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Static structural testing of trans-tibial composite sockets

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Abstract

The purpose of this investigation was to quantify the structural strength of various trans-tibial composite sockets. To conduct the study, loading parameters and methods were developed that emulate the International Standards Organisation (ISO) standards for structural testing of lower limb prostheses since specific guidelines for the testing of the trans-tibial socket portion of a prosthesis have not yet been established. The experimental set-up simulated the instant of maximum loading during the late stance phase of gait. Ten trans-tibial sockets were evaluated. Five different reinforcement materials and two resin types were used to construct the sockets. A standard four hole distal attachment plate was used to connect the socket and pylon. Each sample was loaded to failure in a servo-hydraulic materials test machine at 100 N/s.

None of the composites in the study met the ISO 10328 standards for level A100, loading condition II (4025 N), as required for other prosthetic componentry. All failures occurred at the site of the pyramid attachment plate. Ultimate strength and failure type were material dependent. Load point deflection was significantly different for the resin variable ($p<0.05$). Statistical differences according to reinforcement material were noted in composite weight and strength-to-weight ratio ($p<0.05$). The fibre volume fraction was also estimated and recorded. Reinforcement material type was the primary determinant of performance for the tested samples. Carbon reinforcements performed better than fibreglass reinforcements of similar weave type. The greatest ultimate strength and strength-to-weight ratio was observed with the unidirectional carbon reinforcement.

Introduction

The use of fibre reinforced plastic (FRP) composites in orthotics and prosthetics has primarily involved the transfer of technologies from the marine and aerospace industries. While the application of these materials in prosthetics is widely practised, specific information on their structural properties as they relate to the unique geometry of the trans-tibial socket is not reported in the scientific literature. This has resulted in a diversification of fabrication techniques within the profession. The material properties of composites vary greatly and depend on composition, lay-up, and processing method (Hubbard, 1995). The predominant processing method in prosthetics and orthotics is the vacuum bag moulding lamination technique. The type and amount of material applied determines the composition while the sequence in which they are applied dictates the lay-up. More recently, the introduction of hybrid resins has added to the variety of composite structures available in prosthetics and orthotics.

Faulkner *et al.* (1987) evaluated the tensile strengths of composites used in prosthetics and orthotics utilising standard coupon test samples. While this is valuable when the general

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mechanical properties of materials are needed, these samples do not represent the geometry of the clinical devices. This creates difficulties in the translation of the data into socket design criteria. Head (1994) states: "Material design data are normally derived from the testing of specimens. For maximum reliability the specimens and test conditions should represent as closely as possible the materials and conditions of use of the final product."

The fabrication of FRP composites is riddled with several points of debate. One issue focuses on the use of reinforcement materials. Klasson (1995) reports that when using carbon fibre (CF) instead of fibreglass (FG) in equal amounts the strength will be about the same. Roberts (1984) states that using CF will result in a 30% to 40% increase in strength. Berry (1987) reported higher increases in strength, claiming that under compression CF is twice as strong as FG. All authors agree that replacing FG with CF will result in a reduction in weight. Klasson (1995) predicts a 10-15% lighter composite while Roberts (1984) predicts about a 30% savings in weight.

Excellent fatigue resistance can be achieved with the use of CF as compared to FG because the CF are approximately three times stiffer than FG. However, due to its high stiffness, CF is more susceptible to impact forces. For this reason both Berry (1987) and Roberts (1984) recommend mixing CF with either FG or Kevlar. Klasson (1995) recommends caution when mixing fibre types due to possible mismatches in the strengths of the fibres.

Several authors have recognised the fact that strength can be increased and weight reduced by using unidirectional materials instead of plain woven cloths (Roberts, 1984; Luger, 1982; Strong, 1989; Taylor, 1996). One of the problems associated with plain woven fabrics is that the fibres tend to bind or cut each other when stress is applied. In contrast, alternating layers of unidirectional fabric will provide strength in two directions without binding (Roberts, 1984; Luger, 1982; Taylor, 1996). Another advantage of unidirectional composites with regard to strength is that more fibres can be packed into a given space, thus increasing the fibre volume fraction (Roberts, 1984, Taylor, 1996). An interesting compromise can be reached between the two types using satin or long-shaft weave cloths (Strong, 1989; Humphrey, 1981; Mohr *et al.*, 1973; Taylor, 1996).

