DEVELOPMENT OF A NEW PYLON MATERIAL IN TRANSTIBIAL PROSTHESIS

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2012

UNIVERSITI MALAYA

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HANIE NADIA SHASMIN

DISSERTATION SUBMITTED IN FULFILLMENT
OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2012

Acknowledgements

I would like to express my deep gratitude towards my supervisor, Associate Professor Dr. Noor Azuan Abu Osman for his scientific guidance and whole-hearted advices to encourage me throughout this thesis.

My special thanks to my co-supervisor, Associate Professor Dr. Lydia Abd Latif for her valuable comments, advice, and guidance during the course of research.

My warm thanks go to all colleagues at the Motion Analysis Laboratory (Sofiah, Hazliana, Fariza, Syazwani, Aleesha and Azman). In particular I would like to acknowledge the help of Mohd Firdaus Mohd Jamil for his technical support. Also my thank you to Mr Haider from Prosthetics and Orthotics Workshop of University Malaya Medical Centre for his support in related to the patients.

My final and most deeply felt appreciation goes to my parents and my heartening husband, Herman Shah Abd Rahman, for their love, understanding, endless patience and encouragement when they were most required.

List of Publications & Awards

The research described in this thesis has led to the following presentations, publications, awards and patent:

Journal:

- **H N Shasmin,** N A Abu Osman, L Abd Latif and W A B Wan Abas (2007), A New Pylon Materials in Transtibial Prosthesis: A Preliminary Study*, Journal of Biomechanics,* vol. 40 (S2): pp.297.

Proceedings:

- **H N Shasmin**, N A Abu Osman, L Abd Latif and W A B Wan Abas (2007), Comparison between Biomechanical Characteristics of Stainless Steel and Bamboo Pylons: A Preliminary Study, *4th Kuala Lumpur International Conference in Biomedical Engineering*, 25-28 June 2008, vol. 21, no. 4, pp. 851-853.
- **H N Shasmin**, N A Abu Osman, L Abd Latif and W A B Wan Abas (2007), Economical Tube Adapter Material in Below Knee Prosthesis, *4th Kuala Lumpur International Conference in Biomedical Engineering*, 25-28 June 2008, vol. 21, no. 3, pp. 407-409.
- **H N Shasmin**, N A Abu Osman, L Abd Latif and W a B Wan Abas (2009), Bamboo pylon Below Knee Prosthesis, XXIInd Congress of the International Society of Biomechanics, Cape Town, South Africa, July 5-9.
- **H N Shasmin**, N A Abu Osman, L Abd Latif and W A B Wan Abas (2007), Development of New Pylon Material in Transtibial Prosthesis, *International Conference on Engineering, Applied Sciences and Technology, ICEAST07*, Bangkok, Thailand, 21-23 2007.

Patent:

- **PYLON**, Grant Number: **MY – 143247**

Awards:

- **Gold Medal -** Design (Technical), The Invention & New Product Exposition (INPEX), 11-14 June 2008.
- **Gold Medal**, 18th International Invention, Innovation & Technology Exhibition (ITEX), 18-20 May 2007.
- **Bronze Medal**, Research, Invention & Innovation (UMEXPO), 26-28 July 2007.

Abstract

Introduction: Amputations among Malaysia citizens is increasing at an alarming rate. This people are in need of lower leg prostheses but are unable to afford the high costs of current prosthetic components. In this study, bamboo was used to replace the conventional pylon material to reduce the cost in below knee prosthesis. Bamboo is a natural fiber-reinforced composite material possesses good mechanical properties to warrant its use as a structural material.

Methodology: The bamboo pylon was produced from proper harvesting of *Bambusa Heterostachya.* It was then dried in an oven at 200^o Celsius for 72 hours. Before lamination, the bamboo culm underwent pre-treatment with V-Sawit oil at about 120°C for about 30 to 90 minutes. Bamboo pylon was laminated with at least 3 layers, using vinyl urethane adhesive and polyvinyl acetate. The processes involved in producing bamboo pylon ensure its durability and protection against pest. In second part of the study, bamboo pylon was tested for flexural, compressive and tensile properties under Universal Testing Machine based on ASTM standards. In addition, computer simulation of subject walking with bamboo pylon was performed. The third part of the study involved gait comparisons on six transtibial amputees while walking with bamboo and stainless steel pylon with the prosthetic legs.

Results and Discussions: The results showed with yield compressive stress and Young's modulus of 132.6 MPa (SD ± 3.3 MPa) and 30.7 GPa (SD ± 4.7 GPa) respectively, bamboo pylon was three times stronger than fibre reinforced plastic and two times stronger than Aluminum. There was no significant difference found in vertical and antero-posterior ground reaction forces ($p > 0.05$) in Bamboo prosthetic leg compared to Stainless steel prosthetic leg. Joint kinematics for Bamboo prosthetic leg was also comparable to joint kinematics for Stainless steel prosthetic leg ($p > 0.05$) except for the hip extension ($p < 0.05$). In spatio-temporal parameters; cadence, step length and walking speed of Bamboo prosthetic leg were comparable to Stainless steel prosthetic leg ($p > 0.05$).

Conclusions: Bamboo is a low-cost material and possesses great mechanical properties. It will make an excellent new pylon material in transtibial prosthesis.

Abstrak

Pengenalan: Amputasi di kalangan warga Malaysia semakin meningkat pada kadar yang membimbangkan. Golongan ini amat memerlukan kaki palsu tetapi tidak mampu untuk membayar kos kaki palsu yang tinggi di pasaran semasa. Dalam kajian ini, buluh telah digunakan untuk menggantikan bahan konvensional untuk mengurangkan kos kaki palsu. Buluh adalah bahan komposit semulajadi dan memiliki kekuatan mekanikal untuk menjamin penggunaannya sebagai bahan pembinaan.

Metodologi: *Bamboo pylon* dihasilkan daripada kaedah penuaian yang betul dari spesis *Bambusa Heterostachya*. Ia dikeringkan di dalam oven pada suhu 200^{o}C selama 72 jam. Sebelum laminasi, buluh menjalani pra-rawatan dengan minyak V-sawit pada suhu 120°C selama kira-kira 30 hingga 90 minit. *Bamboo pylon* dilaminasi dengan 3 lapisan menggunakan pelekat urethane vinil dan asetat polyvinyl. Proses ini memastikan ketahanan dan perlindungan *bamboo pylon* terhadap makhluk perosak. Dalam bahagian kedua kajian ini, *bamboo pylon* telah diuji dengan sifat mekanikal seperti lenturan, mampatan dan tegangan berdasarkan piawaian ASTM. Di samping itu, simulasi komputer bagi *bamboo pylon* telah dilakukan. Bahagian ketiga kajian melibatkan perbandingan gaya berjalan bagi enam pesakit menggunakan *bamboo pylon* dan *stainless steel* pada kaki palsu.

Keputusan dan Perbincangan: Keputusan menunjukkan dengan tekanan hasil mampatan dan modulus Young 132.6 MPa (SD ±3.3 MPa) dan 30.7 GPa (SD ±4.7 GPa) *bamboo pylon* adalah tiga kali lebih kuat daripada plastik gentian fiber dan dua kali ganda lebih kuat daripada Aluminium. Tidak ada perbezaan yang signifikan di dalam daya tindak balas menegak dan antero-posterior ($p > 0.05$) di kaki palsu *bamboo pylon* berbanding dengan kaki palsu *stainless steel*. Kinematik sendi bagi kaki palsu *bamboo pylon* juga setanding dengan kinematik sendi untuk kaki palsu *stainless steel* ($p > 0.05$) kecuali bagi sudut lanjutan pinggul. Dalam spatio-temporal parameter, *cadence*, panjang langkah dan kelajuan berjalan kaki palsu *bamboo pylon* setanding dengan kaki palsu *stainless steel* ($p > 0.05$).

Kesimpulan: Buluh adalah bahan kos rendah dan mempunyai sifat-sifat mekanikal yang hebat. Ia akan menjadi bahan *pylon* baru yang cemerlang dalam kaki palsu transtibia.

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List of Abbreviations

3D	Three Dimension
kPa	$1x10^3$ Pascal
Mpa	$1x10^6$ Pascal
Gpa	$1x10^9$ Pascal
ASTM	American Society for Testing and Materials
A/P	Anterior-Posterior
BPL	Bamboo Prosthetic Leg
cm	Centimeter
CCD	Charge-coupled device
F/E	Flexion-Extension
GRFs	Ground Reaction Forces
IPOP	Immediate Postoperative Prosthesis
kg	Kilogram
m	Meter
mm	Milimeter
N	Newton
PTB	Patellar Tendon Bearing
POP	Plaster of Paris
PVC	Polyvinyl Chloride
ROM	Range of motion
RB	Reformed Bamboo
SAPs	Shock-absorbing pylons
SACH	Solid Ankle Cushion Heel
SPL	Stainless Steel Leg
SD	Standard deviation
UTM	Universal Testing machine
VSP	Vertical Shock Pylon

Chapter 1

Introduction

Chapter 1 defines the background of transtibial amputations as well as the history of prosthetics. The sections are followed by a summary of the study objectives.

1.1 Transtibial Amputation

Amputation of a lower limb body is defined as a surgical procedure that involves the removal of a leg or part of a leg, usually as a result of severe traumatic injury or diseases such as cancer and peripheral vascular disease. National Limb Loss Information Center reported that in America, 90 percent of the amputations performed were resulted from neuropathy (Dillingham et al., 2002). In India about 74 percent of lower limb amputations were due to serious trauma sustained in road traffic accidents (Paudel et al., 2005) and in war-torn countries such as Cambodia and Afghanistan, about 80 percent of lower limb amputees are land mine survivors (Pe, 2005).

The current situation in Malaysia is that more than 65 percent of non-traumatic lower limb amputations are performed on patients with diabetes (Hazmy et al., 2001). Foot ulcers that occur as the result of high blood glucose levels in diabetics contribute to peripheral vascular disease causing poor blood circulation and neuropathy or nerve death which causes sensory loss in the feet (Tang, 2006).

As the foot tissue dies, infection can set in providing a strong base to various type of bacteria which lead to critical phase of irreversible gangrene (dead tissue throughout the limb). When there is no hope for the damaged tissues can be restored to a healthy condition an amputation is crucial to protect the whole limb from the spreading infection. During the procedure the surgeons will determine the level of amputation and cut off the damaged tissues but still preserve the maximum possible amount of muscle and nerve tissue to leave the patient with the greatest possible range of motion for effective rehabilitation post-procedure (Sajja, 2005). Lower limb amputations can be categorized by several levels; partial foot, ankle disarticulation, transtibial, knee-disarticulation, transfemoral and hip disarticulation. The position of lower limb amputations is shown in Figure 1.1.

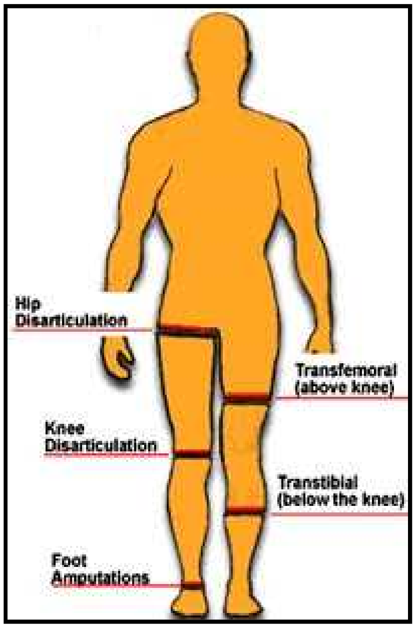

Figure 1.1: Classification of lower limb amputation. Reproduced from Abdullah & Uday (2005).

Transtibial amputation is an amputation performed anywhere between the ankle and the knee joints (Smith, 2001). The transtibial amputee, who preserves the knee joint after the surgery, has an advantage compared to transfemoral patient particularly. The knee joint has a major function in maintaining overall body balance and provides the power to lower body. Many transtibial amputees are reported to successfully establish total ambulatory as the advantage retaining the knee joint (Smith, 2003).

After amputation surgery is performed, most of the patients experience pain in the residual limb, as well as pain in phantom limb where they feel as if the amputated limb is still in its former place (Carnesale, 2003). As the pain persistently bothered the patients, many of them give up on therapy and abandon their prosthesis. Hence to reduce the incidence rate of this problem, rehabilitation and physical therapy start as early as possible after the surgery, usually within 48 hours after amputation, and better prosthetic-fitting are introduced. Early rehabilitation develops a positive relationship between effective functioning of the prosthesis and residual limb (Sajja, 2005).

1.2 History of Prostheses

The story of prostheses spans a long historic period, from its ancient beginnings to its contemporary present to the exciting visions beyond what is currently possible. Amputations in the early history were performed for legal punishment, religious sacrifice and war injury (Padula & Friendmann, 1987). The first record of an amputation is in "Rig-Vieda", an Indian poem written sometime between 3500 and 1800BC. The poem tells the story of a warrior queen who lost her leg in a battle was equipped with a prosthesis made of iron (Sanders, 1986). In other ancient cultures, prosthesis began as simple leather cups and crutches tied to the upper which then grew into modified peg to free the patient's hands.

The Egyptians also made use of prosthetic limbs; archaeologists have found a prosthetic leg which made from fibres in the wrapping of an Egyptian mummy. These prostheses were conceivably made by the burial priests for a sense of “perfectness” and not for functioning purposes (The Cultural Body, 2006). Figure 1.2 is the drawing found in France dating back to 500 BC shows a man working in a field with a wooden stick under his knee showing how important it was for people to have functioning legs in those times.

Figure 1.2: From the ancient pyramid to the present day, the field of prosthetics has changed due to more sophisticated designs. Reproduced from Norton (2007).

Despite these early findings, humankind’s concern for rehabilitation is very difficult to establish as many of these primitive civilizations had few written document, most history being conveyed through generations verbally in poems and songs. Herodotus, a Greek Historian, wrote in 484 BC about a Persian soldier called Hegistratus who was locked up by his enemies. He was able to successfully escape by amputating his own foot and later replaced it with wood filler prosthesis (Wilson, 1970). Pliny the Elder who was the Roman scholar, wrote that a Roman General in the Second Punic War (218-210 BC) who had his right arm amputated. He had a hand fashioned from iron to hide his missing limb and was able to return to battle. Enhancement of prosthesis started during the Dark Ages, and even then it was not limited just to hand hooks and peg legs. Most prostheses of that time were made for battle and hiding deformities or injuries. A knight would be fitted with prosthetic leg which is designed to connect with stirrups (Wilson, 1970). Efficient as they were for their intended use, this particular device could not much use to any group other than the knights. Civilian amputees for the most part would have relied upon pylons and other rudimentary prostheses. During this era, the practice of ligature to stop amputee sites from bleeding was a dead end when the surgeon at that period used to crush the residual limb or dip it in boiling oil. A French army surgeon, Ambroise Paré later discovered a better way to perform amputations in 1529. After a number of successful procedures, he designed the first artificial leg for hip disarticulation which employed an articulated joint. His design is shown in Figure 1.3. The renaissance era later steered and revitalized scientific development through refinements in medicine, surgery and prosthetic science employed by the Greeks and Romans. This greatly improved amputation surgery and the function of the prosthesis.

