Engineering a Trans-Tibial Prosthetic Socket for the Lower Limb Amputee

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Abstract

Introduction: This review addresses the different prosthetic socket designs for trans-tibial amputees, the biomechanics behind the designs and the current state of the field. Of particular focus is the classic patella-tendon bearing (PTB) socket and the more recent sockets manufactured using pressure casting techniques and the theory, biomechanics and clinical implications of the two designs. Methods to examine and compare these designs are also addressed. Materials and Methods: Journal papers by various investigators which have clinical significance/impact on the field of trans-tibial socket design were chosen for this review. Articles were chosen over a period of over 50 years to demonstrate the evolution of knowledge. Results: The engineering of the trans-tibial socket has been largely subjected to empirical derivations and biomechanical theory that remains, for the most part, unproven. The fundamental principles of the PTB socket have been widely refuted. Hydrostatic theory based on pressure casting techniques, on the other hand, provides an optimal scenario to produce a more uniform stump/socket interface pressure. Conclusion: Preliminary studies indicate the pressure casting technique has the potential to produce comfortable sockets, providing an alternative to the PTB design. Various studies have been attempted to quantitatively compare the 2 types of socket designs. However, further quantitative biomechanical studies are needed to explain the fundamental theory surrounding the pressure cast technique. Methods that could help further understand the pressure cast concept include amputee gait analysis, stump/socket interface pressure measurements, computer aided socket design and finite element modelling techniques.

Ann Acad Med Singapore 2011;40:252-9

Key words: Biomechanics, Patella-tendon bearing, Pressure casting, Pressure measurement, Prosthetic socket, Trans-tibial amputee

Introduction

Amputation of the lower extremities continues to be a major problem due to vascular-related diseases e.g. diabetes. It is also a prevalent occurrence in countries affected by landmines, high incidents of motor vehicle accidents and natural disasters like earthquakes. A key component of amputee rehabilitation is the engineering of devices suited to individuals in order to recover physical capabilities. A prosthesis or artificial limb is one such device that aims to substitute the loss of a limb with cosmetic and functional desirability for the amputee. Lower limb prostheses can consist of an assembly of several components such as the socket, shank, ankle and foot (Fig. 1). The socket can be considered as the most important aspect of the artificial limb, which constitutes the critical interface between the amputee's stump and prosthesis. The design and fitting of the socket is also the most difficult procedure due to the uniqueness of each amputee's stump. An uncomfortable socket fit is a common complaint from lower limb amputees with surveys revealing that amputees believe comfort is the most important aspect of the prosthesis and over half of all wearers are in moderate to severe pain for most of the time whilst wearing the prosthesis.[1]

Socket design has evolved from basic conical designs to total-surface bearing sockets. Determining an optimal socket design and fitting method is difficult due to the uniqueness of each amputee's stump. Differing opinions still exist regarding the biomechanical characteristics that a prosthetic socket should possess. The biomechanics of trans-tibial prostheses were first proposed by Radcliffe[2] in 1961. Since then, a range of studies using pressure transducers and finite element analysis (FEA) have been attempted to quantify the load bearing characteristics of the prosthetic socket. What is clear is that a design is required which allows for comfortable weight bearing during gait and the systematic production of consistent and quality sockets by prosthetists. To this end, this review aims to compare the different prosthetic socket designs available for trans-tibial amputees. The theory behind these socket designs and their biomechanics and clinical implications will be addressed. In addition, this review also examines

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the methods used to analyse and compare these designs and the type of future studies which could help advance the field of trans-tibial socket design.

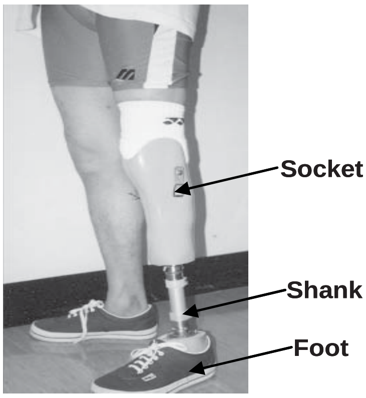


Fig. 1. Typical trans-tibial prosthesis.