The last subject relevant to this study is the minimum allowable inside radius (MAIR). The MAIR= *r(fibre)/r(curve)* and must be less than the fracture strain. Woven fabrics have a greater MAIR than unidirectional fabrics due to the initial bend applied to the fibres by the weave. The tighter the weave the greater the MAIR. Mohr *et al.* (1973) and Sonneborn (1954) report a MAIR of 6.35mm and 12.7mm respectively while using the vacuum bagging lamination technique. Taig (1972) claims that the MAIR can be as small as 1mm for fibreglass materials and 11.6mm for large CF materials without damaging the fibres. Klasson (1995) recommends a MAIR of 40mm. Levan (1996) states that in order to determine the MAIR the fibres modulus and diameter must be known. For this information he recommends contacting the supplier or the manufacturer. All of the authors agree that larger radii are preferred over smaller ones though a measure of the optimal radii for socket design is still in question.

Understanding the material properties of composite design is important to ensure the structural integrity of the devices being fabricated. The purpose of this investigation was to quantify the strengths of various FRP trans-tibial sockets utilising a four hole attachment system. Techniques and materials used reflect those currently in widespread use within the United States of America. Testing was limited to the static load test. The static load test is used to reveal structural or design weakness associated with severe loading conditions. Ultimate strength, load point deflection curves and failure mode were adopted as the measures to assess structural properties of the trans-tibial socket. Additional comparisons were made between the sockets according to composite weight, strength-to-weight ratio rankings. To the authors' knowledge there are no studies evaluating structural testing of trans-tibial composite sockets.

Methods

Trans-tibial structural test model

In order to produce identical test samples for each composite type, a trans-tibial model was developed using a prosthetic CAD/CAM software package (Shape Maker, MIND Corp., Seattle, WA, USA). The model was created by averaging the measurements of 25 definitive trans-tibial limbs which contain the customary modifications performed by an experienced prosthetist. The model was milled by conventional means with additional modifications completed by hand to remove any undercuts. Holding the model in normal bench alignment a distal attachment plate (AP-04, Prosthetic Design Inc., Dayton, Ohio, USA) was hand modified onto the distal end using plaster. Additional plaster was applied until the build-up followed the shape of the model body. This modification left a sharp angle between the model body and the distal end. Final modifications to this region resulted in a 10-12mm radius. To produce accurate and consistent corner radii, first the angle was flattened with an abrasive tool so that there was a surface of regular width for the full length of the angle. Then, the flat cut was blended in with the rest of the surface without making it any deeper (Humphrey, 1981).

The designated knee centre represented a point 19mm proximal to the mid-patellar tendon (MPT) (Coombes and MacCoughlan, 1988). This measurement was necessary for alignment of the proximal lever arm fixture used to load the prosthesis.

Socket fabrication and alignment

All sockets were fabricated from the trans-tibial test model a minimum of 14 days prior to testing. Lamination was done using the vacuum bagging method in the vertical position at room temperature. All resin was catalysed between 2.8 and 3 percent by weight and no pigment was used. All laminations were completed under a minimum of 2666 Pa (20mmHg) of vacuum and left under vacuum a minimum of one hour from the time the resin was catalysed. Gel times were all within normal limits. Following curing of the composite material, both the socket and the waste materials were again carefully weighed. The weights were taken for estimating the fibre-volume fraction.

A total of 10 sockets was fabricated in which the reinforcement material type was the primary variable and the resin type was the secondary variable. Two sockets were fabricated for each of the 5 types of reinforcement material (Table 1). One socket was laminated using acrylic resin and the other using carbon acrylic resin.

