Prosthetics and Orthotics International, 1984, 8, 16–20

A method for determining the mechanical characteristics of orthotic knee joints

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Abstract

All orthotic equipment must operate at the highest possible standards of safety and, should structural failure of a loaded component occur, there must be a minimal possibility of injury to the user. Because of the lack of definitive data on the in-service loading of lower limb orthoses it is not possible to base a test procedure on "real" loading conditions. In this paper a method of destructive testing, based on the assumption that the predominant loading consists of bending about the medio-lateral and anterior-posterior axes, is described. This method makes it possible to measure the bending strength of a knee joint side member assembly and to define the brittleness of the failure. It is suggested that the latter definition makes it possible to predict the potential safety of a particular knee joint should in-service failure occur. Some laboratory failures are described and recommendations, based on the test programme, are made for new joint designs.

Introduction

Any item of equipment supplied to a patient must operate at the highest possible standards of safety. In particular, this implies that any load bearing component, should it fail, must not do so in such a way as to cause injury. This requirement is of particular importance in the case of lower limb orthoses which, in many cases, must carry substantial loads in order to support the patient during gait and other activities such as stair climbing. In addition they must operate under the more severe conditions imposed, for instance, by the patient tripping or stumbling. It is essential, therefore, that the load bearing components in such orthoses should be designed in such a way as to avoid catastrophic failure.

At present, few data exist on the in-service loading of orthotic knee joints, although information at present available suggests that a major part of the loading of a knee-ankle-foot orthosis (KAFO) consists of bending moments about medio-lateral (ML) and anterior-posterior (AP) axes (Trappitt and Berme, 1981). However, the magnitude of these loads cannot, at present, be estimated for the wide range of possible uses and prescriptions of a KAFO.

Until such data become available, useful information on the mechanical properties of existing designs can be acquired by laboratory testing. Potentially such tests can provide data on static mechanical strength and mode of failure, stiffness and fatigue strength. This paper is concerned with a programme of destructive testing to identify the strength and mode of failure of orthotic knee joints under the action of bending moments in the AP and ML directions. This particular type of test was chosen because it approximated to the loading pattern discussed above.

Testing equipment and procedure

In order to interpret the results of a bending test, it was necessary to determine the angular deflection versus bending moment relationship for the knee joint and side member assembly under test. In order to make realistic comparisons between a variety of sizes and types of joint it was decided that a test section incorporating the joint itself together with a portion of each side member should be loaded under a uniform bending moment. This can be achieved by the 4 point bending method illustrated in Figure 1. The simple loading systen illustrated will only produce a constant bending moment if the deflections are small and the forces acting remain parallel and at right angles to the test section. However, because of the relatively low bending stiffness of the side members and the need to test to destruction, the

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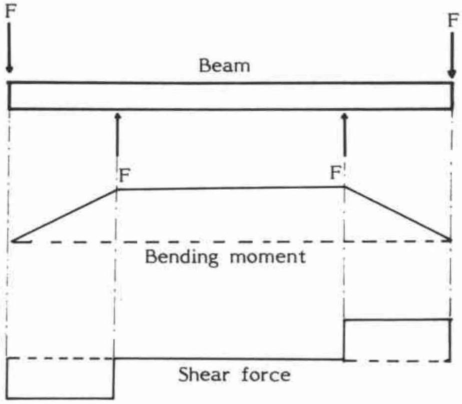

Fig. 1. Four point bending of a beam.

resulting deflections of knee joint assemblies are likely to be large. It was necessary, therefore, to redesign the test rig using the arrangement of Figure 2 in which the knife edges were replaced by rollers which were mounted in pairs on the faces of two pulleys. Equal and opposite torques were then applied to the pulleys by cables attached to a pivoted cross beam which was then connected to the hydraulic jack of a test machine via a load measurement cell. The angular deflection of the joint assembly under test was measured using a Linear Variable Differential Transformer (LVDT) displacement transducer coupled to one of the pulleys by a thread whose change of length was proportional to angle of rotation. A schematic drawing of the test rig can be seen in Figure 3.