Evolution of the Trans-Tibial Socket

The end of World War II (WWII) saw the discovery of new materials, a greater understanding of biomechanics and, as a result, the beginning of a new, more modernised approach to socket design. Prior to these advances, thigh corsets were often utilised to off-load the stump and sockets were loaded only around the proximal brim regions. Such designs allowed for migration of the limb in the socket which resulted in skin irritations and pains. In 1959, a fundamental change in socket design was introduced with the advent of the patella-tendon bearing (PTB) sockets,[3] the first to remove the corset and sidebars so that the entire amputee's weight is taken up at the stump/socket interface. Still, the most commonly prescribed socket design today, the PTB socket relied on the concepts of socket biomechanics as proposed by Radcliffe.[2] The design of the socket takes advantage of the pressure tolerant areas in the stump, especially that of the patellar tendon and the posterior aspect of the stump. With the removal of the corset or sidebars, the entire amputee's weight will be taken up at the stump/socket interface. As such, the socket shape is indented to increase the load on areas that are more pressure tolerant, such as the patella tendon area. The advocates of the PTB socket determine that the patellar tendon area could carry a substantial amount of the total load. This is achieved by creating an indentation on the socket commonly known as the patellar tendon bar (Fig. 2). The patellar tendon bar would therefore relieve loading at the other regions of the stump that are considered less tolerable to load, reducing discomfort.[4] However, considerable skill is required in order to generate a good PTB socket fit. Whilst there have been advancements made to allow for the systematic production of PTB sockets, the process is still reliant on largely artesian techniques and the skill and experience of the prosthetist. Table 1 highlights some of the main advantages and disadvantages of the PTB sockets.

It was almost 30 years before the next substantial advancement was made in socket design concepts with the introduction of the total surface bearing (TSB) socket. Using suction as the suspension method, the TSB socket concept relies on anatomical accuracy at the stump/socket interface.[5] An example of the TSB concept is the development of the Icelandic Roll-On Silicon Socket (ICEROSS).[6] Using a silicon liner turned inside-out and rolled over the stump, the silicon liner forces the stump's skin in a distal direction stabilising the soft tissue. In addition to the silicone liner, padding is placed over bony areas of the stump during the casting process. Casting is performed on the patient using an air bladder system to produce a socket shape based on the hydrostatic principle for load transfer. The hydrostatic principle assumes that soft tissue in the stump behaves as a fluid and abides by Pascal's law of fluids. Pascal's law states that a confined fluid will transmit external pressure uniformly in all directions perpendicular to the containers surface. In theory, if a socket behaves as a hydrostatic system when loaded, equal distribution of pressure throughout the socket is ensured and areas of high pressure eliminated,[6] hence leading to a more comfortable socket fit. The first use of hydrostatic theory in socket production was by Murdoch[7] in 1965, with the introduction of the Dundee socket. Murdoch aimed to reduce some of the manual dexterity required to produce a quality socket, using fluid as a medium to apply uniform pressure around the stump during casting. This pressure casting concept was revived by Kristinsson with the introduction of the ICEROSS silicon liner and the air bladder casting system.[6] Advocates of the ICEROSS liner claim superior comfort, suspension and relief of dermatological problems, however, studies have revealed that 91% of subjects fitted with the ICEROSS liner experience skin problems.[8] The most common complaints are excess sweating, skin itching and redness. These results indicate that whilst the hydrostatic theory is successful in eliminating regions of high pressure, the total surface bearing characteristics can result in a different slew of dermatological problems.

More recent studies by Lee et al[9] attempted to cast the patient in a standing position using a fluid pressure chamber, a very similar procedure to that of Murdoch's early work. Lee et al[9] described pressure casting (PCAST) as a technique using objective parameters such as stump anatomy and the amputee's body weight, to generate an evenly distributed pressure over the stump to create a unique socket shape (Fig. 2). The PCAST technique involves wrapping plaster over the amputee's stump, before placing it in a sealed pressurised water chamber. A diaphragm separates and protects the plaster covered stump from the water. While the plaster

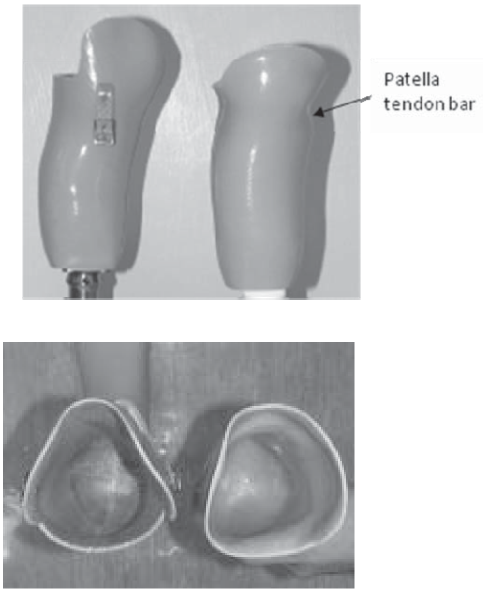


Fig. 2. PCAST (left) and PTB (right) sockets.