Composite lay-up was held constant for non-reinforcement materials. Each socket included an inner and outer layer of nylon stockinette (623T10=9 Otto Bock Nylon, Duderstadt, Germany) and 4 intermediate layers of fibreglass-nylon stockinette (623T11=9 Otto Bock Nylglass, Duderstadt, Germany). Three (3) layers of reinforcement were added to each socket, 1 layer between each layer of fibreglass-nylon stockinette. Each layer of nylon and fibreglass-nylon stockinette was cut to length and one end was sewn closed. In addition, between the outer layer of fibreglass-nylon stockinette and the final layer of nylon, there was a single piece ($^1/_2$oz - 14gm) of dacron felt covering, but not overlapping, the distal end. This piece was added to allow surfacing of the distal end without affecting the integrity of the reinforcing materials. The end result for all sockets provided 6 plies of reinforcement material over the distal end, 3 plies of reinforcement material in the body of the socket, and 2 plies of reinforcement material in the proximal medial/lateral extensions. The sockets were cut to near identical trim lines and attached to an endoskeletal system (Otto Bock, Duderstadt, Germany). Components were assembled according to the manufacturer's instructions, with the socket and distal attachment plate connected with 4 bolts.

Table 1. Fibre reinforcement material types evaluated in static structural tests of trans-tibial sockets.

Unidirectional Carbon	Bock#616B2
Carbon-fibreglass stockinette	Bock#616G14
Fibreglass stockinette	Bock#616G13
Carbon fibre cloth	Bock#616G12
Fibreglass cloth	Bock#616G18

The alignment of the lever arms in relationship to the prosthesis equated to the parameters for structural testing strength of lower limb prostheses (ISO 10328 Standards for Load Level A100, Loading Condition II). Due to the specific offsets required, a method was needed to align the lever arms attached to the prosthesis quickly and accurately. Furthermore, the technique had to affix the proximal lever arm to the socket without affecting the performance of the device (Fig. 1). To achieve these goals a Socket Loading Fixture (SLF) was fabricated out of polyurethane elastomer (H.B. Fuller, Co. St. Paul, MN, USA) which held the proximal lever arm's force reaction point at the specified height and offsets. The SLF extended

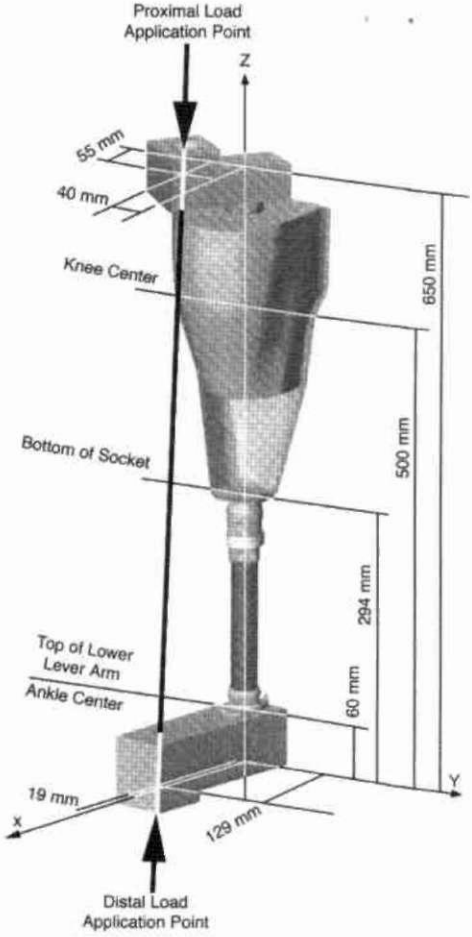

Fig. 1. Computer-generated image of the test apparatus used for static structural testing of trans-tibial prosthetic sockets. A cut-out sectional view of the sockets reveals the position of the Socket Loading Fixture (SLF). The illustration shows the reference planes, reference lines, dimensions, load application points and components.

approximately 9cm into the socket distal to the knee centre and the remainder of the socket was left hollow. The SLF has been used successfully in previous studies to load trans-tibial sockets (Coombes *et al.,* 1988; Wevers and Durance, 1987). However, it was not used for the explicit purpose of testing the structural integrity of the socket.