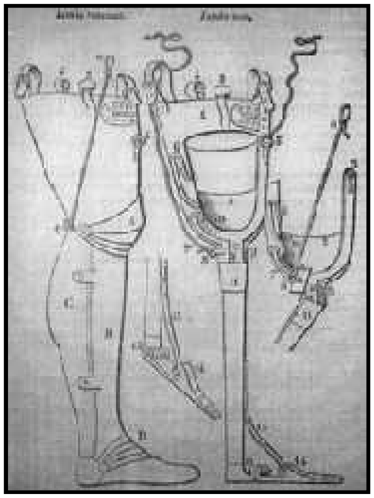

Figure 1.3: Artificial leg invented by Ambroise Paré in the mid-sixteenth century.
Reproduced from The Cultural Body (2006).

After the world wars, many soldiers returned home with missing limbs and, with the escalated number of amputees, the awareness of the problems these people faced while attempting to return to the normal lifestyle increased. Functional prostheses were still uncomfortable to wear but the user was much more independent and mobile with the use of such devices. Prosthetics has come a long way; from immovable, heavy limbs to models that are lighter, more functional and easier to wear. More recently, prostheses with advanced designs which allow the patient to perform better ambulation and expend less energy have become more common.

1.3 Components of Prosthetics

A prosthetic leg acts as an artificial replacement for any or all parts of the lower limb. By using prosthesis, an individual with an amputated limb has an opportunity to perform functional tasks, such as ambulation, more normally. Throughout the years, many important developments in prosthetics have brought us the variety and complexity of artificial limbs available. The basic design of the transtibial prosthesis has three major components; socket, pylon, and foot-ankle assembly (Figure 1.4). The socket is the custom made top portion of the prosthesis; it attaches to the residual limb and disperses pressure around it. There are two types of socket; hard socket and soft socket. The hard socket is directly in contact with the residual limb. It has less friction, is easy to clean and is more durable. However, this socket is difficult to fit and adjust with residual limb changes. The soft socket surrounds with liner as a cushion between the residual limb and the socket. It provides comfortability to patients but may increase bulk and friction. Transtibial socket types include silicone suction, energy-storing, patellar tendon bearing (PTB) and bent knee designs. Figure 1.5 shows the conventional steps on making the prosthesis socket.

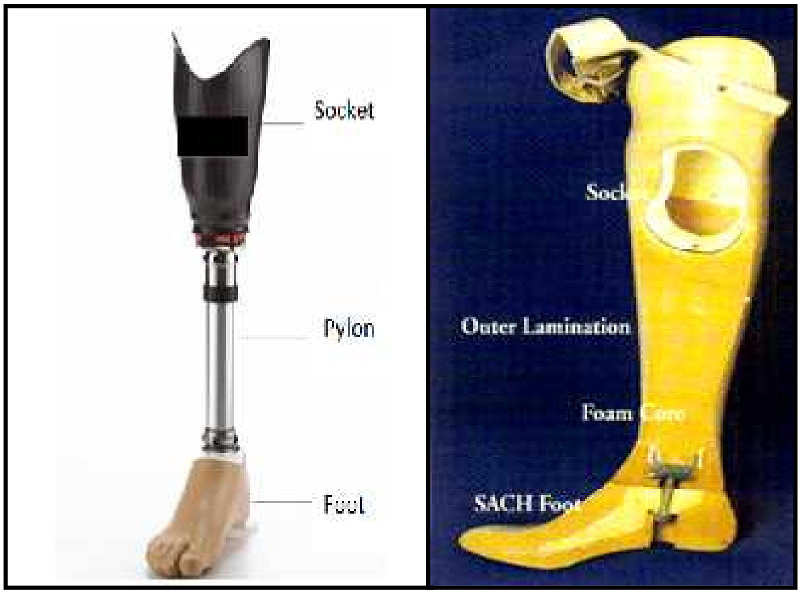

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Figure 1.4: Main components in a transtibial prosthesis. From Left: The endoskeletal system and exoskeletal system. Reproduced from Schuch (1998).

Figure 1.5: Traditional process for fabricating prosthesis socket. From top left: Wrapping residual limb/stump with moistened cast sock, dried negative mould, filling POP to obtain positive mould. From bottom left: Rectifying positive mould, socket lamination, lower limb socket. Reproduced from Francis et al., (2002).

Of all the transtibial sockets, the most common model fabricated by a prosthetist is the PTB socket as it fully utilise the presence of patellar ligament as one of the principle weight-bearing areas. In a regular PTB prosthesis, patient seated with knee flex about 30^{o} and residual limb/stump relaxed. The prosthetist will identify bony landmarks by palpation and draw them for later use in modification of the model (Fleer & Wilson, 1962). The negative cast is produced by applying Plaster of Paris (POP) bandage to the stump. Then, a positive mould is created by filling the negative mould with water and POP and then allowing it to harden (United Nations, 1997). This mould is rectified and smoothed by prosthetist and padding is added to create pressure relief areas. Finally, the mould will be laminated by polyethylene or carbon fibre to create a socket that can be used by the amputee.

The pylon component corresponds to the anatomical shank and is used to connect the socket to the foot. In an endoskeletal shank the shape is tubular as in a tube adapter, a narrow vertical support, and sometimes rests inside a foam leg cosmetic cover. The exoskeletal shank is made of hard outer shell that is hollow inside or filled with lightweight material (Figure 1.4). The advantage of endoskeletal systems is it allows for realignment of prosthetic components and it is lighter, but it less durable when compared to the exoskeletal system. The third component of transtibial prosthesis is the foot. The foot provides a base of support during patient’s ambulation, in addition to provide shock absorption and additional push off during walking. Foot-ankle assemblies usually fall into four categories; articulated, non-articulated, elastic keel and dynamic response (Figure 1.6). The most widely prescribed foot around the world is the solid ankle cushion heel (SACH) foot due to its simplicity, durability and low cost (Michael, 1999). The SACH foot is inappropriate for active community ambulators and sports participants. Articulated assembly allows motion on a similar level to the human ankle; the motion depends on whether it is a single or multi axis foot while the dynamic response foot is designed to benefit athletic users with additional power for running and jumping included in the design.

Figure 1.6: Different types of prosthetic feet. Clockwise: SACH foot, dynamic response foot and multi-axial foot. Reproduced from Umbehr (2008).

1.4 Prosthetics in Malaysia

Today, transtibial and transfemoral amputees have a variety of fully functioning options for their prosthesis. For instance, amputated athletes have an equal number of options available in the market to fit sprinting, skiing, golf, swimming and other extreme activities. However, these high-tech prostheses can cost several thousand dollars in western countries and benefit to a very minimal patients in Malaysia. Having affordable prosthetic legs is vital for every amputee as most jobs in the country require some level of physical labour.

Moreover, a basic transtibial prosthesis which consists of SACH foot, aluminum pylon, PTB socket and low-priced polyethylene liner is likely to cost RM4800 and above (Baitulmal News, 2009). This price is considered too high for average-income transtibial amputees and therefore most of the amputees cannot afford to buy the prosthesis. In 2008, the government reported that the average annual income per household in Malaysia central areas and rural areas were RM4000 and RM2200 respectively (Utusan Malaysia, 2009). According to the Malaysian Social Welfare Department, less than 10 percent of amputees use prosthetic devices (Syed Putra, 2007). The remaining 90 percent chose crutches and low-priced wheelchairs to assist their daily ambulation. As a result of this problem, many amputees fail to achieve complete rehabilitation and most likely give up their pre-amputation life including their occupations and careers. In some instances amputees have to resort to begging on the streets in order to survive.

The Social Welfare Department, based on their National Health and Morbidity Survey findings, also reported that the incidence of below knee amputations in Malaysia is estimated to be 1500 per annum (Syed Putra, 2007). Figure 1.7 shows the distribution of disabled people in Malaysia in 2007, noting that the most common cause of amputation is diabetes. The Minister of Health declared that in 2008 nearly 1.4 million Malaysians, including teenagers, suffer from diabetes and this number is likely to rise if Malaysian food consumption habits remain unchanged (Cruz & Goran, 2004).

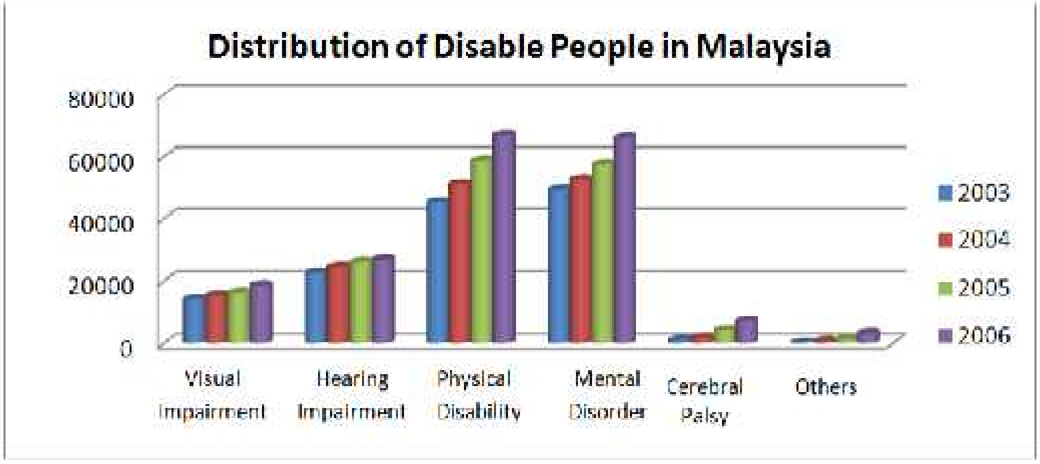


Figure 1.7: Statistics of disabled people in Malaysia from 2004 to 2006. Reproduced from Syed Putra (2007).

The first prosthetic workshop in Malaysia was set up in 1937 by a British doctor, Dr. B. D. Molesworth in the small town of Sungai Buloh, Selangor, close to the capital Kuala Lumpur. Unwanted prostheses donated by Britain and Australia veteran's administration were shipped to Malaysia or, as it was known at the time, Malaya. In 1949, a similar workshop was set up in the Kuala Lumpur General Hospital by Mr. Mellowship (Omar, 1998). This little workshop was then converted into the National Limb Fitting Centre Kuala Lumpur in 1969 and had three main staffs, each comprising of one rehabilitation physician and three prosthetic technicians (Category III). Staff in the prosthetic centres primarily had on-the-job training and the number of staff that underwent appropriate Category III training was very limited. The function of a prosthetic technician (Category III), as described by International Society of Prosthetics and Orthotics (ISPO), is to work under direct assistance of Category I and II in fabricating sockets and assembling prosthetic components. However, Dr. Zaliha Omar stated in 1998 in her final report to the ISPO workshop that Malaysia, and the South East Asia (SEA) region in particular, suffers from a lack of certified prosthetists (Category I) and prosthetist technologists (Category II).

This problem leads to lack supervision of Category III staff and causes difficulties in final production of prosthetic legs that have been subscribed to amputees.

Proper construction, aligning, fitting and adjusting a prosthetic limb requires a high level of skill, thus there is high demand for people with these expertise. This in turn contributes to an increase in the device's final price. Furthermore, prosthetic components are usually imported from western and industrialized countries. In an effort to help the low income amputee victims, the Malaysian Government's Rehabilitation Medicine Unit and other non-government organizations, such as Social Security Organization (SOCSO) and Lions Clubs International, are playing a vital role by subsidising artificial limbs to patients and supporting them with physiotherapy sessions. However, only a small number of the patients have the chance to rehabilitate as the aid from the organizations and hospital machinery required are very limited. In some cases, the amputees wait for 3 or 4 years to obtain a prosthetic leg. Below is an example story from a newspaper about an amputee who went out into his local community to appeal for contributions and donations as his application for a prosthetic leg through a subsidiary plan was rejected.

> *"When he was able-bodied, Veeran Vingan, 53, owned mini-markets in Bukit Pelanduk and Seremban in Negeri Sembilan. But fate dealt him cruel blow as he suffers from diabetes and lost his right leg. He used to receive aid from the Social Welfare Department but, after a while, the money stopped coming. His wife S. Saroja, 44, is still unemployed and the childless couple who live in Semenyih are finding it difficult to make end meet. "With a prosthetic leg I will be mobile and hope to start small business again, maybe selling snacks and titbits from home. These few months we have been surviving by selling milk and flowers;" Veeran told the Kajang Rhanee who visited him recently. Rhanee said that Taman Kajang Raya would help Veeran by checking on his aid status with the Social Welfare Department" (*Krishnan, 2007).

Because of costs and manufacturing, transtibial prosthetics are not readily available in this nation. At RM 4800 to RM 8000 per unit, they are too expensive for the average income person. Though research on advanced functional prosthetics continues, it illustrates that sometimes improving the technology is not the solution. As the demand increases, it is becoming more significant to take the cost and complexity out of the design to make more affordable prosthetic devices for everyone. In an effort to describe appropriate lower limb prosthetic function for the low income amputees, some articles have been made statements suggesting they be “only for walking” (Edelstein, 1998) and restore some “function and appearance” of the human limb (Craig, 2005) including the provision of a “base of support”.

The previous method used for producing a low cost prosthetic by researchers employed simple techniques, minimalistic designs and even utilized recycled items. The hydrostatic cast system developed by Syed Shikh (2008), for example, introduced socket fabrication methods that did not required a highly skilled prosthetist. The system applies uniform water pressure to produce the negative mould. When uniform pressure is applied in this way the socket takes the exact shape of the residual limb, thus creating total contact for the socket. Mukti Limb by the Mukti Organization is another research project that used techniques requiring less skill to generate a low-cost prosthetic leg.

A high density polyethylene (HDPE) irrigation pipe is used to make the socket and the shank of the limb. The pipe moulds easily when it has been heated. Once a plaster mould is made of the residual limb, a cardboard cone is glued to the bottom of the mould and the cone is filled with POP to make a positive mould for the shank of the limb (Strait, 2006). Another well-known, low-cost prosthetic component is the Jaipur foot. The Jaipur foot has an appearance like a real foot, is able to bend in all directions enough to allow a person to squat and walk on uneven terrain and is manufactured at a very low cost (less than $5 USD) (Werner, 1998). The foot is made from wood, sponge and rubber and is created using a heat-moulding process in iron moulds. The outer rubber gives the foot its realistic appearance and natural colour as well as providing waterproofing for the wooden block inside. This is shown in Figure 1.8.

Figure 1.8: From left: Jaipur Foot, Niagara Foot. Reproduced from Strait (2006).

The Niagara foot as shown in Figure 1.8 is a simple yet practical, inexpensive and sturdy alternative. The foot is made of a single piece of Delrin plastic formed to imitate the biomechanic function of a normal human foot. The shape of the foot provides energy return similar to high-end feet models offered in the United States. Although weight and energy expenditure are not an issue, the cosmetic appeal of the foot and the ability to wear shoes create a few problems for this design. The foot appears to be less stable as it produces an irregular motion throughout the gait cycle (Strait, 2006).

