. An example of this output is displayed in Figure 3.

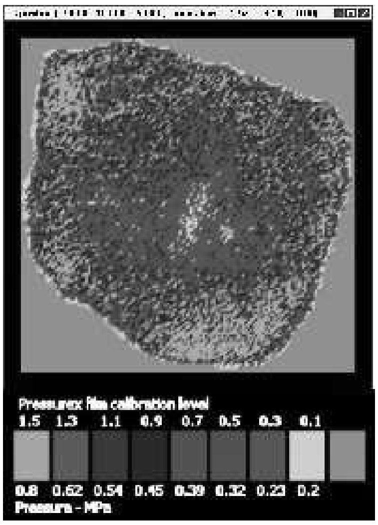

Figure 3: Pressure Distribution across film

The mechanical stability of these arthrodesis constructs was then measured by compressing the joint as previously, but without pressure sensitive film in the joint. External loads were then applied in order to induce motion at the ankle joint in the various directions that the actual joint can move in, namely plantarflexion/dorsiflexion, inversion/eversion, and internal/external axial rotation. The level of displacement in such directions was measured in response to increasing loads, allowing load/deflection data to be obtained for the various directions.

3. RESULTS

3.1 PRESSURE DISTRIBUTION

It was discovered that only small differences exist in the levels and distributions of pressure within the joint far varying pin positions and joint shape. Following a MANOVA analysis (p=0.05), it could be stated that:

When the opposing bone surfaces are cut with flat shapes, the optimum contact pressure was obtained with an anterior pin and an applied Achilles tendon load, and that in all cases the Achilles tendon load increases the joint pressure.

When the curved joint shape is retained, optimum contact pressure was obtained with an anterior pin. Again, the Achilles tendon load increases pressure in all cases when a curved shape surface is maintained.

Overall it can be stated that for curved cut models, pressures remain in the main constant with slight improvements possible when using anterior pins. For flat models, overall pressures are slightly higher than for curved joint shapes, and increase even more when using anterior pins.

These results are illustrated in Figure 4.

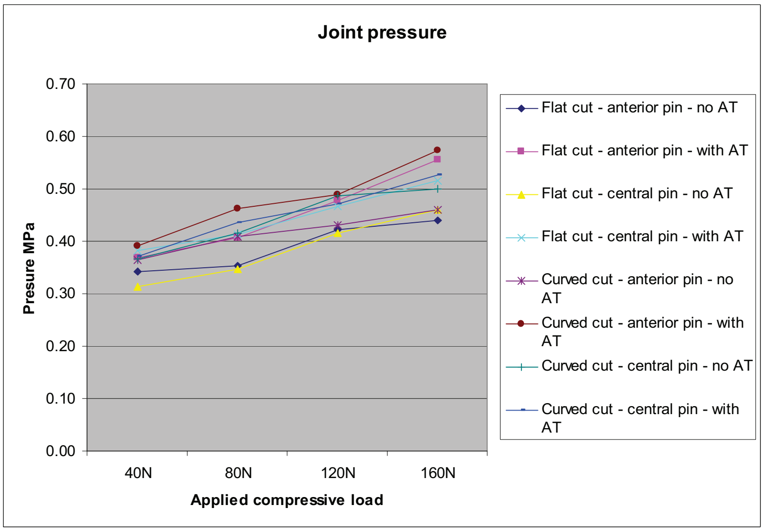

Figure 4: Pressure Distribution Results

3.2. MECHANICAL STABILITY

Figures 5 to 7 show a summary of the results of maximum deflection obtained for the various stability tests following one-way ANOVA analysis (p p=0.05). The matching opposite motions i.e. dorsiflexion against plantarflexion were found to follow a similar pattern to the data shown and so only results for one of the motions are provided.