Test procedure

After selection of the direction of testing, the joint was placed in the test rig with the lock mechanism in the centre of the test region. In order to prevent the joint from moving during the test, one end only was lightly clamped to the pulley (Fig. 3). Load was then applied to the rig and the resulting moment - deflection graph was recorded on a pen recorder. The load was slowly increased until one of the following events occurred:

(a) Any part of the joint assembly fractured.
(b) The mechanism of the lock opened.
(c) The deflection of the specimen became so great that the loading geometry was adversely affected, the mechanism became unsafe or one pulley had rotated through an angle greater than 25°.
(d) The deflection of the specimen continued to increase with the bending moment remaining constant.

Each type of joint in the study was tested in 4 directions.

Flexion
Extension
ML bending (2 directions)

Interpretation of results

When mechanical testing of engineering components is carried out it is normally relatively straightforward to relate the applied loads and the stresses to the intended use. However, as has already been discussed, these data do not exist for orthotic components. It is suggested that two parameters may be used to compare one joint with another and to describe the mode of failure in the laboratory. In order to discuss the method derived here it is necessary, first, to examine a typical moment versus deflection curve produced during the bending test (Fig. 4). This graph can be divided into two regions.

(a) Elastic, during which any deflection is totally recoverable after removal of the load. This region ends at the limit of proportionality after which the graph is in the plastic region.
(b) Plastic, in this region permanent deformation of the assembly is occurring.

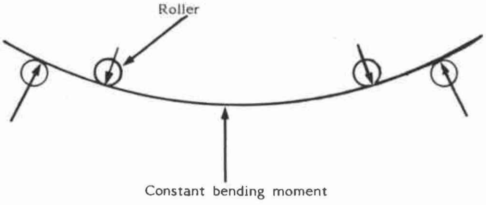

Fig. 2. Four point bending with large deflections.

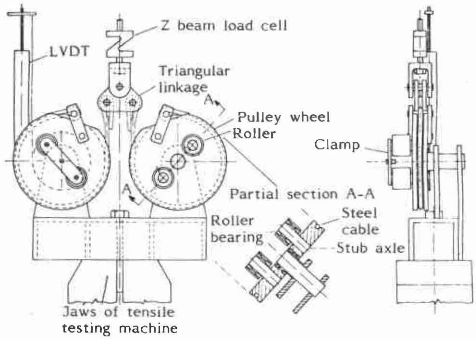

Fig. 3. Four point bending apparatus.

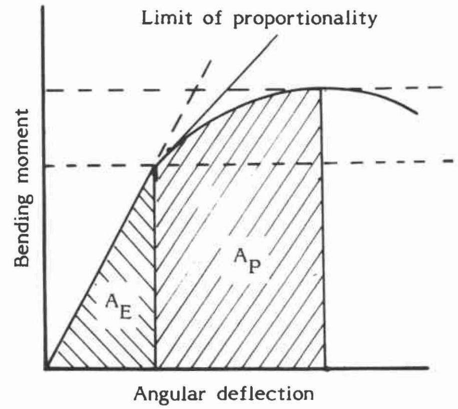

Fig. 4. Typical bending moment - deflection curve.

The end of the plastic region was defined as one of the following events:

(i) Fracture of any component.
(ii) The point of maximum bending moment.
(iii) If neither of the above has occurred, then the point corresponding to a rotation of 25° of one pulley.

Within the elastic region, energy is stored with increasing load whereas in the plastic region energy is dissipated in the permanent deformation of the specimen; the energy associated with the two regions of the graph may be calculated from the areas Ae and Ap. A full description of the test procedure may be found in the draft standard from the British Standards Institute (1983).

It will be noted that these definitions of energy differ, in certain respects, from those to be found in engineering textbooks. The present definitions were necessarily adopted to accommodate the differences between the present test procedure and the standard tensile test on which the more normal definitions are based.

The bending strength and a measure of brittleness of the failure were obtained from the moment versus deflection curve in the following manner.

Bending strength

It is reasonable to assume that any permanent deformation—even if small—is unacceptable for an orthosis in use. This requirement implies that the bending moment during use must not exceed the limit of proportionality. The bending moment at this point was defined as the bending strength.