There are numerous published articles on producing low cost artificial leg, but according to ISPO consensus conference on appropriate technology in developing countries in 1995 most rehabilitation research target low cost production of socket fabrication and foot components (Heim, 2000). This study attempts a new approach to reduce transtibial prosthetic price by creating an economical pylon from a naturally-sourced material;

bamboo. Bamboo is a natural fibre-reinforced composite material which possesses favourable mechanical properties to warrant its use as a structural material. In this paper, the bamboo pylon was evaluated in mechanical properties tests and clinical tests with transtibial amputation patients.

1.5 Objectives of Study

The objectives of this study are:

- To evaluate the mechanical strength of bamboo to asses that it is appropriate as a prosthesis component.
- To develop a bamboo pylon from natural resources with minimal manufacturing process and cost.
- To determine through gait analysis test whether a change in prosthetic pylon will affect the prosthetic leg efficiencies.

Chapter 2

Literature Review

Bamboo is a unique plant on earth and it is acknowledged as “the wood of the poor” in India, “the friend of the people” in China and “the brother” in Vietnam (Farrely, 1984). Bamboo is a composite materials, built with combination of fibres and cellulose. Bamboo plants are utilized for many different applications since thousand years ago. A few species are chosen for specialize uses, while other species are still abandon. The bamboo has been seen into diversity of products ranging from household products to industrial purposes. Among the examples of bamboo products are food containers, handicrafts, toys, furniture, flooring material, pulp and paper, boats, charcoal, musical instruments and weapons. The outstanding of the mechanical behavior of bamboo in various daily usages has shown its great potential to be used as a supportive material for amputees. In many overly populated regions of the tropics, certain bamboos supply the one suitable material that is sufficiently cheap and plenteous to meet the need for eco-material pylon.

2.1 Taxonomy, Growth and Climate

Bamboo belongs to the member of the natural grass family *Gramineae*, under the subfamily Bambusoideae, in the group of angiosperms (Chapman, 1996; 1997). Some examples of bamboo genera are *Bambusa, Arundinaria, Chimonobambusa, Holttumochloa, Oxytenanthera* and *Sinarundinaria.* It grows in a warm atmosphere, plentiful moisture, and fertile soil, except for extremely sandy, saline, or drenched soils with about 1250 species. The bamboo plants are identified throughout the globe (Austin & Ueda, 1972; McClure, 1966; Wang & Shen, 1987) and half of these species grow in Asia, typically within the

Indo-Burmese region, which is measured to be their area of origin (Grosser & Liese, 1971). In the study of bamboo habitat, Lee et al., (1994) found that the smaller bamboo species are mostly found in high elevations or temperate latitudes, and the larger ones are abundant in the tropic and subtropic areas. Bamboo new line can be distinct by its root system as either sympodial (clumping) or monopodial (running) (Figure 2.1). The monopodial bamboos are invasive and spread rapidly, while the sympodial bamboos generally stay cramped to a single area. Even though there are species that flower annually, bamboo reproduces asexually without flowering and without seeds, but sometimes it can also reproduce with flower throughout the year.

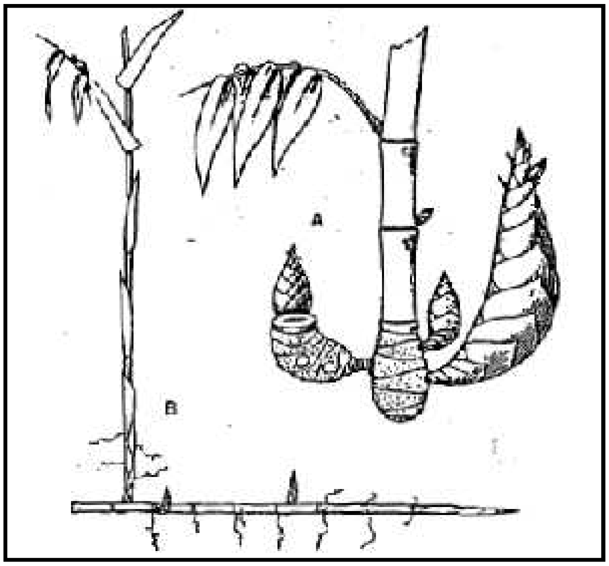


Figure 2.1: (A) Sympodial rhizome of Bambusa beecheyana. (B) Monopodial rhizome of Arundinaria amabilis. Reproduced from Farelly (1984).

Malaysia, a tropical country has approximately 70 known bamboo species, 50 in Peninsular Malaysia, 30 in Sabah and 20 in Sarawak (Wong, 1989). However, only l0 to 15 species are known to be valuable and commonly used (Abd. Latif, 1987). In this country, bamboo distributes from sea level to 3000 meter above. All the species are grouped under

10 genera: *Bambusa, Chusquea, Dendrocalamus, Dinochloa, Gigantochloa, Phyllostachys, Racemobambos, Schizostachyum, Thyrsostachys* and *Yushania.* The most common species are *Gigantochloa scortechinii, Dendrocalamus pendulus, bambusa heterostachya, Schizostachyum grande* and *Schizostachyum zollingeri* in the Southwest coast and *Bambusa farinacea*, *Gigantochloa ligulata*, *Bambusa blumeana, Gigantochloa levis,* and *Gigantochloa latifolia* in the Northern area of Malaysia (Mohamed & Appanah, 1998).

2.2 Anatomy of Bamboo

The anatomical structure of bamboo has been discovered for decades and numerous studies have been published (Velasquez & Santos 1931; Ghosh & Negi 1959; Grosser & Liese, 1971; Wu & Wan, 1976; Hsiung et al., 1980; Farelly, 1984; Kawase et al., 1986; Abd Latif et al., 1990; 1993a; 1993b; Janssen, 1991; Liese, 1992; Wu et al., 1996). Generally, the main components of a bamboo plant include rhizomes, culms/stems, branches, and leaves as shown in Figure 2.2.

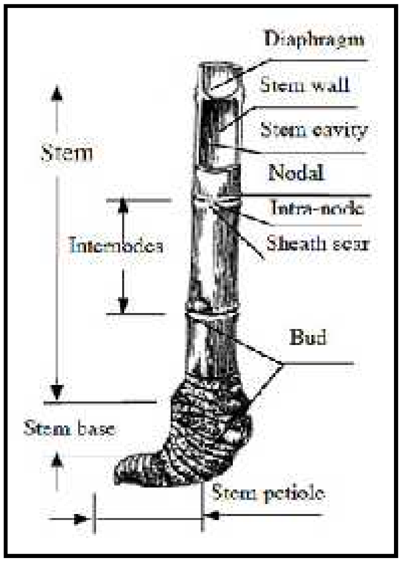


Figure 2.2: Anatomy of Bamboo. Reproduced from Farelly (1984).

Culms or Stems are the most noticeably element of a bamboo plant. It is comprises of about 60 percents parenchyma, 40 percents fibres and 10 percents conducting tissue. The culm consists of internodes and nodes. At the internodes, the cells structures are axially oriented, while at the nodes, cells provide the transverse interconnections (Liese, 1986). The internodal sections of the culm are hollow and the vascular bundles in the cross section are scattered throughout the culm instead of in a cylindrical arrangement. The properties of the culm are determined by its anatomical structure of a transverse section by the shape, size, arrangement and number of the vascular bundles (Ghavami et al., 2003). The vascular bundles of bamboo internodes consist of two metaxylem vessels, phloem, protoxylem attached fibre sheaths and depending on the species, additional fibre bundles (Figure 2.3). Figure 2.4 represents a three-dimensional (3D) structure of the vascular system at the nodal region. The model was reconstructed from successive sections and vascular bundle figure left in decomposed culm.

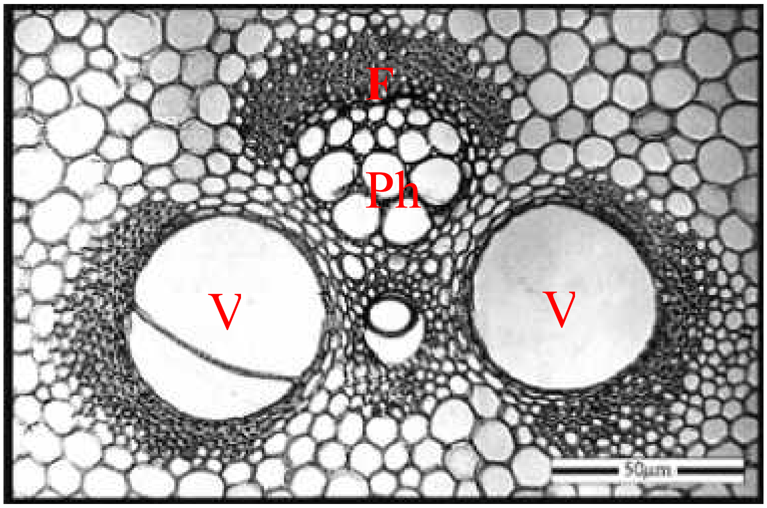


Figure 2.3: Vascular bundle with two metaxylem vessels (V), phloem (Ph) with sieve tubes and companion cells, protoxylem, and surroundings fibre (F) sheaths in *Phyllostachys edulis.* Reproduced from Liese (1998).

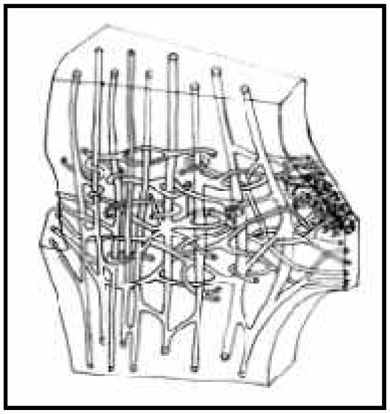


Figure 2.4: Illustration of vascular bundles within the nodal region. Reproduced from Liese (1998).

At the peripheral zone of the culm, the vascular bundles are smaller and more numerous (Figure 2.5). Across the culm wall, the total number of vascular bundles decreases from bottom outside to the inside, while their density (parenchyma) increases at the same time.

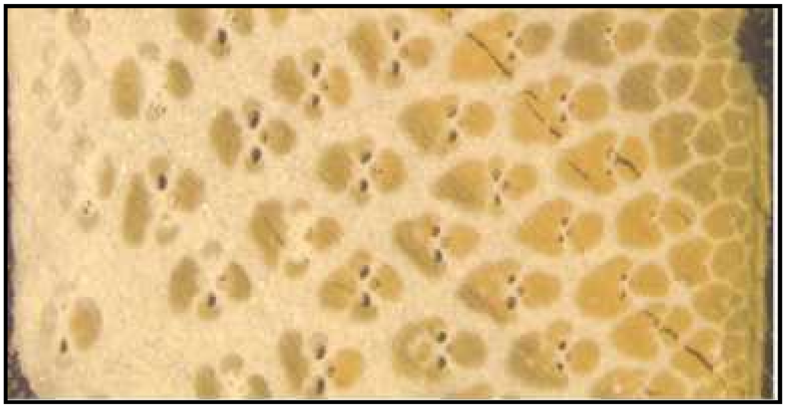


Figure 2.5: Cross section of a bamboo culm. Reproduced from Liese (1985).

Both the metaxylem vessels and the phloem tissue are surrounded by sclerenchyma sheaths. The sheaths vary significantly in size and shape according to their position in the culm and the bamboo species (Grosser & Liese, 1971, 1973; Wu & Wang, 1976; Jiang & Li, 1982). Liese (1985) has come out with a simple classification (Table 2.1) of vascular bundle of the bamboo to differentiate between genera and species. Monopodial rhizomes, such as *Sinanundinaria* and *Chimonobambusa,* represent the Type I and have generally lower fibre content than sympodial rhizomes, such as *Bambusa Dendrocalamus* and *Gigantochloa,* especially with Type III and IV. These differences in arrangement of vascular bundle affect (Figure 2.6) the physical and mechanical properties like density, strength, bending behavior, splitting and shrinkage.

Table 2.1: Description of vascular bundle. Reproduced from Grosser & Liese, (1971)

Type	**Vascular bundles configuration**
I	Consisting of one central vascular strand; supporting tissue only as sclerenchyma sheaths
II	Consisting of one central vascular strand; supporting tissue only as sclerenchyma sheaths; sheath at the intercellular space (protoxylem) strikingly larger than the other three
III	Consisting-of two parts, the central vascular strand with sclerenchyma sheaths and one isolated fibre bundles
IV	Consisting of three parts, the central vascular strand with small sclerenchyma sheaths and two isolated fibre bundles outside and inside of the central strand

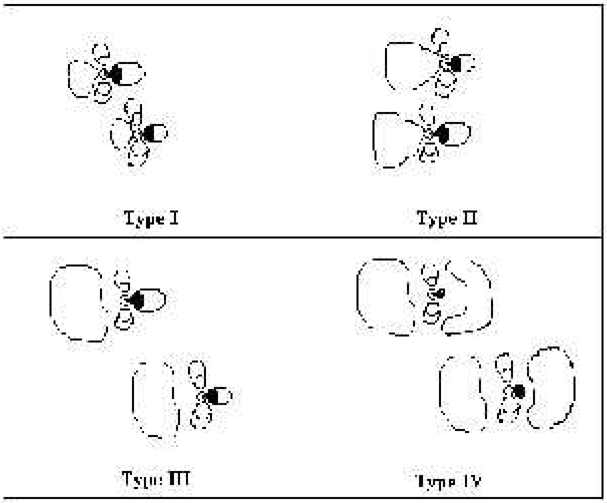


Figure 2.6: Basic vascular bundle types. Reproduced from Grosser & Liese, (1971).

2.3 Physical and mechanical properties

Bamboo has an appealing microstructure and macrostructure with outstanding features which contribute to its structural integrity (Amada, 1992; Amada & Lakes, 1997). The bamboo consists of 50 to 70 percents cellulose, 20 to 30 percents hemicellulose and 20 to 30 percents lignin, depending on the species (Liese, 1992). Cellulose fibres are aligned along the length of bamboo providing maximum tensile, flexural strength and rigidity in the direction of growth (Lakkad & Patel, 1981). Apart of this, density of bamboo is closely related to the relative proportion of vascular bundle and ground tissue, in which increases from the centre to the periphery of the culm (Sekhar & Bhartari, 1960; Sharma & Mehra, 1970) and this explains the variation of strength along the culm height. The maximum density can be gained once the culm reaches three year old (Liese, 1986; Kabir et al., 1993; Espiloy, 1994).