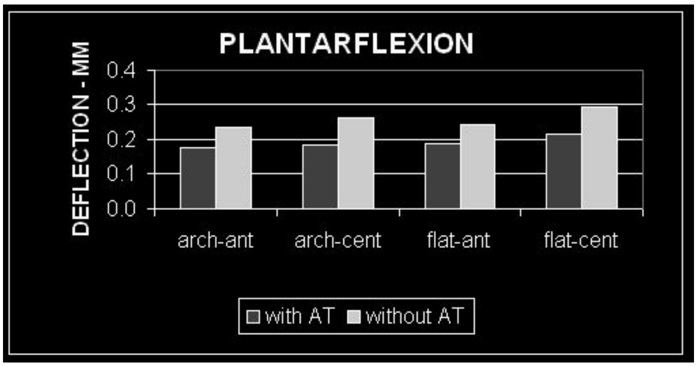

Figure 5: Plantarflexion deflection

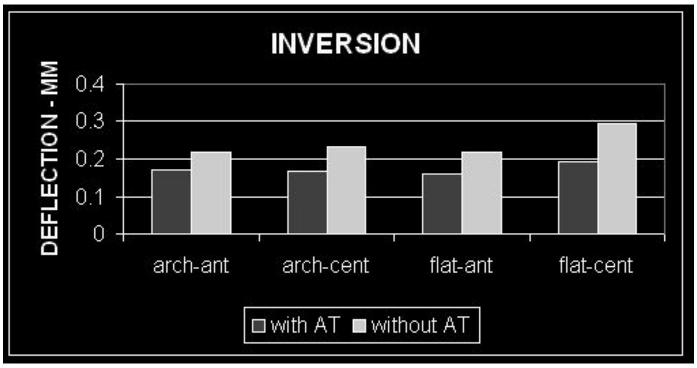

Figure 6: Inversion deflection

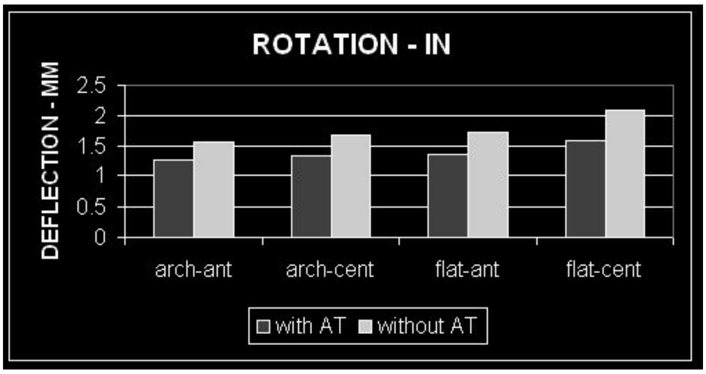

Figure 7: Rotational deflection

The mechanical stability tests demonstrated that the joint deflection for directions in which physical opposition to motion exist due to the physical formation of the joint, such as plantarflexion/dorsiflexion and inversion/eversion, the deflections recorded were very small (below 0.3mm). These did however illustrate that the Achilles tendon was important in resisting motion and balancing the joint. These tests showed that the weakest combination of variables occurred when a central pin was combined with a flat joint shape, the optimum scenario being an anterior pin and curved joint shape. In between these two extremes came the other combinations i.e. flat with anterior pin and curved joint with a central pin.

The most significant findings however came in the rotational tests where it was clearly demonstrated that a curved joint shape had a major effect upon resistance to motion, which was noticeably larger than in the other loading directions.. When coupled with an anterior pin noticeable improvements in resistance to motion were found. The worst situation was again a flat cut with a central pin. The deflections recorded during the rotational tests were in the order of magnitude almost 10 times larger than those measured during the inversion/eversion and plantarflexion/dorsiflexion tests, illustrating the importance of this load factor in resistance to joint micro-motion, and the weakness of such constructs in relation to this type of motion.

4. DISCUSSION

A number of biomechanical studies have sought to define the optimum technique for arthrodesis. These studies have succeeded only in confirming that specific pin, screw or plate configurations performed better than one another. Miller [6] investigated the effect of joint shape, but could not find any statistical differences between flat cut and contour preserved specimens, possibly due to the low number of cadaveric test specimens available. The lack of availability of consistent cadaveric specimens led to this study using polyurethane models to represent the bone. Further validation of this experimental work is currently being performed using finite element modelling, and the results from these experiments correlate well with those found in other finite element studies [7].

This study has also considered a situation of perfect joint congruency, with solid bone material that is not affected by degeneration, however in most rheumatoid cases requiring surgery the joint surfaces remain intact within a painful joint due to cartilage destruction. Investigation into the application of different material properties representing poor bone stock would be a useful addition to this work.

5. CONCLUSION

It can be seen form Figure 4 that the pressure sensitive film tests showed only slight variations in pressure across the joint for different pin and joint shape combinations. They did however illustrate the importance of considering the Achilles tendon during such experiments. It was discovered that marginally better results were obtained using an anterior pin position, with little difference between curved and flat joint shapes.

The mechanical stability tests however clearly illustrated the benefits that could be obtained in resistance to motion across the joint when using an anterior pin and curved joint shapes. This was especially true for rotational resistance, which is the major weakness of arthrodesis constructs. Whilst there may be a slight reduction in joint contact pressure when curved models are used, these differences are insignificant in comparison to the additional joint stability that can be afforded in rotational displacement when such surface shapes are retained.

These findings have been further substantiated by additional 2-dimensional finite element studies that have been performed, and confirm the hypothesis that a curved shape and an anterior pin will give greater stability during the arthrodesis recovery period, improving likelihood of fusion.

Ongoing work includes the development and utilisation of 3-dimensional finite element models of these joints in order to further study the contact across this joint both in terms of pressure and displacement under load during compression.

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