hardens in the pressurised chamber, the amputee is standing upright without aid, the contra-lateral limb positioned over a weighing scale to ensure half the body's weight is distributed to the stump (Fig. 3). The uniform pressure causes an elongation of the soft tissue surrounding the stump resulting in more padding at the sensitive distal end, and firmer tissue consistency.[6] Once the plaster has hardened, the system is depressurised and the plaster removed. A positive mould is generated and normal lamination methods follow to fabricate the socket. An important aspect of the procedure is that no rectification to the positive mould use to fabricate the socket is performed. The principle underlying the PCAST is to "let nature dictate the most realistic and achievable pressure distribution".[10] The advantages of the PCAST design include ease in implementing the technique, improved manufacturing times and as no rectifications to the positive mould are required, issues pertaining to manual dexterity and inter-prosthetist variances are eliminated.[9]

Fig. 3. Trans-tibial amputee in a normal standing posture unaided; supported by the pressure cast system.

Evaluations of sockets made using pressure casting have found that a hydrostatic pressure profile or a uniform stump/socket pressure was not evident during either standing or gait.[11] For an ideal hydrostatic socket to exist, the system must be closed i.e. the total volume of soft tissue in the stump must be contained in the same volume in the socket. Such a system is not possible at the complex stump/socket interface due to various factors such as stump tissue non homogeneity and muscular activities. Regardless of the lack of a uniform pressure profile, studies have shown that a socket made using pressure casting methods is able to provide a more comfortable fitting socket than its PTB counterpart.[12] Kahle et al[13] compared the PTB and hydrostatic socket designs by way of patient preferences, which were then related to the patients stump anatomy. It was found that 68% of patients preferred the hydrostatic design, the majority of whom had medium to long stumps with a firm tissue consistency. Reasons for this preference included increased range of motion, uniform pressure and decreased weight perception; most likely due to increased suction. Those who preferred the PTB socket (14%) complained the hydrostatic socket caused a pulling sensation at the distal end or experienced throbbing and/or cramping in the stump. Of those who preferred the PTB socket, most had a short stump with a conical shape. The remaining 16% rejected both designs and mostly had stump tissue of soft consistency. Table 1 summarises the advantages and disadvantages of the 2 types of sockets.

Table 1. Comparison of Key Socket Designs

	Advantages	Disadvantages
Patella Tendon Bearing	• Patella tendon (PT) bar carries substantial amount of load	• Reliant on largely artesian techniques and skill and experience of the prosthetist
	• Reduced loading at less tolerable regions of the stump reduces discomfort	• Ill-fitting sockets result in deterioration of stump, excessive shrinkage or edema[4]
	• Indentations at Supra-condyles aid suspension	
Hydrostatic	• Ease in implementing	• Can cause throbbing and/or cramping[13]
	• Improved manufacturing times	• Often incompatible with patients of short stump of conical shape[13]
	• Minimal or no rectifications to the positive mould are required	• Does not make allowances for stumps of irregular morphology
	• Inter-prosthetist variances eliminated[9]	
	• More padding at the sensitive distal end, and firmer tissue consistency[6]	

Trans-Tibial Stump/Socket Interface Pressure Analysis

Whilst the results of subjective studies indicate that patients show a preference for the hydrostatic socket,[12,13] the ongoing debate between the PTB and hydrostatic socket lies in their biomechanical principles. In evaluating the biomechanics of the different socket designs, pressure at the stump/socket interface is considered a critical factor. As such, measuring or predicting pressures at the amputee stump/socket interface is one of the most direct methods to gain data on the quality of fit/comfort of the socket. However, the stump is non-homogenous, consisting of regions of bone, muscle, fat and skin. This non-homogeneity leads to complex pressure distribution throughout the stump and complicates the measurement of this key parameter. Interface pressure studies have been attempted for over 40 years and currently rely on one of three methods; transducers built into the socket, in-situ transducers placed in between the stump/socket interface, and finite element analysis (FEA) methods (Table 2).

Table 2. Comparison of Pressure Analysis Techniques

Pressure Analysis Technique	Advantages	Disadvantages
In-built Transducers	• High accuracy and sensitivity	• Requires the manufacture of modified test sockets
		• Altered socket shape may affect pressure measurements[14]
In-situ Transducers	• Very thin (<0.2mm)	• Does not account for shear stress
	• Flexible	• Crinkles along the longitudinal axis, reducing sensing capabilities[15]
	• No need for fabricating a test socket	
	• Compliant around transverse axis	
Finite Element Analysis (FEA)	• Allows for the easy alternation (parametric studies) of patient specific parameters such as weight, socket shape.	• FEA estimates for pressure are, on average, 11% lower (SD 9%) than the clinical measurements[16]
	• Predicts both normal and shear stresses	• Comprehensive experiments such as gait analysis, soft tissue characterisation are needed to build a reliable model.