Water exists in intra-cellular and extra-cellular fluid contributes the most to the weight of the bamboo culm. Water in bamboo culm is normally referred as moisture content which can affect the behavior of bamboo culms (Dransfield & Widjaja, 1995), thereby it influences the usage of bamboo. Dransfield & Widjaja, (1995) had found that the moisture content is determined by the weight of water in bamboo culm and expressed as a percentage of the oven dry weight of bamboo culm (Equation 2.1). The moisture content of bamboo varies vertically from the bottom to the top portions and horizontally from the outer layer to the inner layers. Bamboo possesses very high moisture content with green bamboo may have 100 percent moisture and can be as high as 155 percent for the innermost layers (Sharma & Mehra, 1970).

$$\mathbf{MC(\%)} = \frac{\mathbf{GW\text{-}ODW}}{\mathbf{ODW}} \times \mathbf{100} \qquad \textbf{Equation 2.1}$$

Where **MC** = Moisture Content (%)
GW = Green Weight of bamboo
ODW = Oven-dry Weight of bamboo

Bamboo dominates excellent strength properties, especially tensile strength. It depends on the species, the climatic conditions and also differs along the culm height (Sekhar & Gulati, 1973). Compressive strength increases with height but for bending, it’s the opposite trend (Sekhar & Bhartari, 1960; Liese, 1986; Espiloy, 1987; Janssen, 1987; Sattar et al., 1990; Kabir et al., 1991; 1993). While Liese (1986) had found that, at three to four years of growth, the bamboo strength increased and it will decrease in the year after. Thus, aging of a bamboo culm influences physical and mechanical properties, and consequently it’s processing and utilization. Culm maturity is a must for the optimum utilization of bamboo in construction and other structural uses.

Moreover, bamboo has functional gradient properties in which there is a variation of Young's modulus across the culm section (Amada et al., 1996). Bamboo also exhibits significant anisotropy in strength: it is more than ten times stronger in tension in the longitudinal direction than in the transverse direction (Jain et al., 1992). The difference in anisotropy with density in the bamboo is ascribed to the greater number of vascular bundle sheaths in the denser bamboo (Amada et al., 1996). In addition, the specific gravity determines to a large extent for the mechanical properties of the culm. It can be concluded that the mechanical strength is all depends on the fibre build up, fibre diameter, and cell wall thickness.

A different profile of species often results from a different anatomical, as it has been shown for some Philippine bamboos by Espiloy (1987), Indonesian bamboos by Widjaja & Risyad (1987) and Malaysian bamboo by Abd. Latif et al. (1990). However, a lot of research has a common finding that, in the dry condition, the strength is higher than in the green condition.

Bamboo shows advantages in relation to other natural fibre materials for its lightness, high bending capacity and the fact that it is the fastest growing plant on earth. In addition bamboo is a renewable natural resource and requires simple and low cost processing techniques (Ghavami & Hombeeck, 1981; Liese, 1986; Ghavami & Zielinski, 1988; Ghavami 1988; Ghavami & Solorzano 1995; Amada 1996; Ghavami & Rodrigues 2000).

The development of a low cost pylon material in prosthetic leg involves multidisciplinary studies. One must look into the possibility of introducing a natural resource to the system as an alternative to produce a pylon. The most important aspect to consider when producing a new pylon for prosthetic leg is the high in compression, long durability and lightness. In order to achieve this, a suitable bamboo culm had been selected to replace the conventional pylon.

2.4 Lower Limb Prosthetic in Developing Countries

In developing countries, when amputees cannot access a mobile clinic, they resort to anything they can construct at home in an effort to continue engaging in their daily lives. The hand-held pole leg was one of the simplest lower limb assisting devices which used either a leather strap or a platform to support residual limb during walking (Fillauer, 1999). This device also can be transformed into “crutch leg” by cutting away the top half of a crutch and secured the residual limb with several straps (Figure 2.7). These types of limbs are temporarily fine when nothing else is available. However, the device can lead to long term fitting problems as contractures can easily form in the knee. Moreover, the contractures will appear very rapidly if the muscle in the limb is not stretch daily (Finney, 2000).

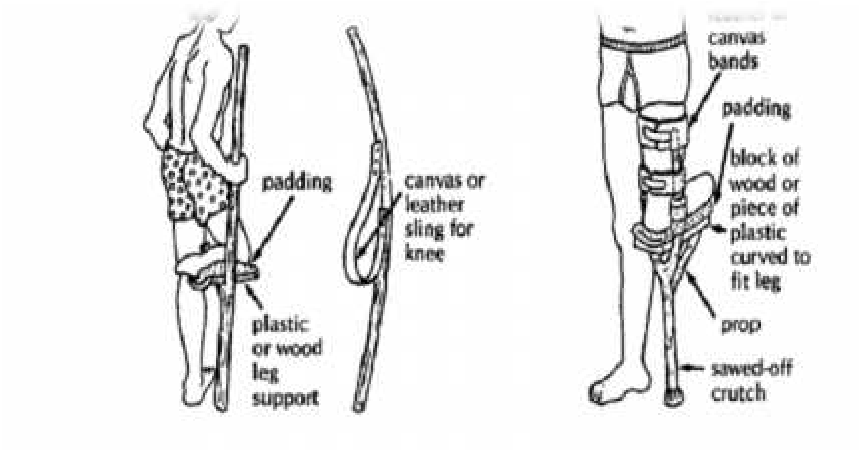


Figure 2.7: From left: Hand-held pole legs, and "sawed-off crutch" leg. Reproduced from Strait (2006).

Akiode et al., (2005) described the bicycle-based limb which utilize the materials and knowledge, used to be popular in Bangladesh. The components of this leg are adjustable for the growth of children and parts of the limb can be adjusted with the use of a wrench. Initially the weight of this prosthesis was an issue, but a slightly increased weight in limb can resultant in improvement stability. The leg is built from the foot up by first removing the seat of the bike from the frame and separating the seat post from the seat by loosening and using the bolts and washers. The seat post is the base upside down and forms the lower shin which then attached to a prosthetic foot. A one inch thick piece of wood is cut to resemble a foot and lined with rubber on the undersurface for traction. The seat support frame and rear wheel supports are separated from the bike, and the rear wheel supports are bent to form the calf support for the socket (Akiode et al., 2005). This prosthesis is held on with a suspension strap connecting the prosthesis to a belt worn around the waist. The shin and foot are attached to the socket holder and the length can be adjusted at this juncture.

Another common lower limb prosthesis used for developing countries is the "bamboo leg" that is a step above from pole legs as the limb is held in a more natural, in line position with socket. The limb design is similar to the "Peg Leg" from Dark Ages in the 15th century (Figure 2.8). Sockets from the limb prevent the formation contractures during patient ambulation because the knee has full range of movement. The "bamboo leg" is constructed by adding padding to the bottom of the stump and long socks are used to hold the padding in place. The limb is then ready to be circumferentially wrapped in plaster bandages and attached to a piece of bamboo with a thin wire (Fillauer, 1999).

Figure 2.8: From left the traditional peg leg, and adjustable bicycle limb. Reproduced from Strait, 2006.

The "bamboo leg" in the limb differs from prosthetic bamboo pylon since it comes straight from bamboo plants and does not encounter any manufacturing process. Though it will greatly work as a temporary limb, the limb has a small base of end support that contributes to high pressure and lead to stump contractures if it has less padding. Besides, this limb risks on cracks of its ground base (disperse of bamboo fibres) after a series of walking and less durable compared to traditional peg leg which was made of solid wood.

Patients who wear the “bamboo leg” has unbalanced gait and usually limp when walking down an uneven terrain due to foot-ankle assembly absence (Kate et al., 2009).

2.5 Prosthetic Pylons

There are three types of prostheses appropriate for different stages after amputation. These include postoperative prostheses, temporary prostheses and definitive prostheses. Immediate postoperative prosthesis (IPOP) is a device applied in the operating room before wound closure that protects the suture site and allows limited weight bearing and gait training. The prosthesis is applied to mainly young traumatic amputees. Individuals with vascular risks are seldom put on the IPOP system despite its safe utilization in dysvascular amputees as reported in the Folsom et al. (1992). Though some surgeons fear that walking on fresh amputation would be harmful to the healing process and horribly painful on patient, many others believe that wounds heal faster and IPOP allows for early activity, load bearing and resultant to less swelling at the residual limb (Smith, 2003). A study carried out by Harrington et al. (1991) applied IPOP to 56 transtibial patients and elastic bandages to 27 patients right after their surgery. Patient with IPOP was allowed to take partial or full weight as it tolerated, and was encouraged to continue walking throughout hospital stay. Meanwhile, soft dressing group had daily compression stump bandaging, exercises to prevent flexion contractures of hip and knee. They used Wu et al. (1979) method of estimation of healing time, who recorded the interval between amputation and the ordering of a temporary prosthesis. The result showed that for the IPOP group, average time for healing was 40.4 days and for the soft bandage group, average healing time was 98.4 days. The study claimed that the method of surgeons who favour soft dressing whenever IPOP method is possible and delayed weight-bearing after amputation is unreliable. The biggest benefit of IPOP is that patients often become less focused on the loss limb but switches to a mind set of recovering and regaining an active life.

The temporary prostheses also known as interim prosthesis are used in the interval between amputation and the fitting of a permanent prosthesis (Fulford & Hall, 1968). Superior to IPOP, this prosthesis is applicable for every amputee while it still allows early ambulation and promotes residual limb shrinkage and continued process of residual limb maturation which can take 6 months and sometimes longer (Pandian et al., 2001). Definitive prostheses as described in Chapter 1 may have either endoskeletal (modular) or exoskeletal design. The endoskeletal design is more common (Harrington, 1984) which is made of metal, titanium, steel, aluminum alloys or sometimes from carbon fibre. Pylons in the IPOP and interim prosthesis systems are always endoskeletal and modifiable. The pylon in IPOP and interim prosthesis usually has an adjustment mechanism so that the prosthetist can alter the alignment as the patient's ability to walk improves. The adjustable coupling (Figure 2.9) consists essentially of two plate assemblies which is held together by a central toggle pin. It is mounted to a middle plate and part of one plate assembly comes with four screw subassemblies, spaced 90 degrees apart, which contain independently adjustable to provide adjustment for flexion-extension and adduction-abduction. Modifications to the adjustable pylon of these two prostheses may correct gait deviations and increase energy efficiency while the sockets significantly reduces edema (Seymour, 2002).

Another interim prosthesis for transtibial, Scotchcast® P.V.C was introduced by Wu et al. (1980). The Scotchcast tape is applied all over the residual limb as the stump socket and wound protector, then pylon unit is made of thermoplastic polyvinyl chloride (PVC). The pipe is softened on one end with a heavy-duty hot air blower such as heat gun, then snugly fitted to the metal plug attached to the top of the SACH foot. The junction of pipe over plug is further reinforced with a hose clamp. Then, the proximal end of the PVC pipe is then sliced longitudinally into four sections, and bent outward into X-shaped bars (Figure 2.9). An advantage of this technique, besides light weight, comfortable fitting, and only rare need for realignment, is the reduction of fabricating time, often to less than 2 hours. Wu et al. claimed that using Scotchcast® interim pylon had resulted in improved patient care at Veteran Affairs Medical Centre, Chicago.

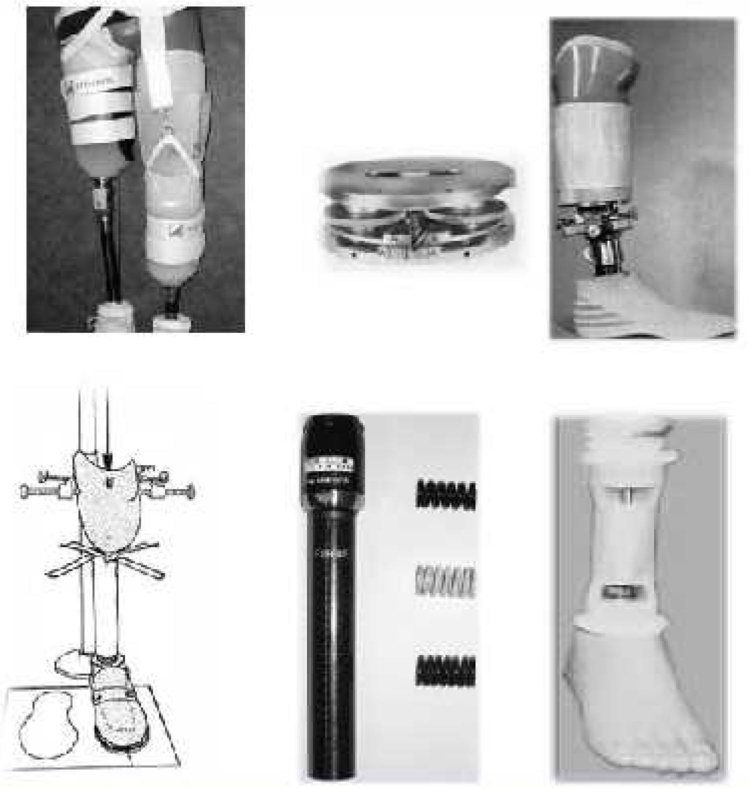


Figure 2.9: From top left: IPOP prosthesis in bilateral amputation, the adjustable coupling assembled used in IPOP and interim prosthesis, a below knee adjustable pylon used in current practice. From bottom left: Scotchcast® interim pylon in alignment process, Endolite® Telescopic-Torsion pylon, Sathi limb. Reproduced from Wu et al. (1979).

Therefore, the choice of appropriate prosthetic components as part of prosthetic prescription is critical to user comfort. Shock-absorbing pylons (SAPs) are designed to reduce shock forces during walking and other high impact activities. SAPs are spring like mechanisms that are fitted in the shank section of transtibial prostheses (Figure 2.9). They shorten telescopically with applied axial loads, thereby decreasing the stiffness of the prosthesis and presumably reducing the impact forces associated with walking. The kinematic responses of locomotor system during walking actively attenuate impact forces, while passive attenuation is provided by the structure and viscoelastic properties of tissues (Lafortune, 1994). Insufficient shock absorption during gait has been attributed to low back pain (Voloshin & Wosk, 1982; Collins & Whittle, 1989), cartilage degeneration at the joints (Radin et al., 1973), and osteoarthritis in the ankle, knee and spine (Collins & Whittle, 1989; Nack & Phillips, 1990).

Mooney et al. (1995) examined the differences in the ground reaction forces (GRFs) and moments of force during gait between the sound and residual limbs of a single transtibial amputee using the Flex Foot Re-Flex Vertical Shock Pylon (VSP), a type of SAP that uses a pistoning pylon assembly along with a leaf spring. The subject was tested at with the VSP and then with the shock absorber immobilized. The investigators found that when the VSP was disabled, the vertical GRF during prosthetic stance exhibited a third peak in midstance and slightly decreased forces during the loading response phase and the anterior-posterior GRFs were slightly decreased. Based on Gard & Konz (2003) study, shot term benefits for amputees walking with SAPs may include comfort and better prosthetic performance during gait, whereas long-term use of these devices may prevent joint and back problems that can arise from walking on a rigid prosthesis.