For alignment of the test samples, the SLF was inserted into the socket and a plumb line situated at the forward axis of the proximal lever arm. The alignment screws were adjusted on the endoskeletal system for each socket to ensure the loading surface of the proximal lever arm was parallel to the distal lever arm. The socket was then rotated at the tube clamp until the plumb line was aligned with the forward axis on the distal lever arm. With the components properly positioned and all the set screws torqued to manufacturer's specifications, the entire system was mounted in a materials test machine. This configuration is not in accordance with ISO 10328 which requires the alignment to be set to the manufacturer's guidelines and then set to a "worst condition."

Test procedure

Testing was conducted on a closed-loop computer controlled 100kN capacity servo-hydraulic test system. The tests were conducted in displacement control at a rate of 100mm/s. A +/- 80kN load cell was calibrated to standards traceable to NBS before and after testing. Linearity of the load cell was to 0.05% of full scale. Displacements were measured with a +/- 50mm LVDT, which was also linear to within 0.05% of full scale. All samples were loaded at the specified offsets and loading rates until failure was achieved. The offsets used relate to the instant of maximum loading occurring in the late stance phase of the gait cycle. The load was transmitted to the lever arms through a ball and socket joint design. Two (2) 47.6mm (1 7/8in) diameter automotive trailer hitch balls rated to 8.9kN (2000lbs) were attached to the testing apparatus. These pieces mated with the lever arms attached to the socket and pylon to provide a reaction point in which pure vertical force could be applied to the prosthesis as it deflected. A set force of 920N (ISO standard 19328) was applied as described above, held for 30 seconds, and then removed. The test device was then loaded to failure. Ultimate failure was designated as the point at which the prosthetic socket lost the ability to support an increasing load.

Data analysis

The results of this pilot study were evaluated using descriptive measures as well as Analysis of Variance (ANOVA). Specifically, a two-factor main effects ANOVA was performed with Duncan's Multiple Range test used for follow-up comparisons. The two factors were Resin consisting of 2 levels, and Materials, were consisting of 5 levels. Statistical significance

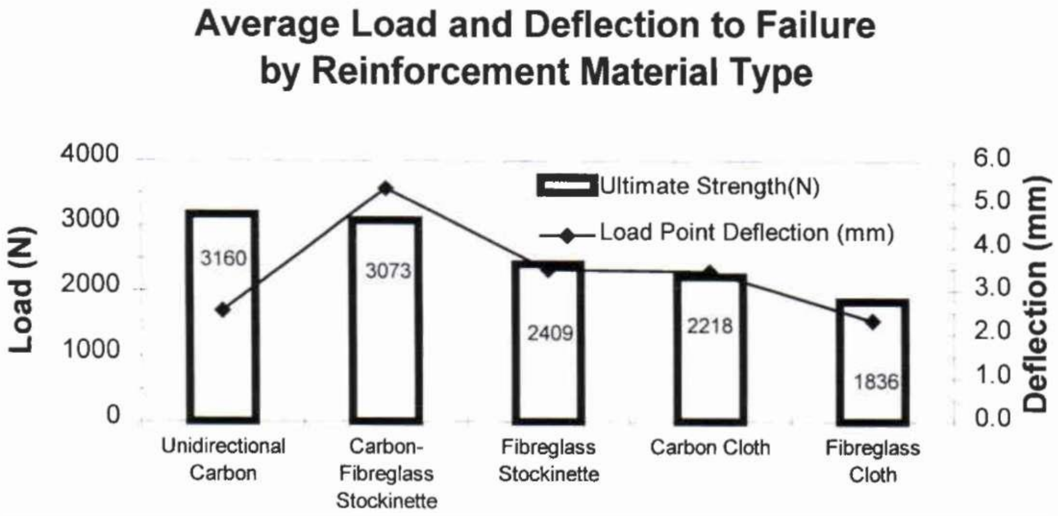

Fig. 2. Comparison of load point deflection and ultimate strength for each material, evaluated.

was set at the 5 percent level, although given the pilot nature of this work, specific p-values were also examined.