In-built Transducers

The method of inbuilt transducers requires that openings be made in the socket to allow for the pressure transducers to be mounted and contacting the stump. This method was used by various investigators to record the static (standing) and dynamic (walking) pressure profiles for different socket designs.[11,12] Held in place with araldite glue and surrounded by housing to avoid cross sensitivity to shear loads, the pressure transducers were inbuilt in the socket in locations of significance. The transducer assembly is composed of a cylindrical piston in close contact with the stump, which transfers the stump pressures to a strain gauge type load cell that offers high accuracy and sensitivity. However, in order to place the transducers, a modified test socket needs to be fabricated with the in-built transducer housing. The fabrication process can be laborious and difficult. It may also change the socket shape, affecting stump/socket interface pressure measurements.

In-situ Transducers

Unlike inbuilt transducers, placing thin sensors in situ at the socket/stump interface enables measurements to be made without the need of fabricating a modified test socket. Studies have used systems such as the F-Socket (Tekscan Inc, USA), which can be inserted between the stump and socket with minimal interference.[17] The pressure sensor is an assembly of 2 sheets of polymer, sandwiched are ink or carbon power and metal conductors. The application of force will cause an increase in contact area resulting in a change in electrical resistance calibrated with pressure readings.

Finite Element Analysis

Finite element analysis (FEA) is a computational modelling technique which gives an approximation to many complicated engineering problems. The success of using FEA in socket design has been sluggish due to the complex material and geometric parameters. However, with advances in high speed computing, FEA has gained increasing clinical significance in prosthetics research. The FEA models use parameters such as geometry of the stump and internal skeleton, friction/slippage conditions at the stump/socket interface, the mechanical properties of stump's tissue and the external loads applied to the stump to predict stump/socket interface pressures and the stresses distribution inside the stump. A study by Zhang et al[16] compared static stresses on trans-tibial stump predicted by FEA with clinical measurements. Using inbuilt transducers for the clinical measurements, it was found that the FEA estimates for pressure were, on average, 11% lower (SD 9%) than the clinical measurements. In addition the measured shear stresses were well predicted by the FE analysis. Recent advances have seen FEA used in real-time to analyse the internal stresses in the deep soft tissues of the stump, evaluating the biomechanical interactions between the stump and the socket, assisting in the production of a quality socket.[18]

Biomechanics of Trans-Tibial Sockets

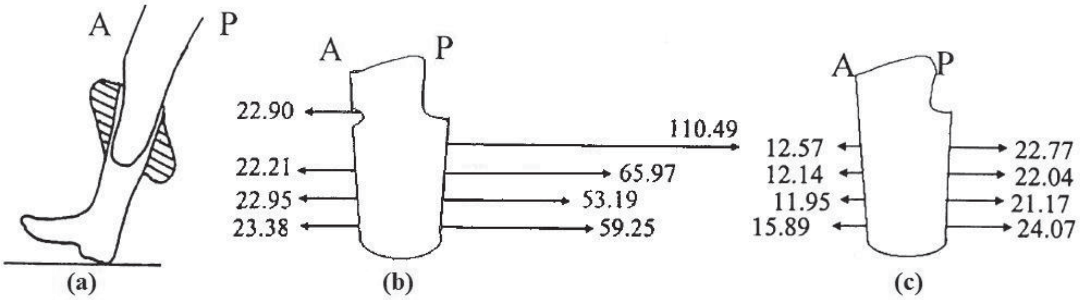
The first attempt to describe force patterns at the stump/socket interface was by Radcliffe[2] in 1961. Radcliffe proposed a stump/socket force distribution pattern which changes throughout the gait cycle, influenced by the alignment of the prosthesis, muscle action, and the angular position of the stump with respect to the ground reaction force (GRF).[2] Radcliffe assumed that the amputee can be expected to walk in a manner similar to that of an able-bodied person, compensating for loss of ankle function with hip and knee action to achieve a gait which closely approximately the norm. Three phases of gait were considered; heel strike (10%), mid stance, or shock absorption (25%) and toe-off (50%). As the heel strikes, the hamstrings prevent the GRF's acting anterior to the knee centre from causing the knee to extend. Within the socket, the action of the hamstrings causes high pressure at the patellar tendon and in the posterior distal tibia (Fig. 4a). Immediately following heel-strike, the GRF passes from a location posterior the knee joint, to a position anterior to the joint. This would result in the largest change in the pressure profile as the knee extension moment changes to flexion. During mid-stance (from flat-foot to heel-off), the knee undergoes controlled flexion. As the body advances over the stabilised knee, the GRF's act posterior to the knee. Action by the quadriceps and forceful extension of the hip prevents the knee from collapsing; as a result forces are concentrated at the patellar tendon, anterior distal tibial and popliteal area (Fig. 5a). During toe-off, the GRF passes behind the knee, as such the same 3 areas experience high pressures (Fig. 6a). In addition to the antero-posterior forces are the medial-lateral forces which, Radcliffe proposed, are relatively similar throughout the gait cycle. GRF's have a medial inclination due to the horizontal acceleration of the centre of gravity.[2] As a means to counteract this medial inertia, stabilising forces are established in the lateral distal and proximal medial tibia (Fig. 7a).