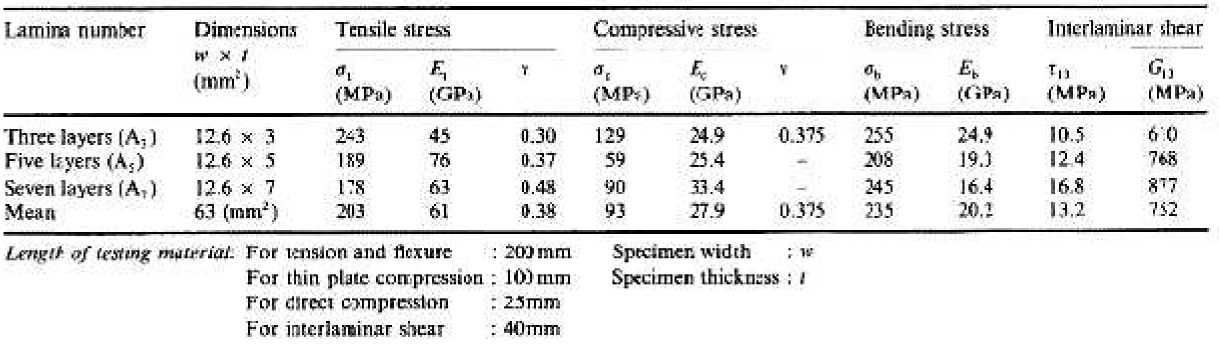
In developing countries, the Transtibial Plastic Modular Component also called as Sathi Limb can be used with any socket design and any foot including the bare foot models. The use of thermoplastic components in prosthetics enables technicians to utilize the inherent characteristics of plastics in that they are lightweight, inexpensive, non-corrosive, and water resistant. The lighter the prosthesis, the less energy the amputee has to use to walk. A light prosthesis also reduces shear forces on the limb and decreases the pistoning action on the limb (Sarani, 2004). The Sathi limb is made out of lightweight, high–density polyethylene water pipes with four ribs to give the pipe strength (Figure 2.9). The Sathi limb is made up of a polypropylene pylon, and has 20 different sizes to suit almost all lengths of residual limbs below the knee, a socket adapter and 2 discs, one placed below the socket and the other above the foot piece for alignment in the anterior-posterior, medial-lateral and able to tilt in all directions.

Several types of prosthetic pylons were described in this sub-chapter as well as the techniques used for their manufacture. The advantages of traditional modular pylon from Titanium or Steel Alloys are it has great accuracy in alignment, alignment can be changed at any point of time and the other components can be reused after changing sockets to definitive prosthesis. On the other hand, the traditional endoskeletal pylon can be expensive, heavy and unlike the Sathi limb, it cannot be assemble to the feet without a pyramid adaptor. The current study concerns is the same as Sathi Limb to produce a low cost pylon with easy and quick alignment but rather than manufacture pylon from high density polyethylene, the bamboo pylon is made from natural resources with less manufacturing process and come along with biodegradable properties.

2.6 Mechanical Properties of Bamboo

Researchers in the last twenty years had focused on mechanical properties of green, dried and reinforced bamboo. Other literatures on bamboo had discussed on methods to enhance the strength and durability by altering the original structure of the plant. To maximize the utilization of bamboo, its fundamental physical and mechanical properties must be fully understood. Studies have demonstrated that the physical and mechanical properties of bamboo mostly depend on the species, soil, silvicultural treatment, harvesting season, felling age and moisture content (Jain et al., 1992; Sulaiman et al., 2006; Lee et al., 1994). Shin et al. (1989) investigated tensile, compressive, flexural and inter-laminar shear properties of bamboo-epoxy composites of varying lamina numbers. In this study, the bamboo tested belonged to species *Bambusa Paravariabilis* which is laminated into three layers, five layers and seven layers. These samples were then tested on Universal Testing machine (UTM) with crosshead speed of 1 mm/min. The samples dimensions and results of the tests are presented in Table 2.2.

Table 2.2: Mechanical Properties of Bamboo-Epoxy Test Laminate Specimens. Reproduced from Shin et al. (1989).



Lamina number	Dimensions $w \times t$ (mm²)	Tensile stress			Compressive stress			Bending stress		Interlaminar shear	
		σ_t (MPa)	E_t (GPa)	ν	σ_c (MPa)	E_c (GPa)	ν	σ_b (MPa)	E_b (GPa)	τ_{13} (MPa)	G_{13} (MPa)
Three layers (A_3)	12.6 × 3	243	45	0.30	129	24.9	0.375	255	24.9	10.5	610
Five layers (A_5)	12.6 × 5	189	76	0.37	59	25.4	–	208	19.3	12.4	768
Seven layers (A_7)	12.6 × 7	178	63	0.48	90	33.4	–	245	16.4	16.8	877
Mean	63 (mm²)	203	61	0.38	93	27.9	0.375	235	20.2	13.2	752

Length of testing material: For tension and flexure : 200 mm
For thin plate compression : 100 mm
For direct compression : 25mm
For interlaminar shear : 40mm

Specimen width : w
Specimen thickness : t

Additional in lamination layers was accompanied by a decrease in tensile strength and an increase in Poisson Ratio and Young's modulus. This is possibly because the decrease in longitudinal strain is greater than decrease in tensile strength. The group investigated compressive properties by using a thin-plate compression set up which was modified from American Society for Testing and Materials (ASTM) D3410 standards. To ensure that fractures occurred in the middle portion of the test laminate, the two ends were reinforced with aluminium tabs. Flexural properties of specimens were tested by three-point bending. In Figure 2.10 the load-displacement curve showed an early linear segment, followed by a non-linear segment beyond 50 percent of fracture load until ultimate strength was applied. Following that, an irregular, staggered decreased in load was observed. This can be attributed to a demonstration of strength in the respective laminae and at the end of the study, Shin et al. (1989) could conclude that, at 61 GPa of Tensile Modulus, 27.9 GPa Compressive Modulus and 20.2 GPa of Flexural Modulus; bamboo reinforced composites posses specific strength superior to that of ordinary fibre-glass reinforced composites and is 3 to 4 times stronger than mild steel.

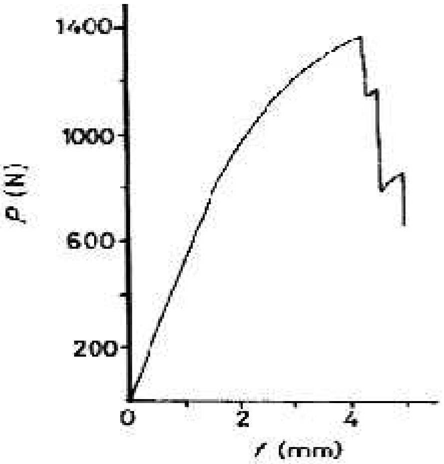


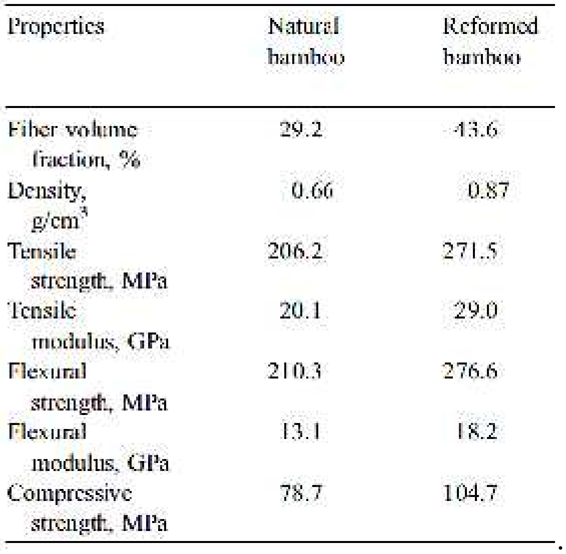
Figure 2.10: A load-displacement curve for a bamboo-epoxy laminate specimen under three-point bending. Reproduced from Shin et al. (1989).

2.7 Mechanical Properties of Modified Bamboo

In order to make a pylon for a prosthetic leg, one must consider the weight, durability, shock absorption rate, life span and also the strength of bamboo in order to get a successful prosthetic restoration. Reformed bamboo is one kind of bamboo which uses a simple technique that will increase the properties of a normal bamboo. It is said that this reformed bamboo is denser than normal bamboo, and thus contains more bamboo components within the same volume (Yaoa & Lib, 2003). There are several ranges of reformed bamboo which currently being produced: the plain reformed bamboo, the reformed bamboo/aluminum composite, and the reformed bamboo/glass fabric/aluminum composite.

Various types of reformed bamboo resultants to different mechanical properties of bamboo (Chung & Yu, 2002, Amada et al. 1997, Gibson et al., 1995, Ray et al. 2004, Silva et al., 2006, Li, 2004, Ghavami et al., 2003) and many of researchers tends to replace tubular steel to bamboo for construction purposes due to its superior properties like high strength to weight ratio, high tensile strength and other factors like low cost, easy availability and harmless to the environment during service. The average properties of reformed bamboo and natural bamboo were listed in Table 2.3. It was found from the table that all the properties of reformed bamboo are obviously better than that of natural one (Yaoa & Lib, 2003).

Table 2.3: Average properties of reformed bamboo, and natural bamboo. Reproduced from Yaoa & Lib (2003).



Properties	Natural bamboo	Reformed bamboo
Fiber volume fraction, %	29.2	43.6
Density, g/cm^3	0.66	0.87
Tensile strength, MPa	206.2	271.5
Tensile modulus, GPa	20.1	29.0
Flexural strength, MPa	210.3	276.6
Flexural modulus, GPa	13.1	18.2
Compressive strength, MPa	78.7	104.7

This study will use only one type of modified bamboo which is plain reformed bamboo as prosthetic pylon because in the end, the researcher wants to produce a reliable, strong, durable and economical using natural ecomaterial that can be disposes with minimum impact on the environment.

2.8 Mechanical Properties of Prosthetic Pylon

Within the field of prosthetics in the world today, there is a great variation in fabrication techniques and choices of pylon-to-socket attachment systems. The prosthetist chooses a combination materials and components that will provide sufficient strength and function. When presented with fabrication and componentry options, the practitioner prefers to be guided by empirical, objective data. Because of the lack of data, the prosthetic device is often overbuilt. The result may be the extra weight of unnecessary materials or a pylon attachment system that one assumes is safer but may be only heavier. Very few published research has been conducted on the stiffness and mechanical properties of pylon-to-socket attachment systems.

Current et al, 1999 is one of the first published articles which introduced the testing method on a whole set of prosthetic leg. Loading parameters and methods were developed practically to imitate the International Standards Organisation (ISO) standards since structural testing of lower limb prostheses have not yet been established. However, this design method makes the results are relatively doubtful. The purpose of the investigation was to quantify the structural strength of various transtibial composite sockets. The experimental setup simulated the instant of maximum loading during the late stance phase of gait. A standard four holes 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. Their results showed that all failures occurred at the site of the pyramid attachment plate and none of the composites in the study met the ISO standards for level A100, loading condition II (4025 N), as required for other prosthetic componentry.

According to Neo et al, (2000) from National University of Singapore; in order to achieve compound loadings via the application of a single test force likewise Current et al. (1999) study, the prosthesis tested must be aligned and set up strictly according to the specifications as documented in ISO 10328. In Neo et al. (2000) study, a simple alignment device and method is applied to prepare transtibial prosthetic assemblies for structural tests. Actual socket and pylon were used in the test but the foot was replaced by an aluminum foot block as there were concerns that the flexibility of a prosthetic foot might cause excessive deflection altering the loading conditions on the socket.

The alignment apparatus consisted of the main frame, the top plate, the knee locator and an alignment rod (Figure 2.11). With the aid of the alignment apparatus, the test prosthesis was aligned as stipulated in ISO 10328 as follows:

a. The knee joint centre was directly above the origin of the (loading) coordinate axes and lying on the u-axis (a line extending from the origin and passing through effective ankle and knee joint centres)
b. The knee joint centre was at a height of 500 mm from the origin
c. The knee joint centre-line was parallel to the o-axis (a line perpendicular to u-axis and parallel to effective knee joint centre-line)
d. The components were adjusted to a "worst alignment" configuration

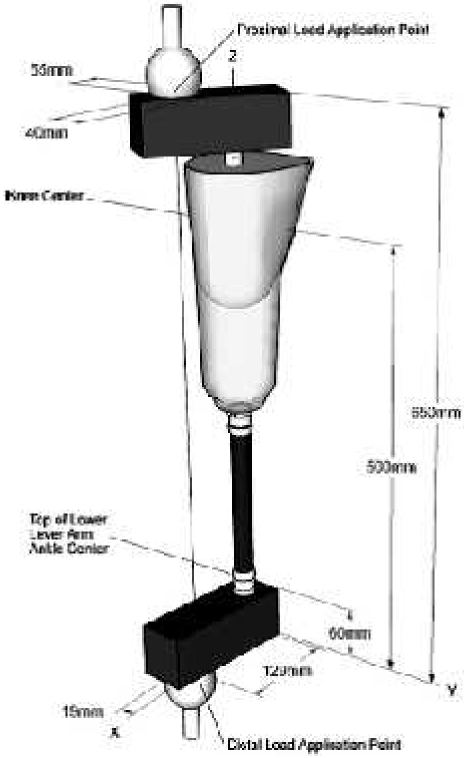


Figure 2.11: A schematic of the entire test fixture setup. Reproduced from Neo et al. (2007).

For the transtibial prosthetic socket, the location of the knee centre-line and knee centre is not easily identified due to the absence of a knee unit. In the study, a simple knee locator was designed to provide a mechanical means of identifying the direction of the knee centre-line and the position of the knee. The locator, together with the main frame and the alignment rod enabled the various components within the prosthetic assembly to be properly orientated and positioned.

In year 2000, Hahl and Taya from Seattle modified Saito et al. (1997) transtibial prosthesis design by replacing the Aluminum pylon with fibre reinforced plastic material. The new design was then tested to ensure that it satisfied the ISO 10328 standard prostheses. At first Young's Modulus of the new material fibre reinforced plastic was discovered. The Young's Modulus of fibre reinforced plastic in form of tube shell is 12.23 GPa with Poisson's Ratio 0.03 while the Aluminum Young's Modulus is 48 GPa with Poisson's Ration 0.35.

Figure 2.12 is a photograph of the prosthesis during testing. The test set up consisted of a data acquisition system, a charge-coupled device (CCD) camera and an Instron mechanical testing machine. A set of jigs attached to the machine. The jigs created compound loading conditions on the prosthesis by the application of a single offset axial force. A failure test was performed on the prosthesis to determine the load at which it will break. The prosthesis was arranged in the jigs at a horizontal displacement of 110 mm, which represents the toe-off condition. A compressive load was applied to the prosthesis using position control at a constant displacement rate of 1 mm/min.

Figure 2.12: Photograph of the test set up for mechanical testing of the prosthesis. Satisfies the ISO 10328 Standard. Reproduced from Hahl & Taya (2000).

Figure 2.13 is a graph for a load versus displacement as the prosthesis was loaded. A distinct system of cracks was seen in the base of the stiffener section at a load of 6,600 N (point A on Figure 2.13). The onset of the crack occurred at the midline of the thickness of the foot (2.5 mm) at the base of the stiffener. The authors assumed that the crack was caused by interlaminar failure at a load of 6,600 N. Table 2.4 is a summary of the failure loads for the original prosthesis and the optimized design.