Results

The only significant statistical difference found between composites in regard to resin type was for load point deflection ($p<0.05$). This fact allowed the authors to increase the sample size by combining the results of these two groups for each reinforcement material type

Figure 2 shows the loading profile of each composite socket up to 18mm of load point deflection. It should be noted that the load point deflection also includes the deflection of the loading fixtures, the prosthetic hardware and the socket. The ultimate strength of fibreglass cloth approached a significantly lower value as compared to that of the unidirectional carbon and the carbon fibreglass stockinette ($p=0.06$) (Fig. 2). The ultimate strengths and load point deflection at failure were averaged by

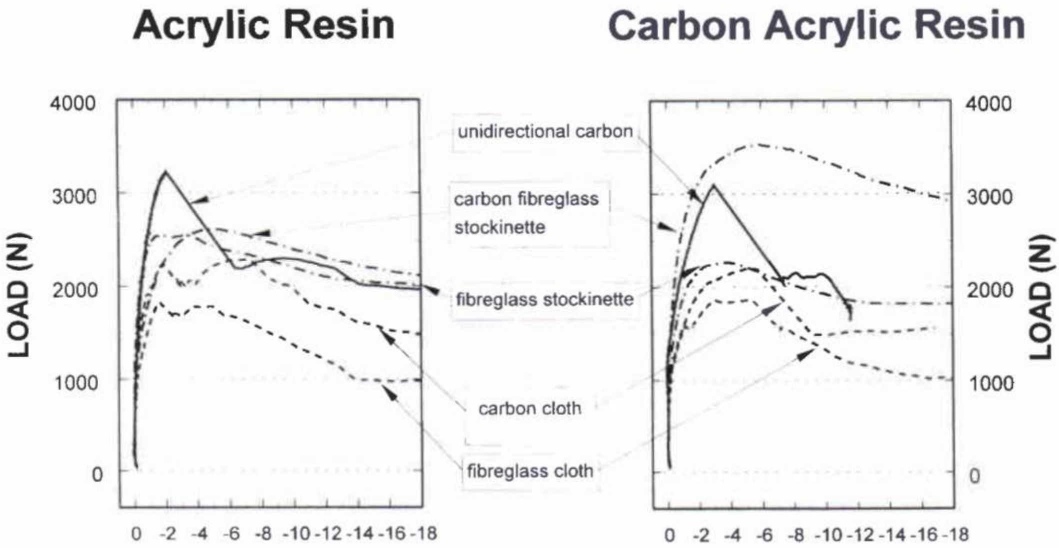

Fig. 3. Load point deflection curves of acrylic resin and carbon acrylic resin with the five different fibre reinforcement materials.

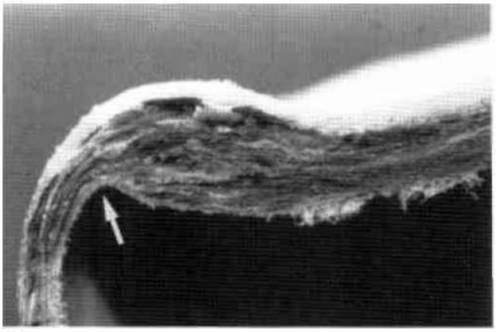

Fig. 4. Photograph of a cross-sectional view of a "buckle" type failure.

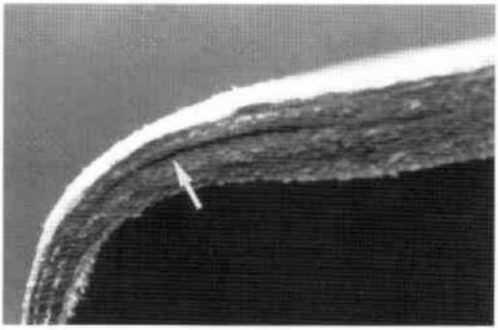

Fig. 5. Photograph of a cross-sectional view of an "inter-laminate" shear type failure.

reinforcement material type for further comparison.

The load point deflection of the carbon fibreglass stockinette approached a statistical difference (p=0.08) as compared to unidirectional carbon and fibreglass cloth (Fig. 3). The deflection was calculated with the position and load data collected by the materials test machine using linear regression $D^*=\mathrm{Pos}^*-(m\mathrm{Load}+b)$ where $m\mathrm{Load}+b$ = slope of the position vs load data in the linear elastic region. The increasing negative values indicate the compressive nature of the test procedure. All failure types were brittle but 3 failure modes were found; buckling in the stockinette reinforced composites, tension in the cloth reinforced composites, and inter-laminate shear in the unidirectional carbon reinforced composites (Figs. 4-6).