Brittleness

If an orthosis fails as a result of the user falling or stumbling then it is reasonable to assume that, immediately prior to the fracture, some of the available potential energy of the wearer will have been used to deform the structure. If fracture occurs, any elastic energy in the orthosis will be released and will be available to injure the user, whereas any plastic deformation will have absorbed energy. Therefore, the more ductile the failure (i.e. the more plastic deformation which has occurred) the smaller the chance of injury to the user. In Figure 4 the ratio ApAe represents the degree of ductility of a failure and from now on will be referred to as the PE ratio. The higher the value of this ratio, the more ductile the failure and, from the argument above, the smaller will be the chance of injury to the wearer. The remainder of the paper will be concerned with the measurement and use of the PE ratio as a criterion for safe design.

Justification of PE ratio as a measure of ductility/ brittleness

While the technical justification for the use of the PE ratio has already been presented, it was felt to be important to examine the correlation between some measured ratios and subjective assessments of mode of failure made by an engineer. In the first instance, it is only on this basis that the threshold between acceptable and unacceptable failures can be set. For this purpose a group of results was classified as acceptable or unacceptable prior to the calculation of PE ratios. Figure 5 shows the subsequent distribution of the ratios for the two groups where it can be seen that the "unacceptable" group is dominated by low ratios and vice versa. From these results it was decided,

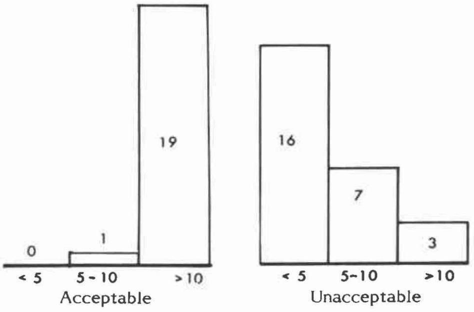

Fig. 5. Distribution of PE ratios of acceptable and unacceptable failures.

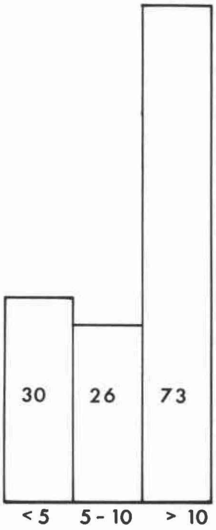

Fig. 6. Distribution of PE ratios for all joints tested.

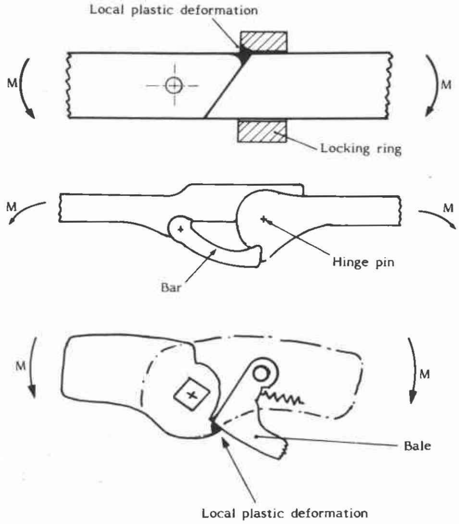

Fig. 7. Undesirable failures. Top, failure of a ring lock. Centre, failure of barlock. Bottom, failure of a bale lock.

arbitrarily, that a ratio of less than 5 represented a totally unacceptable failure, 5-10 represented a failure requiring further investigation and a ratio greater than 10 represented an acceptable failure. The distribution of ratios for all the joints tested is shown in Figure 6.

Some test results

While this paper is not intended to be a critique of different available joints, some failures which occurred during the test programme illustrate the relevance of the method. For the interested reader detailed discussion of a large range of results is presented in Scothern (1982).

Ring lock

Figure 7, top, illustrates a failure of a ring lock which occurred when loaded in flexion. Because of insufficient contact area between the male tongue and the ring, plastic deformation of both of these components occurred and allowed the joint to open under load. While this is not, technically, a brittle failure, it was associated with a low PE ratio because failure of the lock occurred before any appreciable yielding of the structure. It was without doubt, an unacceptable failure. PE ratio=4.