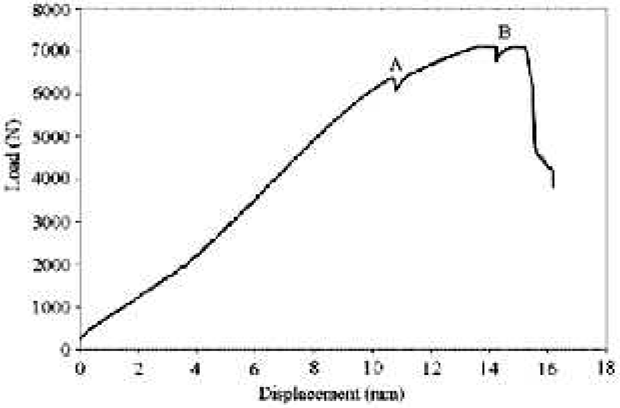


Figure 2.13: Load versus displacement as the prosthesis was loaded in compression. Reproduced from Hahl & Taya (2000).

Table 2.4: Summary of Experimental Failure Loads. Reproduced from Hahl & Taya (2000).

	Optimized Design	Original Design*	ISO Requirement
Failure Load	7,000 N	5,500 N	3,200 N

*—with aluminum stiffeners.

In a study by Lee and Zhang (2006), a fatigue test was done on monolimb prosthetic. Monolimb refers to a kind of transtibial prostheses with the socket and shank moulded into one piece of thermoplastic material. Fatigue test of the monolimb was performed using a material testing machine. As shown in Figure 2.14, the monolimb was offset by an extension aluminum block and mounted to the actuator linked to a linear voltage displacement transducer (LVDT) which shows the vertical displacement of the actuator.

The monolimb was loaded against a 208 rigid tilting block at the frefoot, which was related to the heel-off phase of the gait. The tilting block was attached securely to the load cell. The prosthetic foot was aligned such that there was no toe-in and toe-out, and the long axes of the extension block and the tilting block were aligned with that of the prosthetic foot. At the beginning, a 50 N test force was applied to the forefoot and the original actuator position was recorded by the LVDT. Next, a sinusoidal waveform of pulsating force oscillating between 800 N and 50 N at a frequency of 1 Hz was applied to the forefoot until 500,000 cycles was reached or the test monolimb structurally failed.

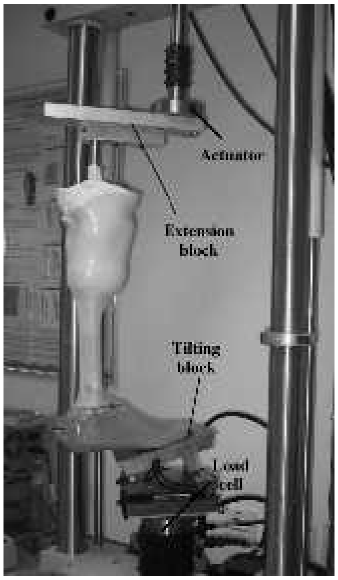


Figure 2.14: Test set-up of the fatigue test. Reproduced from Lee and Zhang, 2006.

The result showed that the monolimb which used an elliptical foot bolt adaptor failed the fatigue test as structural failure occurred before reaching 20,000 cycles. The anterior aspect of the distal end of the shank created a hole on the top surface of the wooden keel of the SACH foot. At the end, the screw broke into two separating the prosthetic foot and the shank portion of the monolimb before completing 20,000 cycles. A better adaptor design spreading and reducing the pressure at the junction between the shank distal end and the top surface of the wooden keel is desired. Previous studies applied loads according to consensus reached at the International Society for Prosthetics and Orthotics (1978) or test methods laid out in the International Standard ISO 10328:1996 (Current et al., 1999; Neo et al., 2000). The Compliance International Standards ensures the structural integrity on loading. However, the authors suggested that it has been commented that the load levels set by the standards are too severe, that many prosthetic components failed to comply with the standards. In addition to the load level, the strict restriction on the allowable deformation makes it difficult for plastic prostheses to comply with the standard.

2.9 Clinical Assessments on Transtibial Patients

Fundamentally, the goal in fitting a lower-limb amputee with prosthetic leg is to restore the ability to perform everyday activities in an easy, natural, and comfortable manner. Gait analysis is useful for evaluating an amputee's prosthesis by providing objective measurements that characterize the walking pattern. As with normal walking, amputee gait is characterised by kinetic and kinematic parameters. Comparisons are made in terms of ground reaction forces (GRF), joint angles, moments and powers and spatial-temporal parameters. The GRF is the propulsive force in the walking. It is equal in magnitude and opposite in direction to the force that the body exerts on the supporting surface through the foot. For the purpose of analysis, it is commonly broken down into vector components. These components are orthogonal to each other along a 3D coordinate system which knows as F_z-vertical component, F_y-antero-posterior component and F_x-medio-lateral component. Figure 2.15 shows common vertical and antero-posterior GRF for transtibial patients.

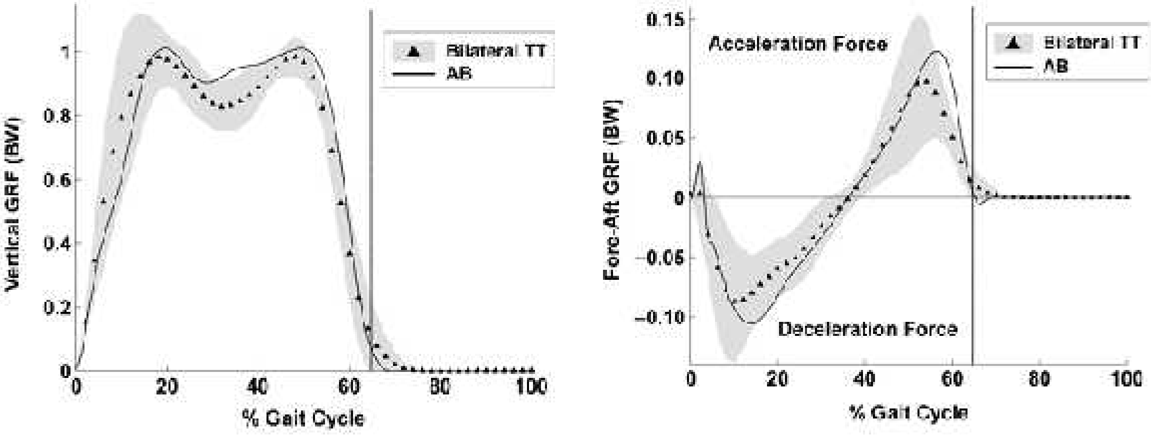


Figure 2.15: GRF for vertical and antero-posterior components for transtibial subjects. Reproduced from Su et al., 2007.

Joint angles are important when describing the kinematics of locomotion. During lower limb gait analysis, joint angles are observed at the pelvis, hip, knee, and ankle. The hip reaches the adduction peak during the stance loading response, extension peak in the terminal stance and flexion peak during the loading response. The small amount of knee flexion observed in the loading response allows for weight absorption. Finally, the ankle shows peak plantar flexion in terminal stance and plantar flexion at heel strike and in the initial swing. Figure 2.16 shows common joint angles for transtibial patients.

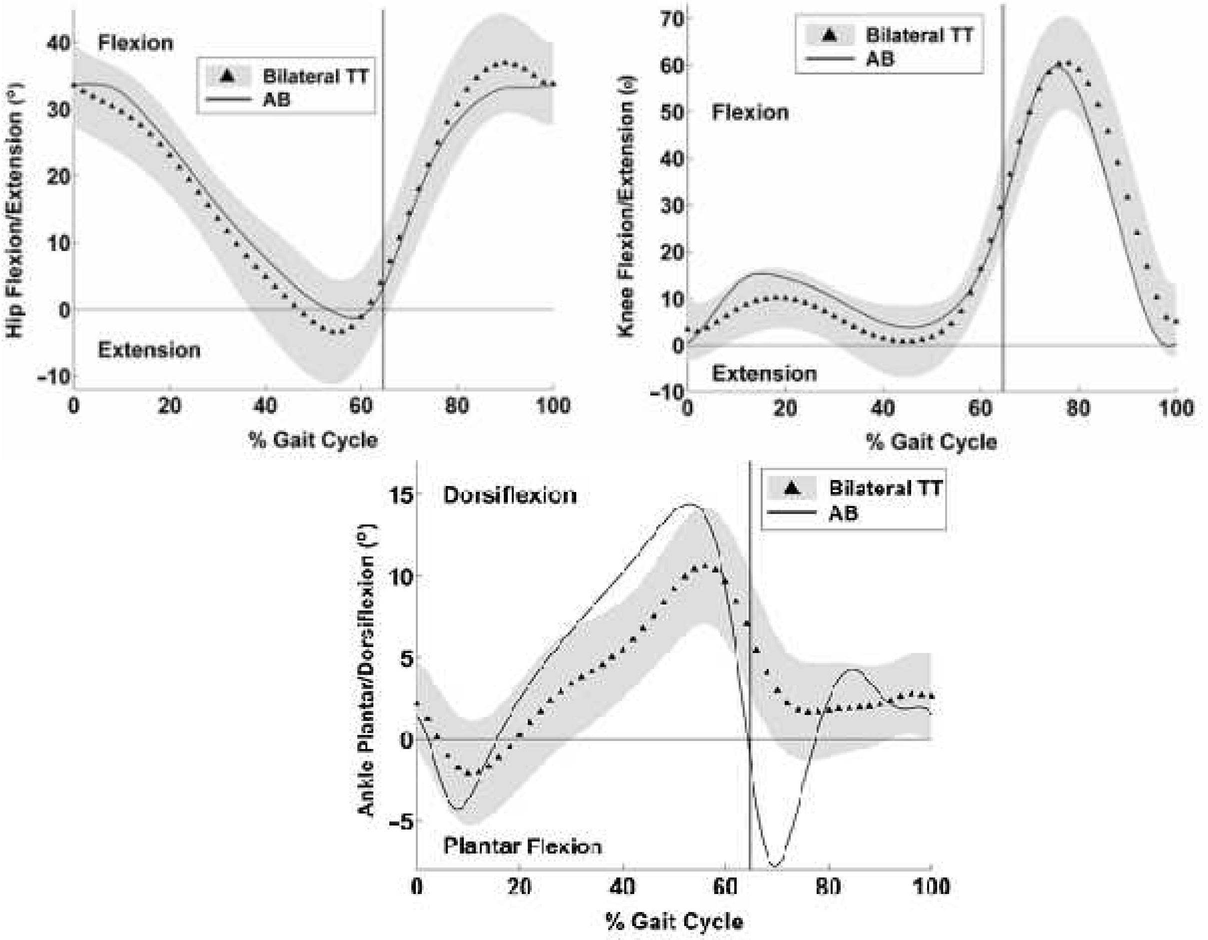


Figure 2.16: Joint angles for hip, knee and ankle for transtibial subjects.
Reproduced from Su et al. (2007).

Chapter 3

METHODOLOGY

Chapter 3 is divided into two sections. The first section illustrates the development of bamboo pylon from the plant in detail. The second part of this chapter describes the mechanical and clinical test procedures that were performed to evaluate the efficacy of the bamboo pylon.

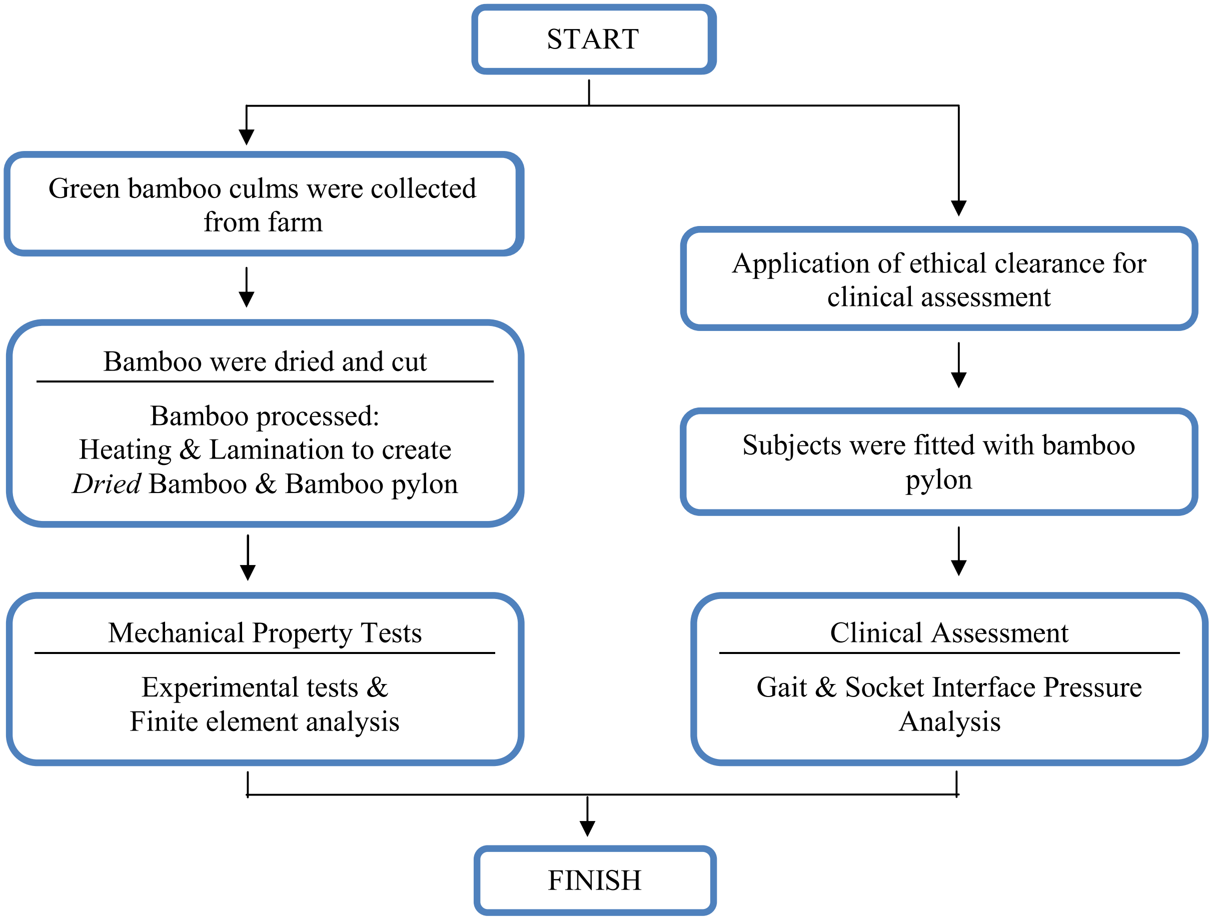


Figure 3.1: Flowchart of the study.