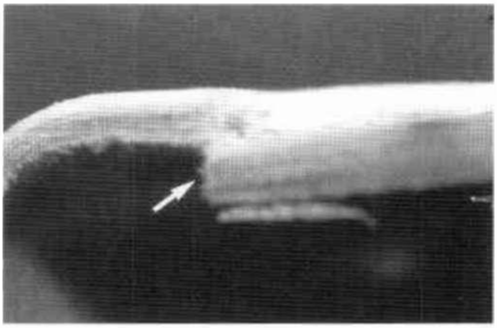

Fig. 6. Photograph of a cross-sectional view of a "tear" type failure.

There was a significant difference in the testing weight of the composites. Fibreglass stockinette reinforcement was found to be statistically greater (p=0.002) than all the others and the carbon cloth to be statistically less (p=0.002) than the stockinette reinforced composites (Table 2). This difference is directly related to the amount of reinforcement material

Table 2. Material characteristics of trans-tibial sockets tested and mode of failure.

Reinforcement material type	Testing weight (N)	Strength: Weight ratio ranking	Reinforcement material dry weight (N)	Fibre-volume fraction	Failure mode
Unidirectional carbon	3.56	100.00%	1.25	34.2%	Shear
Carbon-fibreglass stockinette	3.75	92.24%	1.43	27.7%	Buckling
Fibreglass stockinette	4.41	61.47%	2.27	32.4%	Buckling
Carbon cloth	3.28	76.02%	0.90	28.7%	Tension and shear
Fibreglass cloth	3.51	58.88%	1.25	29.1%	Tension and shear

(by weight) in each composite, which was also found to be significantly different. The stockinette reinforcement weight was found to be statistically greater (p=0.0001) than all the others.

The strength-to-weight ratio of the unidirectional carbon reinforcement was statistically greater (p=0.02) than that of the fibreglass cloth reinforcement, carbon cloth reinforcement, and the fibreglass stockinette reinforcement, but not the carbon fibreglass stockinette. The carbon fibreglass stockinette reinforcement's strength-to-weight ratio was statistically greater (p=0.02) than the fibreglass cloth and the fibreglass stockinette but not the carbon cloth (Table 2).

Although a statistical analysis was not done, differences were also found among reinforcement material types for the estimated fibre volume fraction. The unidirectional carbon reinforced composites had a greater estimated fibre volume fraction than all other composites. The estimated fibre volume fraction is the percentage of material (everything except the resin) by volume within the entire composite. Volumes were calculated using weight and density (Table 2).

The deflection occurring with carbon acrylic resin was statistically greater than with the acrylic resin (p=0.05). This was the only statistical difference between resin variables. However, in the case of the carbon-fibreglass stockinette the ultimate strength of the carbon acrylic socket was notably greater than its acrylic counterpart (Fig. 2). This is the only case where a notable difference was seen for the reinforcement material between resin types. No explanation can be given for the difference with this sample size.

No statistical difference was found among the following variables: total non-reinforcement materials, total resin used, percent promoter used, and resin gel times.

Discussion

This study compared the strengths of various trans-tibial composite prosthetic sockets. A technique was developed for testing trans-tibial sockets that incorporated the loading parameters and methods established by the International Standards Organisation (ISO) for structural testing of lower limb prosthetic components. Failures of the test samples were similar to those reported in clinical situations. None of the composites in the study met the specified parameters for structural testing of lower limb prosthetic componentry (ISO 10328 Standards for Level A100, loading condition II).

Increasing the amount of reinforcing material is one method of improving strength properties. However, the relationship between the amount of reinforcing material and the ultimate strength is not linear. One should not assume that doubling the amount of reinforcing material will double the ultimate strength (Klasson, 1995; Humphrey, 1981). If the cause of failure is interlaminate shear or buckling a change in the composite profile may be necessary to increase ultimate strength. If the cause of failure is tension then simply increasing the amount of material may be of benefit.