Barlock

Figure 7, centre, illustrates a failure of a barlock joint when loaded in flexion. Because this type of joint uses a short strong link as the locking member, the weakest component, in flexion, becomes the hinge pin loaded in double shear. On one particular joint under test, double shear failure of this pin occurred before any plastic deformation of the structure. Because of the typical brittle nature of the double shear failure, the mode of failure was unacceptable. PE ratio=4

Bale lock

Tests on a particular design of bale lock illustrated two related types of undesirable failure, the first of which is illustrated in Figure 7, bottom, showing the lock only partly engaged. This particular joint had previously been adjusted to ensure that no free play was present when the joint was locked—a condition which was achieved as soon as the bale contacted the locking flat. The locking spring was not sufficiently strong to push the bale fully home. Under load there was a local bearing failure of the locking flat which originated at the point of contact and progressed outwards. As a result of the deformation to the tongue the resultant contact force lay to the right of the pivot and this tended to rotate the bale outwards and so unlock the joint. The PE ratio for this failure was 1·0. A variation of this failure occurred with the bale fully engaged. In this case a large wedge of material, extending across the flat, was sheared off.

What are satisfactory failures?

Satisfactory failures are associated with ductility. This requirement implies that, in most circumstances, the first component to fail should not be a casting. Also, as has already been demonstrated, double shear failure of loaded pins should be avoided. Ductile failures are most likely to consist of the bending of wrought components which, in this instance, will probably be side members. It is for this reason that nearly all of the failures in the ML direction, where the side members are relatively weak, were ductile. Similarly, the majority of failures associated with joints machined from wrought material were satisfactory. It can` be seen, therefore that ductility can be "built in" at the design stage by ensuring that the joint head will not fail, under conditions of bending, before the side members. For most designs this will mean that the strength of the joint will be determined by the side member dimensions and the joint mechanism will always be designed to be the strongest link in the load path.

Conclusions

A method has been presented for the assessment of orthotic knee joints both from the point of view of mechanical strength and with regard to mode of failure. While both of these measurements provide new information on the potential safety of orthotic components, interpretation may be difficult in view of the almost total lack of information on the loads to be carried by the complete orthosis in service. Before this information becomes available it is important that the tests described in this paper should be carried out on the widest possible variety of knee joints. An additional task, which must be carried out, is the systematic collection of data on mechanical failure of orthotic components in use. While it may often be suggested that such occurrences are rare it is believed by the authors that a wide variety of unreported failures do occur. In many cases these may not be regarded by the orthotist as failures and may consist, for instance, of an orthosis having to be realigned at regular intervals. Such realignment is probably only necessary because of yielding (i.e. failure) of loaded components. Fortunately, catastrophic failures appear to be far less common. When it is realised that a large number of orthoses are assembled from components which could, potentially, fail in a brittle manner, it must be concluded that the majority of orthoses are over-designed i.e. they contain more metal than is required to carry the imposed loads.

It is suggested that if components, which could only fail in a ductile manner, were to be used exclusively in orthotic construction then it would be possible for the orthotist to supply a lighter orthosis without risk of catastrophic failure. Furthermore, although data on in-service loading is not yet available, the availability of strength data on available orthotic knee joints will give the orthotist information for the comparison of different designs and he may be able, to a limited extent, to relate these strength figures to his knowledge of the patient's weight and activity pattern.

Acknowledgements

The authors are grateful to the Department of Health and Social Security for their generous financial support of the work.

One of the authors (R.P.S.) is grateful to Mr. N. Cubitt, Dept. of Mechanical Engineering, Loughborough University of Technology for advice and guidance throughout the project.

Acknowledgements are also due to Mr. G. McQuilton and Mr. P. Rees, Orthotics and Disability Research Centre, Derbyshire Royal Infirmary for their help in construction and maintenance of test equipment, and to Mrs. J. Whitehead for typing this manuscript.

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