The aforementioned Radcliffe criterion was the design basis of the PTB socket. A study by Goh et al[14] aimed to compare the Radcliffe predictions with the measured pressures at the PTB socket interface. The sockets were manufactured by traditional methods, including modifications to allow for both pressure sensitive and load tolerant areas. Sixteen pressure measurement sites were built-in to the socket wall to create a pressure profile of the socket interface. Each of the anterior-posterior (AP) pressure profiles of the 4 subjects was different and all were found to not resemble Radcliffe's anticipated profiles from Radcliffe (Figs. 4b, 5b, 6b), in contrast all but one subject displayed medial-lateral (ML) profiles consistent with Radcliffe's predictions (Fig. 7b). All subjects displayed an increase in the pressure at the patella-tendon (PT) region during toe off as expected, yet for the remainder of the gait cycle, the largest pressure values were found in the popliteal depression. Additionally, results contradicted Radcliffe's assumption regarding the largest pressure change in the gait cycle, whilst Radcliffe proposed the largest change occurs immediately after heel strike, Goh et al,[14] found that the interface pressure showed the greatest change between mid- and late stance. This contradiction concurs with subsequent investigations regarding interface pressures profiles.[12] Contributing to these discrepancies between theory and practice were factors outside of the GRF's that were not considered by Radcliffe. Such factors include alignment, thigh muscle strength, and stump morphology.

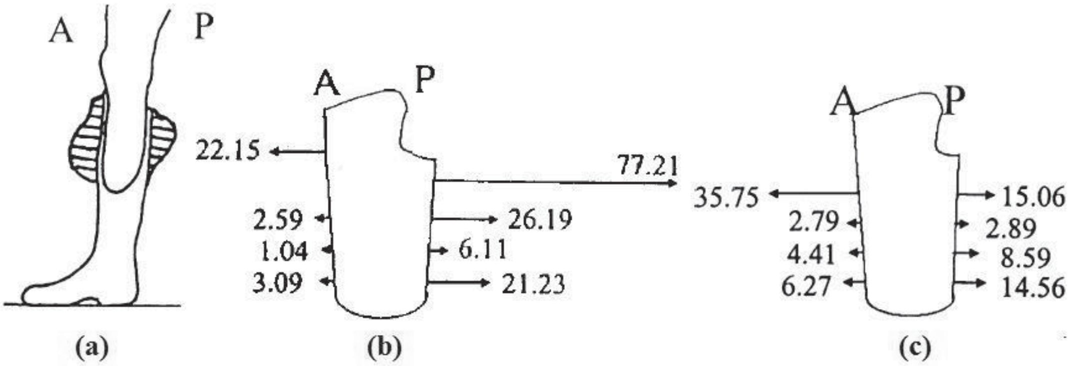
The aforementioned researchers then completed a similar study for the hydrostatic (PCAST) design.[11] A uniform hydrostatic profile was not observed for any of the 5 subjects (Figs. 4c, 5c, 6c, 7c). In an effort to describe the result biomechanically, the pressure profiles were then compared to Radcliffe's anticipated profiles. The AP profile was inconsistent for each subject, showing little correlation to Radcliffe's predictions. In all but one subject, the ML profile however consistently showed high pressures in the medial proximal and lateral distal region, as Radcliffe anticipated. Of particular point of interest is the high pressure found at the PT region at 50% of the gait cycle (Fig. 6c), mimicking the profile of the PTB socket, yet without the PT indentation. It is assumed this profile is obtained due to the action of the PT on the socket wall when full body weight is required for push-off. Though a hydrostatic profile was not evident, the PCAST method was able to fabricate functional and comfortable sockets for each of the 5 subjects.[11]