3.1 Development of Bamboo Pylon

This subchapter explains the process to develop a piece of strong and long-lasting plain reformed bamboo pylon from the raw material. There were 4 stages in bamboo pylon process; harvesting, culm drying, bamboo treatment, and bamboo lamination. Each of this process is explained in detail throughout this chapter. In this study, sympodial rhizomes bamboo, *Bambusa Heterostachya* was chosen to produce a bamboo pylon as this species can be found vastly and abundantly in Malaysia. Besides, the physical properties of the species itself make it an excellent resource for a practical work. Furthermore, the size of the fully grown *Bambusa Heterostachya* was incredibly fit for pylon manufacturing. A flowchart of bamboo process is shown in Figure 3.2.

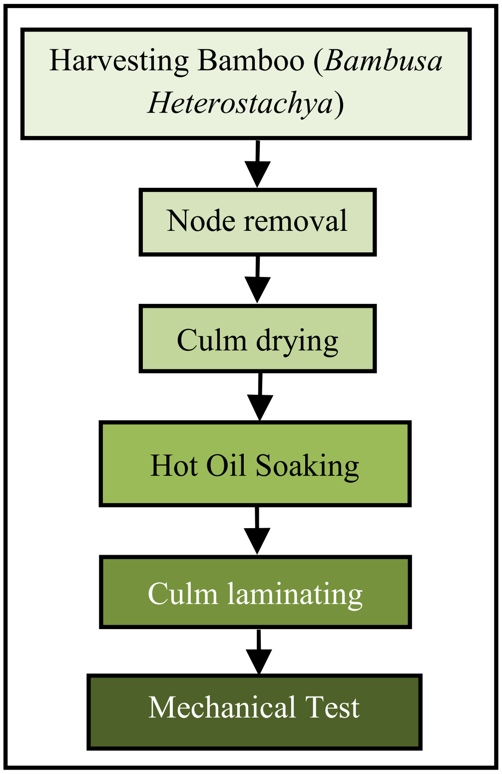


Figure 3.2: Flow chart of the bamboo pylon process.

The strength of bamboo pylon would be uncovered when the bamboo was handled best from the moment of harvesting, transportation, storage, construction and maintenance. Bamboo harvested at the right time of year, and abruptly out in the open to ground contact or rain, would damage just as quickly as improperly harvested material. This would make the physical properties of the bamboo become worst compared to others.

3.1.1 Harvesting Local bamboo

It was very important to harvest the culms when at their maturity and possessed low moisture content, as high moisture content increased the ease and rate of pest infestation. Harvesting of bamboo would be carrying out according to the following condition as this ensure that the end product would last to a maximum years with no substantial defect. Sound internodes of matured bamboo were harvested from bambusetum in Forest Research Institute Malaysia (FRIM) between August 20th and 30th, 2006 (Figure 3.3). The samples were placed under shades before transported to Motion Analysis Laboratory at Department of Biomedical Engineering, University of Malaya for the next process.

Figure 3.3: The officers from FRIM were helping locating the matured bamboo.

Maturity of culm was a requirement for the optimum use of bamboo when harvesting. In comparison to wood trees, bamboo lacks the vascular cambium layer (Nguyen, 2006; Xiaobing, 2007), so that it has no marking of growth diameter and consequently no year rings. Thus, to identify the maturity of the culm (3 to 4 years), the author had employed methods suggested by Fu (2001) by judging the colour of culm and measuring the volume of the bamboo clump from a diameter between 5 meter and 3 meter. In this study, the age of bamboo culms was determined based on experience of FRIM's officer by using a combination of the two methods.

Figure 3.4: Culm colour (*Bambusa Heterostachya*) in different ages. A - one year old culm; B - Two years old; C - Three years old; and D - Five years old.

3.1.2 Node Removal

Once the ideal bamboo had been chosen, it was removed from a clump by cutting them just above a node about 20 cm above the ground as shown in Figure 3.5. This length became a buffer zone for the younger ones to remain for further edibles of the rhizome.

Figure 3.5: The average volume of the bamboo clump was about 4 meter before harvesting.

To prepare the samples, bottom portion of three year old bamboo was used. The length and diameter of each chosen culm was the same with the conventional pylon measurements which was about 200 mm and 30mm ± 2mm (outer diameter) (Figure 3.6). Nevertheless, the length and diameters of the prepared culms could be varied from the above mentioned dimension in order to customize the prosthetic pylon for different need of the patients.

The suitable culm in a bamboo pole was chosen when the inner diameter was half compared to the outer diameter (Figure 3.7) which usually at 4th, and 5th internodes or 2/3 of the bamboo length from the ground level of *Bambusa Heterostachya*. If the inner diameter became less than half, bamboo pylon could easily break. Results from compression test by Ghavami and Hombeeck, (1982) had shown that the bamboo culm with the inner diameter half of the outer diameter produce a strong rigid body compared to inner diameter less than half of outer diameter.

Figure 3.6: The author was holding a potential bamboo with suitable length and size.

Figure 3.7: A good sample of bamboo culm (left) versus poor sample (right).

3.1.3 Culm Drying

The culms were treated soon after having been cut. A key factor was the sufficient preservation of the culm. The well-shape samples were oven-dried to remove its water content thus avoiding fungus growth or decomposition of the culms. The presence of large amounts of starch made bamboo highly susceptible to attack by staining fungi and powder-post beetles (Mathew and Nair, 1988). The drying treatment was conducted in an oven at 200^{o} Celsius for 72 hours (Figure 3.8).

Figure 3.8: The bamboo culms were placed in an oven to remove its water content

The shrinkage in wall thickness and the diameter shrinkage were determined from green to oven-dry condition. The wall thickness was determined at four perpendicular positions while the diameter shrinkage was measured along two diameters perpendicular to each other (Figure 3.9). Shrinkage was measured by using Equation 3.1.

Where **S** = Shrinkage (percentage)

GD = Green Dimension

ODD = Oven-dry dimension

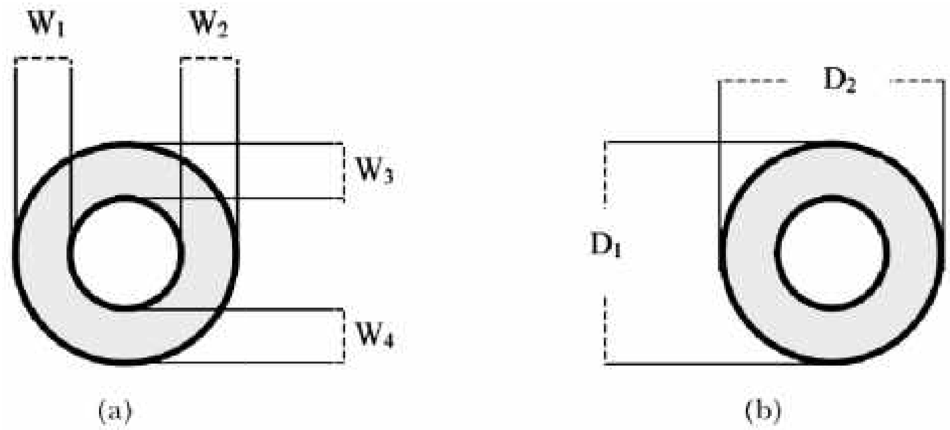


Figure 3.9: Position and direction of measurement: (a) Measurement for wall-thickness shrinkage (b) Measurement for diameter shrinkage. Reproduced from Talukder & Sattar (1980).

3.1.4 Hot Oil Soaking

The bamboo culms were then cut into specific sizes (desired pylon size) and underwent pre-treatment hot oil soaking before the laminating process. In this study the Palm Oil, (V-sawit oil) was used as suggested by FRIM. The oil treatment process of the bamboo was done using electrical oil-curing machine. Palm oil was used as the heating medium as it was organic and had high boiling point. The palm oil was first heated up to a temperature of 60°C. Then the bamboos were submerged in the heated oil by placing them in a metallic enclose. Bamboo was taken out at 120°C to 180°C after 30 to 90 minutes.

The heat treatment did not improve the mechanical strength of the bamboo as the oil penetrates between the cells and reduce the adhesion between them. However, the oil treatment method greatly improved the durability of the bamboo and this method was recognized and widely used. If the bamboo was not treated by oil, the percentage of durability would fall to 34 to 48 percents (Wahab et al., 2004).

3.1.5 Culm Laminating

To develop bamboo pylon, it was important to consider the technological properties of the culm and its low durability against organisms. In a suitable environment, the culms were easily attacked by fungi and beetles. Following the size preparation and drying step, at least one layer of coating was applied on to the external surface of the culms. These external coating would provide aesthetic effect to the culms and served as a protective layer to prevent fungus or mites infestation that might possibly degrade the mechanical integrity of the pylon later. Thus durability of the bamboo pylon derived from the process was greatly improved. For the lamination, one layer of vinyl urethane adhesive with polyvinyl acetate as hardener at ratio of 100:15 tangentially was applied to the outer and inner surface of the culm.

The culms after application of the coating layer was subjected to 24 hours drying. This step would harden the coating materials before adding another layer until it became three and each laminated being approximately 1mm thick (Figure 3.10). After the lamination layers dried, the culms were ready for the mechanical test.

Figure 3.10: The end product of bamboo pylon.

Table 3.1 shows the cost of bamboo pylon.

Table 3.1: Cost to produce bamboo pylon. The cost is for one unit pylon.

No	**Item**	**Cost (RM)**
1	Fresh bamboo (supply by bamboo plantation owner)	2
2	Oven dry	5
3	Polyvinyl acetate (adhesive)	1
4	Labor	2
	Total	**10**

3.2 Mechanical Property Tests

3.2.1 Materials for Mechanical Tests

Fifty bamboo culms of *Bambusa Heterostachya* were collected for the mechanical property analysis at the aged of 3 to 4 years. This bamboo had an average culm length of 5.49 m, culm diameter at the bottom was about 3.5 cm, while the top culm was about 2.3 cm. Average thickness of the culm wall was 0.97 cm. Within the study, ten samples of each culm 1 to culm 5 were chosen for the experiments. Figure 3.11 shows the location of the selected culms in the bamboo coordinate system. During the experiments, every bamboo internodes with physical defects that caused by pests or chemical processed was excluded from the sampling group. There were three mechanical tests designed for the study; tensile, compression and flexural/bending tests. Dimensions as well as shapes for all the samples were cut based on the assigned mechanical test according to American Society for Testing and Materials (ASTM) Standards. In this study, the mechanical property tests were divided into two categories of *Bambusa Heterostachya* bamboo; the dried bamboo and reformed bamboo.

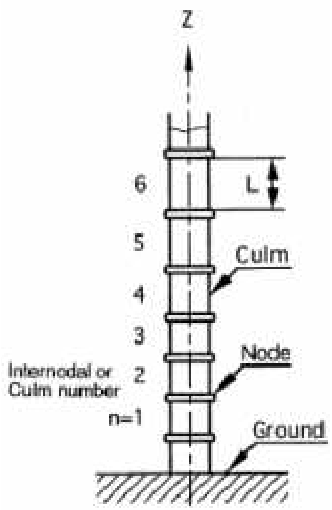


Figure 3.11: Bamboo coordinate system.

3.2.2 Experiments Set-Up

The dried and reformed specimens of *Bambusa Heterostachya* were tested at the Material Laboratory, Department of Mechanical Engineering, University of Malaya to determine the tensile and compression properties. An Instron 4400 Universal Testing Machine, (Figure 3.12) with heavy duty load cell capacity of 50 kN was used to determine the ultimate strength of the material. The loading rate of the Instron UTM was 1 mm/min. Load-displacement curves were generated from each test.

3.2.2.1 Tensile Test

Method to cover the determination of tensile properties of wood based structural panel was described in ASTM D 143-94 (ASTM 1994). This test method employed the specimens should have reduced cross-section at the center of their length to avoid failure in the grip area. Due to the small diameter of the culm, it was not possible to prepare large specimens from *Bambusa Heterostachya.* Thus, smaller dimensions were used following recommendations in ASTM D 143-94 standard (ASTM 1994). The study investigated tensile parallel to the grains which utilized the longitudinal direction. Figure 3.13 illustrates tensile test specimen, as well as the orthotropic directions of bamboo, the longitudinal, radial and tangential. The width, thickness and length of the tension parallel to the grains specimens were 12 mm, 3 mm and 120 mm respectively. The middle section of the specimens was necked-down to 5 mm to resemble a dumbbell shape. Wooden plates were glued on the sample in order to prevent splitting, and to enhance failure at the neck during the test. All the specimens were tested without nodes.

Figure 3.12: Instron Universal Testing Machine

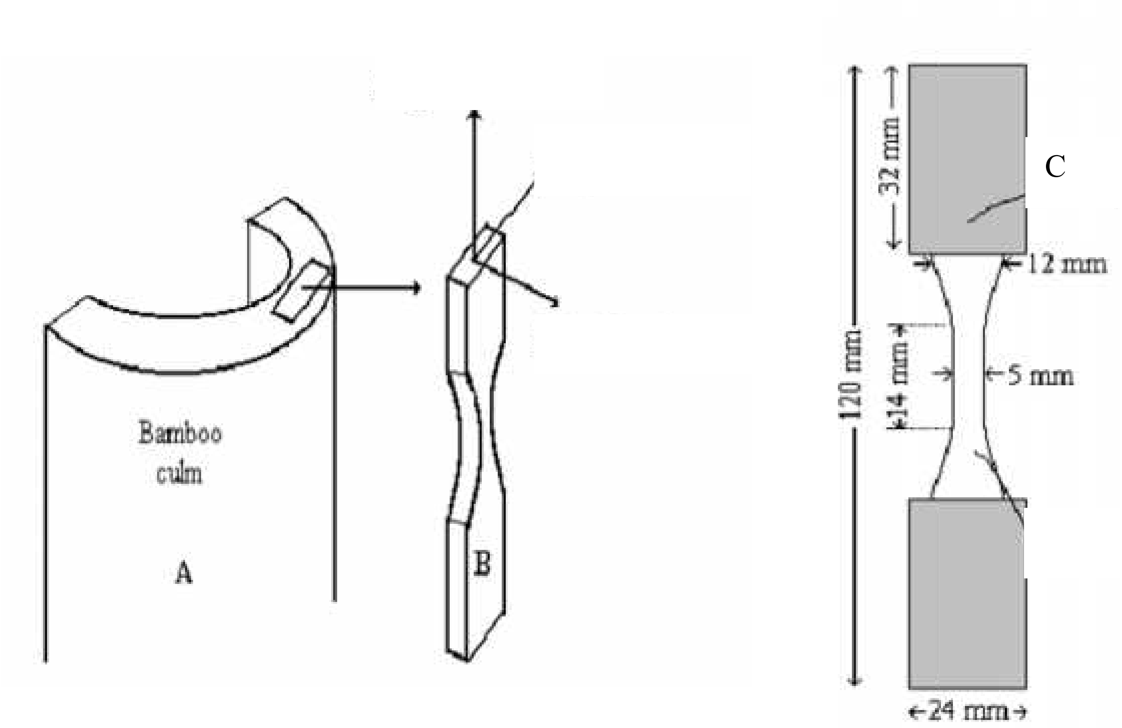


Figure 3.13: From left: Half-culm (A), tension test specimen (B) and specimen dimensions (C).