Two (2) of the 4 cloth reinforced composite sockets tested, 1 fibreglass cloth and 1 carbon cloth reinforced composite, had a complete failure at the pyramid attachment plate. This break resulted in the anterior edge of the pyramid attachment plate being pushed completely through the socket's distal end. These were the only 2 cases where the composite actually broke completely through. These 2 composites were deemed incapable of providing ambulation while the other 2 cloth reinforced composites returned to a position where ambulation might have been possible.

Because all of the sockets failed at the site of the pyramid attachment plate it can be assumed the amount of reinforcement in the socket body and proximal extensions was sufficient. It is not known if increasing the amount of material over the distal end would cause failure in the socket body. The authors suggest that the material in the socket body need only be enough to provide continuous fibre coverage from the body to the distal end. The attachment plate design appears to be an important component to the structural integrity of the socket. This is evidenced by the consistent failure seen in this region of the socket both clinically and in the laboratory.

The weakest point of the attachment system used in the composite design was the anterior edge of the pyramid attachment plate as it interfaced with the distal end of the socket. The anterior edge of the pyramid attachment plate appears to act as a focal point for a stress raiser. If the focal point were reduced by spreading the stress over a larger surface area such as a round pyramid attachment plate system instead of a square one, premature socket failure might be reduced. The focal stress point could be further reduced by rounding the sharp edge of the attachment plate in contact with the socket surface, thus increasing the bend radius for the fibre as it deflects.

Finally, the shape of the distal end may also be a factor with regard to the blending of the attachment plate interface at the distal end of the positive model. If one accepts that the geometry of the distal end radii could change the strength characteristics of the socket as some authors have suggested (Klasson, 1995; Roff, 1956; Taig, 1972), various sized radii could yield different results from that which is reported herein. Inspection of the strength characteristics of different attachment systems is also needed to optimise the composite profile. In addition, further study is necessary to establish the amount of reinforcement needed at the distal end of the socket to maintain high levels of loading for the trans-tibial composite prosthesis.

The primary factor shown by this study to affect ultimate strength is the choice of reinforcing material. The 2 materials that produced the greatest ultimate strengths were the carbon-fibreglass stockinette and the unidirectional carbon webbing. The unidirectional carbon webbing appears to be the best choice when considering all other performance aspects.

Care must be taken when referring to the force deflection curves as they differ from a stress strain curve. A stress strain curve has normalised the data by cross-sectional area. The stress strain curve will be the same for different composites made by identical methods and of identical materials, it would not matter if one composite contained 6 layers of reinforcement and the other 10 or 12 layers. However, using the load deflection curve the difference in ultimate strength between reinforcement material types and/or between the total ply of reinforcement used can be seen instantly. With this data long mathematical calculations can be avoided when trying to determine the proper lay-up needed to obtain any given ultimate strength.

Force deflection curves indicate that the carbon fibreglass stockinette had the greatest amount of deflection at the point of failure. By calculating the area under the curve it can be determined that these composites absorb a greater amount of energy prior to reaching ultimate failure than the other test samples resulting in less recovery. Because the unidirectional carbon absorbed less energy than the carbon fibreglass stockinette reinforced composites, and due to the unidirectional carbon's failure mode, it was capable of better recovery following removal of the load. Both of the carbon fibreglass stockinette reinforced composites and 1 of the 2 fibreglass stockinette reinforced composites were permanently deformed upon removal of the load to the point that they were deemed incapable of assisting the amputee in functional ambulation.

Some of the test devices may be capable of providing limited ambulation immediately after ultimate failure. The load deflection curves of the majority of the samples appear to plateau shortly after failure (Fig. 3). The "plateau" load level of each respective composite tested represents the maximum load these devices could continue to function at on a limited basis. The amount of deflection at the plateau load following a load to failure will be slightly greater than the point at which it levelled off in the graph.