Comparing the PTB and Hydrostatic Designs

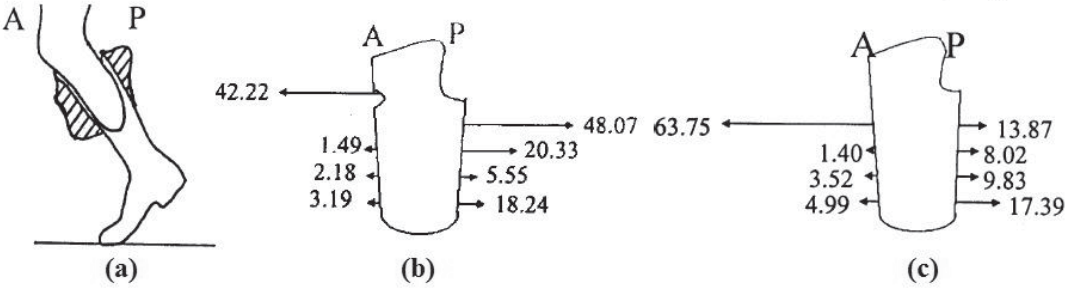
Goh et al[12] measured and compared interface pressure distribution between the PTB and hydrostatic (PCAST) designs. Using a series of transducers built into the socket wall, both static and dynamics pressure profiles were obtained. During stance, the GRF was found to be acting at the same direction for both sockets; regardless the hydrostatic design consistently displayed lower or comparable pressures to the PTB. Results proved varied during dynamic testing; of the 4 subjects, 2 had similar pressure profiles during gait, 1 indicated a 'ring' of high pressure at the proximal brim of the PTB socket and the other showed a region of high pressure distally in the hydrostatic design. The GRF line of action varied between subjects, with only one subject displaying a line of action which followed Radcliffe's assumptions. For individual subjects, the GRF line of action was similar for both prostheses, bar 2 occurrences where differences were noted. The medial-



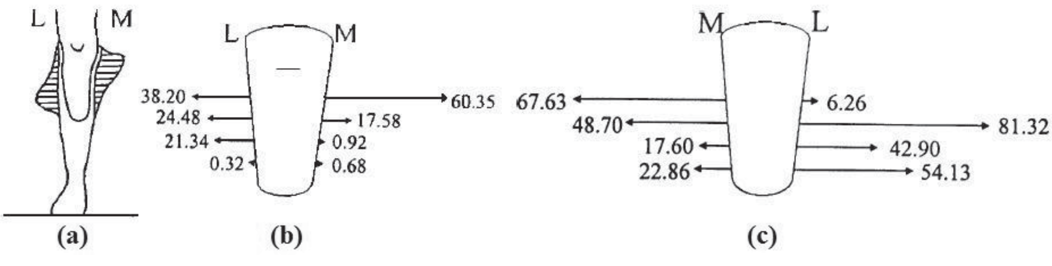
Figs. 4. (a) Anticipated AP pressure profile at 10% of gait cycle and measured values for (b) PTB[14] and (c) PCAST[11] sockets at same phase (all pressure values in kPa).



Figs. 5. (a) Anticipated AP pressure profile at 25% of gait cycle and measured values for (b) PTB[14] and (c) PCAST[11] sockets at same phase (all pressure values in kPa).



Figs. 6. (a) Anticipated AP pressure profile at 50% of gait cycle and measured values for (b) PTB[14] and (c) PCAST[11] sockets at same phase (all pressure values in kPa).



Figs. 7. Predicted (a) and measured ML pressure profile at 50% of gait cycle for the (b) PTB[14] and (c) PCAST sockets[11] (all pressure values in kPa).

lateral weight bearing characteristics were similar between the 2 designs. The medially inclined GRF was expected to result in high pressures at the medial-proximal and lateral-distal tibia regions; while 3 of the 4 subjects exhibited this profile during static tests, only one continued to do so during gait. Differences in profiles could also be due to socket alignment, which was not considered in the study.[12]

Dumbleton et al,[15] conducted dynamic tests using the F-scan (Tekscan Inc, USA) in-situ pressure transducers to map the pressure distribution at the stump/socket interface of the PTB and hydrostatic socket. Using this method, up to 90% of the socket area was analysed and pressure mapped. Similar pressure distribution profiles were found between the 2 types of socket. The hydrostatic design showed slightly higher pressure values, however there was notably less variation in the pressure distribution throughout the interface. The medial-lateral distribution revealed high pressures in the lateral distal region as expected. However, both PTB and hydrostatic designs indicated equal distribution between the proximal and distal regions of the medial aspect as opposed to the medial proximal region as indicated by Radcliffe. The first peak in interface pressure, occurring early stance, was exhibited in the anterior distal and posterior proximal regions. This also contradicts Radcliffe's assumptions, which propose high pressures at the anterior proximal and posterior distal regions. The same pattern is seen in the second pressure peak of late stance.[15,19]

Moo et al[20] used FE analysis in the comparative measurements of interface pressures between PTB and hydrostatic sockets. The pressure data used for the analysis originated from the average of 10 subject trials of pressure measurement. The measurements were collected using inbuilt load cells in the socket walls. By using the average values, the study ensured that the data measurements were reproducible. FEA socket models were created by scanning in CT images of the 2 sockets, the known pressure data applied to the model and the simulation for stress distribution made available. The FE analysis revealed the hydrostatic socket had a relatively uniform pressure distribution, both throughout the socket and throughout the gait cycle. In addition, the pressure magnitudes are lower than those in the PTB socket. The highest pressure values measured in the hydrostatic socket were in the medial aspect; whilst still relatively low, these pressures, peaking at terminal stance, indicate that the socket does not conform to hydrostatic theory. The PTB socket revealed more scattered and higher peak values of pressure throughout the socket. This corresponds to the PTB design criterion as the areas of high pressure correspond to the pressure tolerant areas of the residual limb.[2]

As can be gleaned from the above studies, the method of pressure analysis can greatly impact the results obtained, and depending on the requirements and aim of a particular study, the appropriate method should be chosen with great consideration. Whilst the hydrostatic socket does not consistently produce a uniform pressure distribution, as implied by hydrostatic theory, what is often produced is a pressure distribution with notably less variation.

Future Studies

The aforementioned studies utilised different methods to analyse the pressure distribution at the stump/socket interface, with varying results. In order to obtain a more complete and conclusive analysis of the hydrostatic design, future studies should include a large scale clinical trial to determine if the sound theory behind the hydrostatic design translates into a comfortable and functional socket for a large population of amputees with varying stump morphologies and lifestyles. Such studies would also reveal any unexpected problems with the design such as dermatological pathologies, suspension difficulties, negative effects on the gait of the amputee and whether particular stump morphologies are consistently incompatible with the hydrostatic design.

Computational technology driven studies will also be involved in the progression of this field. Stump volume changes when fitted with either the PTB or hydrostatic socket can provide quantitative information regarding the comfort of the design. Computer-aided design and computer-aided manufacturing (CAD/CAM) methods can be used to conduct such volumetric studies whereby a 3-dimensional model of the stump is obtained from scanned data. The volume of the stump can then be calculated from every possible distance from the distal end of the stump.[21] Also, in addition to assisting with socket interface pressure estimates, recent advances have seen FEA used in real-time to analyse the internal stresses in the deep soft tissues of the stump, evaluating the biomechanical interactions between the stump and the socket.[18]

As the hydrostatic method dictates that minimal or no rectifications are to be performed, the requirement for a positive mould is eliminated. As such, innovative prosthetic socket materials are to be investigated with the possibility of direct casting, further reducing manufacturing times. Lee et al[9] reported the use of braided carbon fibre sock impregnated with quick curing resin. Pre-casting, the sock is donned directly on the stump, instead of a plaster cast, where it hardens within minutes to form the final socket when pressure casting is completed. Commercial corporations have taken advantage of this potential with casting systems such as the Icecast anatomy and Icecast Compact (Ossur, Iceland).[22] Future studies could investigate alternative quick curing sockets materials that are low in cost and good in strength.

Conclusion

Research has shown that although sockets produced using pressure casting methods do not meet the requirements to be classified as a hydrostatic design; the objective of a hydrostatic socket, a more uniform pressure distribution throughout the socket, is largely achieved.[9-13,15,19,20] Less variation in the pressure distribution throughout the socket is thought to lead to a more consistently fitting socket for the patient, reducing problems pertaining to stump migration such as internal limb pain and skin ulcers. In addition, the lower pressure gradient throughout the pressure cast socket generates less shear stress; both interface and internal soft tissue shear; further reducing pain and dermatological problems. The aforementioned studies have concluded that the proximal ring of high pressure present in the PTB is replaced by a region of increased pressure in the distal end of the pressure cast socket.[11] Finally, the interface pressure distributions during gait do not agree with the biomechanical principles proposed by Radcliffe within either the PTB or PCAST sockets.[12,15]

The engineering of the trans-tibial socket has been largely subject to empirical derivations and biomechanical theory that remains, for the most part, unproven. The Radcliffe assumptions, the basis for the PTB socket, have been widely refuted. Hydrostatic theory, on the other hand, provides an optimal scenario to produce a more uniform stump/socket interface pressure, yet is proving to be unfeasible in application due to the complex morphology of the stump.

PTB and hydrostatic sockets differ on fundamental bases. While the PTB is designed to create areas of high pressure at load tolerant sites within the socket¸ the hydrostatic socket aims to produce a uniform pressure profile throughout the interface. It is because of these elementary differences that it is difficult to compare the 2 designs. Preliminary studies indicate the pressure casting technique has the potential to produce more comfortable sockets, providing an alternative to the PTB design.