Three (3) primary types of failure occurred. (Figs. 4-6). All of the composites utilising the stockinette reinforcing material failed with a buckling type of deflection at the transition from the socket body to the distal end. Two (2) of the 4 cloth reinforced composites failed by fibre breakage at the anterior edge of the 4 bolt pyramid attachment plate. In this instance the pyramid attachment plate appeared to act as a focal point to increase stress on the fibres and cause them to break under tension. The other 2 cloth reinforced sockets failed via inter-laminate shear. The unidirectional carbon reinforced composites also failed as a result of inter-laminate shear. All of these failure modes were correlated to the reinforcement material. These mechanisms of failure have been reported in the literature (Klasson, 1995; Humphrey, 1981; Luger, 1982; Titterton, 1951). Coupon testing can be used to confirm the failure mode. This type of testing can be very useful in helping one decide on the composite profile. Complete coupon testing includes tests of: tension, compression, torsion and sharp beam. Although these tests are important for engineering a composite socket, coupon samples do not represent the geometry of a trans-tibial socket.

The testing weight of the sockets was directly related to the type of reinforcement material used. When trying to optimise for weight this information is important. Carbon cloth, when comparing equal plies of material, was notably lighter than both types of stockinette reinforcements tested. Also, when using carbon cloth or carbon fibreglass stockinette in place of their corresponding fibreglass reinforcement material types a 20.8% and 27.5% reduction in weight was noted respectively. Even though the carbon cloth produced the lightest socket it did not produce the greatest strength-to-weight ratio for the composite profiles tested. The greatest ratio was produced by the unidirectional carbon and was notably greater than all the other materials tested except for the carbon fibreglass stockinette. The fact that the unidirectional material produced the greatest ultimate strength and the greatest strength-to-weight ratio is consistent with the literature (Strong, 1989; Roberts, 1984; Luger, 1982; Humphrey, 1981; Mohr *et al.*, 1973).

Determining the fibre volume fraction is an expensive and time consuming process that requires specialised equipment. Because of cost and time constraints, a crude approximation was made by carefully weighting the materials prior to and after fabrication and then converting to volumes using the densities. Using this technique some error is expected in the values reported, the extent of which is unknown. These values seem low compared to the 70% often reported as being the standard (Klasson, 1995; Taylor, 1996). However, those composites which approach the 70% level do not contain any nylon or nylglass. The nylon and nylglass tend to retain more resin and reduce the fibre volume fraction. These materials weaken the composite by reducing the inter-laminate shear strength but increase toughness with their ability to reduce crack propagation.

The acrylic based composites had a statistically lower amount of local deformation than the carbon acrylic ones. This may have been a result of the additive the manufacture added to the resin to provide better "wet-out" of materials. However, better "wet-out" does not necessarily mean greater strength. Three (3) of the 5 different reinforcement material types, unidirectional carbon, carbon cloth, and fibreglass stockinette, had a greater ultimate strength using the acrylic resin.

The data derived from this study is specific unto itself. Any change in the design parameters used herein may produce different results. Such examples would include changes in the composite profile, in the shape or length of the trans-tibial structural test model, or in the socket-pylon attachment system. The data is also limited by the lack of cyclic or torsional loading. Future studies are needed to determine the optimal lay-up of fibre materials based on the patients' pathology, activity, and weight. The methods described in this study could be adapted to establish such guidelines. A more diverse knowledge base of composite fabrication principles for orthotics and prosthetics is essential to meet the specific design criteria for each clinical application.

Conclusion

A new method was developed for the static structural testing of trans-tibial prosthetic sockets. Loading parameters and procedures established by the International Standards Organisation for testing lower limb prosthetic componentry were adopted as the design criteria for test apparatus and methods. The test protocol produced consistent, reproducible results for evaluating the performance of the trans-tibial socket. Although there are no standards for the testing of the trans-tibial socket portion of a prosthesis, it is noteworthy that none of the composite sockets in the study were able to meet the specified parameters set for other prosthetic componentry (ISO 10328 Standards for Level A100, loading condition II). All trans-tibial socket failures occurred at the distal segment near the anterior border of the pyramid attachment plate. Three failure modes were identified: inter-laminate shear, buckling, and tension. Unidirectional carbon and carbon fibreglass stockinette performed similarly with regard to ultimate strength and strength-to-weight ratio. In general, the carbon reinforced sockets were lighter and stronger than their fibreglass reinforced counterparts. Future studies are needed to establish guidelines on material lay-up and structural design features that may increase the ultimate strength of the trans-tibial socket for various clinical situations.

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