Further studies into the hydrostatic design and pressure cast technique are required to fully determine its potential and clinical viability. Such studies should involve a large number of participants to investigate the pressure distribution at the stump/socket interface and how this impacts the dermatology of the stump, the socket biomechanics and the resultant comfort and functionality for the patient. Additional studies are required to investigate the possibility of direct casting and combined CAD/CAM and FEA technologies.

REFERENCES

1. Nielsen CC. A survey of amputees: functional level and life satisfaction, information needs, and the prosthetists role. J Prosthet Orthot 1990;3:125-9.
2. Radcliffe CW. The biomechanics of below-knee prostheses in normal, level, bipedal walking. Artif Limbs 1962;6:16-24.
3. Radcliffe CW, Foort J. The patella tendon-bearing below knee prosthesis. Berkeley (CA): University of California , Berkeley 1961:8-51.
4. Foort J. The patellar-tendon-bearing prosthesis for below-knee amputees, a review of technique and criteria. Artific Limbs 1965;1:4-13.
5. Statts TB, Lundt J. The UCLA total surface bearing suction below-knee prosthesis. Clin Prosthet Orthot 1987;11:118-30.
6. Kristinsson O. The ICEROSS concept: a discussion of a philosophy. Prosthet Orthot Int 1993;17:49-55.
7. Murdoch G. The Dundee socket for below knee amputation. Prosthet Int 1965;3:12–4.
8. Hall M, Shurr D, VanBeek M, Zimmerman M. The prevalence of dermatological problems for transtibial amputees using a roll-on liner. J Prosthet Orthot 2008;20:134-9.
9. Lee P, Goh J, Cheung SK. Biomechanical evaluation of the pressure cast (PCAST) prosthetic socket for transtibial amputee. Proceedings of the World Congress on Medical Physics & Biomedical Engineering. Chicago (IL); 2002.
10. Buis AWP. Dynamic interface pressure measurement: comparing two transtibial socket concepts. National Centre for Training and Education in Prosthetic and Orthotics. Glasgow, Scotland, UK: University of Strathclyde; 1997.
11. Goh J, Lee, P, Chong S. Socket pressure profiles of the pressure cast prosthetic socket. Clinical Biomechanics 2003;18:237-43.
12. Goh J, Lee P, Chong S. Comparative study between PTB and PCAST prosthetic sockets. J Rehab Research Devl 2004;41:491-502.
13. Kahle J. Conventional and hydrostatic transtibial interface comparison. J Prosthet Orthot 1999;11:85-91.
14. Goh JC, Lee PV, Chong SY. Static and dynamic pressure profiles of a patellar-tendon-bearings (PTB) socket. Proc Inst Mech Eng H 2003;217:121-6.
15. Dumbleton T, Buis A, McFadyen A, McHugh B, McKay G, Murray K, et al. Dynamic interface pressure distributions of two transtibial prosthetic socket concepts. J Rehab Research 2009;46:405-16.
16. Zhang M, Roberts C. Comparison of computational analysis with clinical measurement of stresses on below-knee residual limb in a prosthetic socket. Medical Engin Phys 2000;22:607-12.
17. Polliack AA, Sieh RC, Craig DD, Landsberger S, McNeil DR, Ayyappa E. Scientific validation of two commercial pressure sensor systems for prosthetic socket fit. Prosthet Orthot Int 2000;24:63-73.
18. Portnoy S, Yarnitzky G, Yizhar Z, Kristal A, Oppenheim U, Siev-Ner I, et al. Real-time patient-specific finite element analysis of internal stresses in the soft tissues of a residual limb: a new tool for prosthetic fitting. Ann Biomed Eng 2006;35:120-35.
19. Convery P, Buis A. Socket/stump interface dynamic pressure distributions recorded during the prosthetic stance phase of gait of a trans-tibial amputee wearing a hydrocast socket. Prosthet Orthot Int 1999;23:107-12.
20. Moo EK, Osman NA, Pigguan-Murphy B, Wan Abas WAB, Spence WD, Solomondis SE. Interface pressure profile analysis for patella-tendon-bearing socket and hydrostatic socket. Acta Bioeng Biomech 2009;11:37-43.
21. Bolt A, de Boer-Wilzing VG, Geetzen JH, Emmelot CH, Baars EC, Dijkstra PU. Variation in measurements of transtibial stump model volume: a comparison of five methods. Am J Phys Med & Rehab 2010;89:376-84.
22. Ossur. Icecast Anatomy and Icecast Compact. Available at: http://www.ossur.com/?PageID=13436. Accessed 20 April 2011.