3.2.2.2 Compression Test

Compressive strength properties had been evaluated using the specimens made parallel to the grains. The specimens were investigated using modified ASTM D 3410 standards. Shape of compression and bending test specimens was in tubular forms which maintaining the original look of the dried and reformed bamboo. 50 specimens were tested without bamboo nodes. As bamboo in natural tubular forms varies in diameter from bottom to top of bamboo culm, the specimens were carefully chosen by taking the middle section of every internode. The average length of compression specimens was 200 mm with diameter of 30 mm. Samples in this test were clamped by metal adapters at both ends as shown in Figure 3.14. This procedure was to ensure that fractures would occur in the middle portion of the culm. In theory, the compression test is simply the opposite of the tension test with respect to the direction of loading. In compression testing, the sample was squeezed while the load and the displacement were recorded.

Figure 3.14: Specimen for compression test was clamped by metal adapters.

3.2.2.3 Three Point Bending Test

Standard test method to cover the determination of flexural properties of wood based structural panels was described in ASTM D 3043 - 95 (ASTM 1994). The test specimens were rectangular in cross-section and the length of the specimens was parallel to grains. Specimens were prepared without bamboo nodes. Figure 3.15 illustrates how the bending specimens were cut from the culm. The span, width and thickness of the bending specimens were 18 mm, 4.5 mm and 1.3 mm respectively. The bending test was conducted on an Instron 5548 Micro-Tensile Tester Machine at the Biomaterials Laboratory, Department of Biomedical Engineering. The cross head motion was set at 3 mm/min. In this experimental study, the specimen was supported horizontally by two steel pins and the load was applied at the mid-point of the two supports. The resulting deflection was then measured. The test proceeded at a constant rate of head motion until either sufficient deflection data in the elastic range had been gathered or until specimen failure occurred. The BlueHill 2 © Software from the Micro-Tensile Tester Machine plotted load against center point displacement graph.

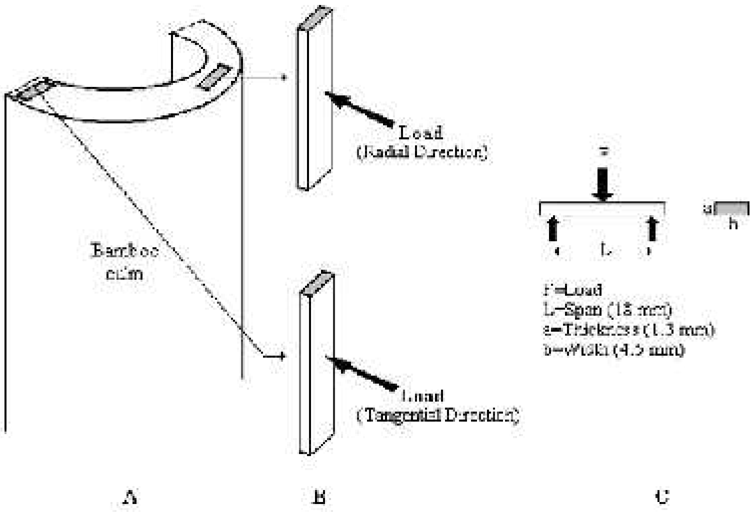


Figure 3.15: Half-culm (A), bending specimens (B), dimension of bending specimens (C).

3.2.3 Finite Element Analysis

Finite element analysis (FEA) is a particularly useful tool for predicting stress behavior and can be employed before producing an optimal prosthetic design so that it can reduce the possibility for clinical failure. In this study, FEA was performed to investigate the maximum stress and displacement of a reformed bamboo pylon during patient ambulation. The aim of this investigation was to assess the changes of its mechanical behavior, specifically compression and flexural properties by using simulation technique.

A finite element model of a reformed bamboo pylon had been constructed in Patran © 2001 r2a software. To aid the convergence tests, simplified loading, constraints and material properties were applied. Each of the components was modelled as a linear geometry model and were represented by 4-noded quadrilateral elements which defined internally by Patran © 2001 r2a software.

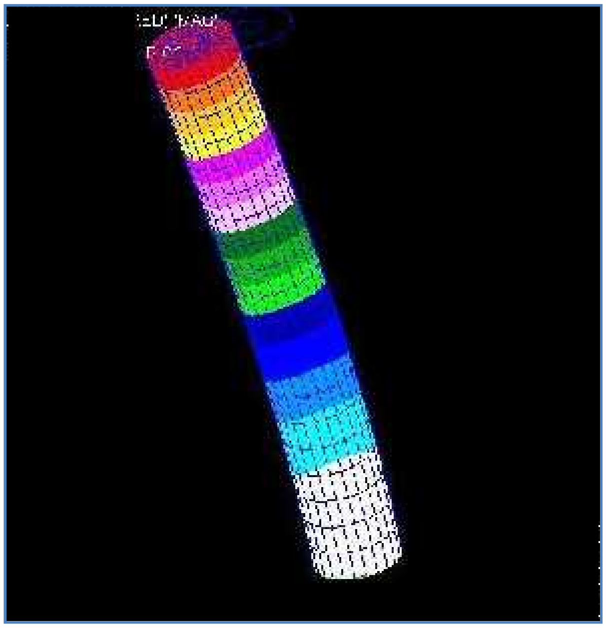


Figure 3.16: Finite element model of a reformed bamboo.

The pylon model was in tubular shape with diameter, length and wall thickness were 30 mm, 200 mm and 10 mm respectively (Figure 3.16). Various configurations which affected the physical properties of this material such as lamination layer and structural composition were in consideration. A load of approximately 100 kg, of human body weight was applied directly on the top part of the bamboo pylon with inclination of 15^o to imitate below knee walking condition. Steel adapters at both end of bamboo pylon were set to connect the pylon to the residual limb. These adapters would be a static constraint to the pylon. The Compressive Modulus, (E_c) and Poisson ratio (γ) applied for the FEA were 132.6 MPa and 30.7GPa respectively. These values were obtained from the previous mechanical tests. The FEA conducted parametric analyses to investigate the stress and displacement distributions. It also demonstrated possible fracture and distortion of the bamboo pylon.

3.3 Clinical Assessment

Apart of the mechanical properties experiments, the study had carried out clinical evaluation on the transtibial amputees. The purpose of this clinical study was to evaluate the bamboo pylon efficiency. Differences between the bamboo pylon over the conventional component in gait and socket interface pressure was assessed. Figure 3.17 shows the flow chart of the clinical study.

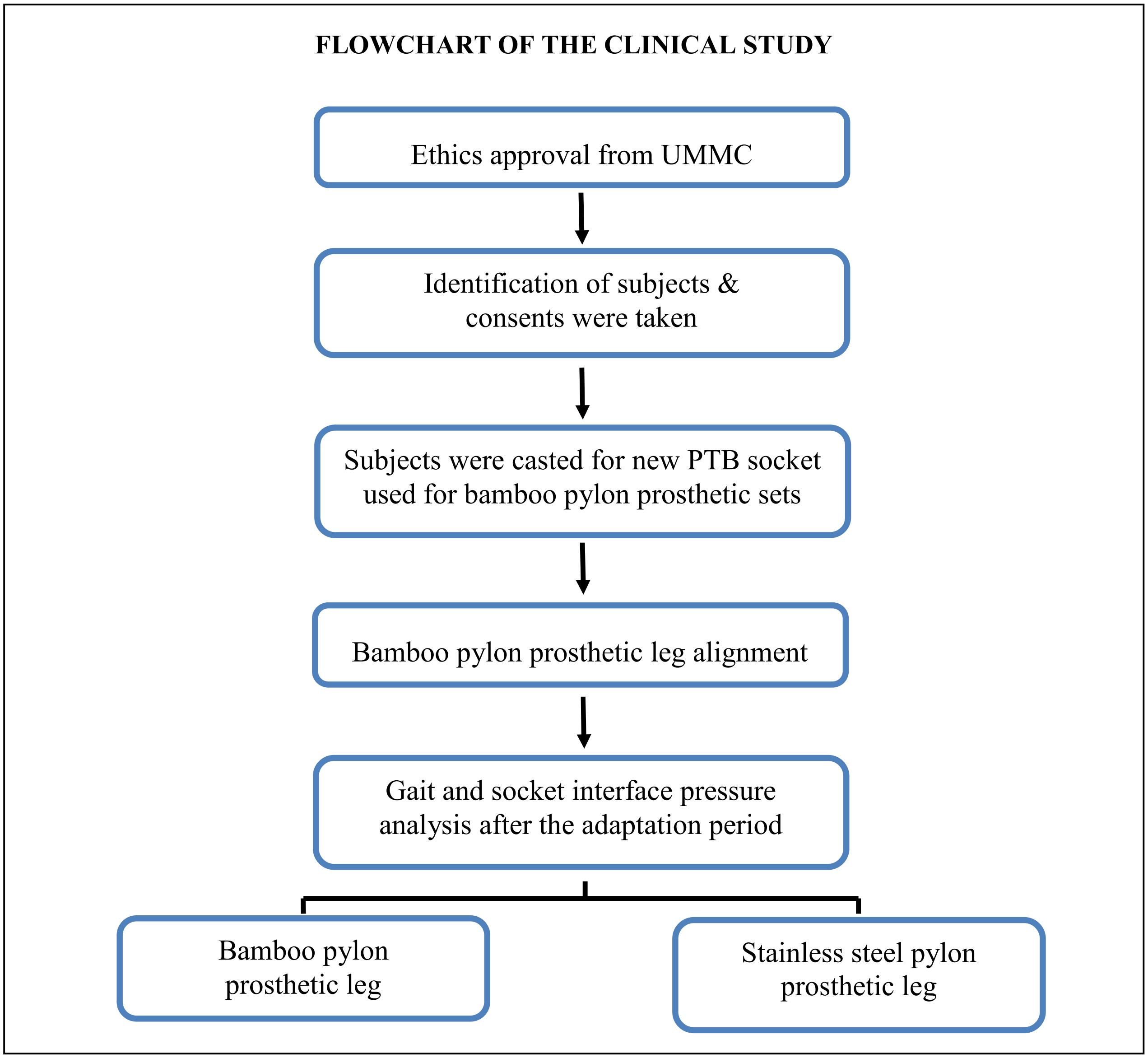


Figure 3.17: Flowchart of the clinical study.

3.3.1 Fitting Bamboo Pylon to the Subjects

Subjects involved in the study were chosen from those who were wearing similar component of transtibial prosthesis. The components were PTB socket with liner, Stainless Steel pylon and SACH foot. Standardisation of the components was made as to minimise potential errors due to different component materials and designs. Each subject was given a new socket and a SACH foot to match bamboo pylon approximately four weeks before the clinical assessments. This was an adaptation period for the subjects to practice on the new prosthesis set in order to obtain optimal results in gait and socket interface pressure analysis as compared to their conventional prosthesis sets.

The new transtibial prosthetic leg was fitted to the amputee subjects at Prothetics and Orthotics Workshop, UMMC. Due to maximum possible control over the variables involved, one prosthetist was responsible for stump casting and subsequent cast rectification for all patients. Manufacture of the prostheses was carried out by one skilled senior prosthetic technician following standard procedures. The prosthetist also made sure the patient was in healthy condition and that no pressure wounds were observed on the residual limb. Production of PTB socket had been described in Subchapter 1.3.

Once the socket was ready, the same prosthetist would install the PTB socket with other prosthetic components and worked on the alignment. The main principle of alignment is to position the prosthetic socket with respect to the foot so that undesirable patterns of force applied to the residual limb were avoided. Another purpose is to produce a normal pattern of gait (Lannon, 2003). Basically, there were three types of alignment; bench, static and dynamic alignment. At first, the prosthesis was bench aligned to the settings recommended by Radcliffe and Foort (1961). Although, good bench alignment alone did not guarantee the patient efficiency and comfort during gait, but it provided a good starting point of prosthesis fitting. Proper bench alignment also meant fewer changes to the prosthesis when initially aligned to the patient especially if the materials were made of wood-based components (Lannon, 2004).

Once bench alignment was complete, the prosthesis must be aligned to the patient in static standing position, therefore not moving. The goal of the static alignment procedure was to place the socket in an optimum position in relation to the prosthetic foot at normal stance. In the static alignment, the weight bearing must be equally distributed between the prosthetic limb and the intact limb.

Assuming a successful static evaluation, a dynamic evaluation followed. During the dynamic alignment, the patient walked while the prosthetist observed the impact on the gait kinematics (Lusardi & Nielsen, 2007). The alignment of the prosthesis depended on the prosthetist skills and experience and also the patient's feeback. To modify the alignment, the prosthetist adjusted the setscrews located on the lower and upper part of the bamboo pylon adapters.

3.3.2 Systems Preparation

Clinical evaluations were done in Motion Analysis Laboratory, Department of Biomedical Engineering, UM. Two systems involved were the gait analysis system and socket/stump interface pressure analysis. Both were utilised to evaluate full biomechanical changes of gait and socket interface pressure between the two different pylons, stainless steel and bamboo.

3.3.2.1 Gait Analysis System

Three-dimensional biomechanics of lower limb of each participant was recorded by using a commercial motion capture coordination known as VICON motion capture System ® integrated with two KISTLER ® force plates and Nexus 1.3 software. The VICON System provided kinematic data for instance angular position, velocity and acceleration while the KISTLER plates gave kinetic information like ground reaction force (GRF) and moment. This integrated VICON system connection is shown in Figure 3.18. Motion capture system within this study consisted of six specialized infra-red, high speed video cameras, Model FX-20. All cameras were mounted about 2.5 meters from the ground to provide a capture volume with length, width and height of 4 m, 4 m, and 2m respectively (Figure 3.19). A capture volume covered an area where any point within it could be detected by at least 2 cameras in order for the system to reconstruct a 3D model of the point. In video acquisition, the FX-20 cameras tracked and resolved the 3D coordinates of small reflective spheres attached to the participant's body segments and joints to construct human 3D model. This 3D model was determined by using Plug-In-Gait template in the Nexus 1.3 software and used for joints range of motion calculation. Force plate is rectangular metal platform that houses force transducers to measure the 3D forces applied to the plate's top surface. The force plates were rigidly embedded into the walkway and its top surfaces were level and equal height with the floor, making it a part of the floor surface. The plates recorded the forces exerted by the participants against the ground with a sampling rate of 1000 Hz. Kinetic data collected from the KISTLER force plates were integrated and synchronized with the VICON Systems ® by using MX Control and MX Ultranet boxes. These boxes provided power, synchronization and communication between all cameras, analog devices and the host PC. There was no time lag between both VICON system and KISTLER force plates as the frame rates were set equally. The advantage of using integrated VICON Systems ® was that it gave a clear view of real time data that were being collected. All the analog signals from the force plates and the 3D view of the retro reflective markers in the capture volume were readily available to the researcher in real time (Mohd Ismail & Abu Osman, 2009).

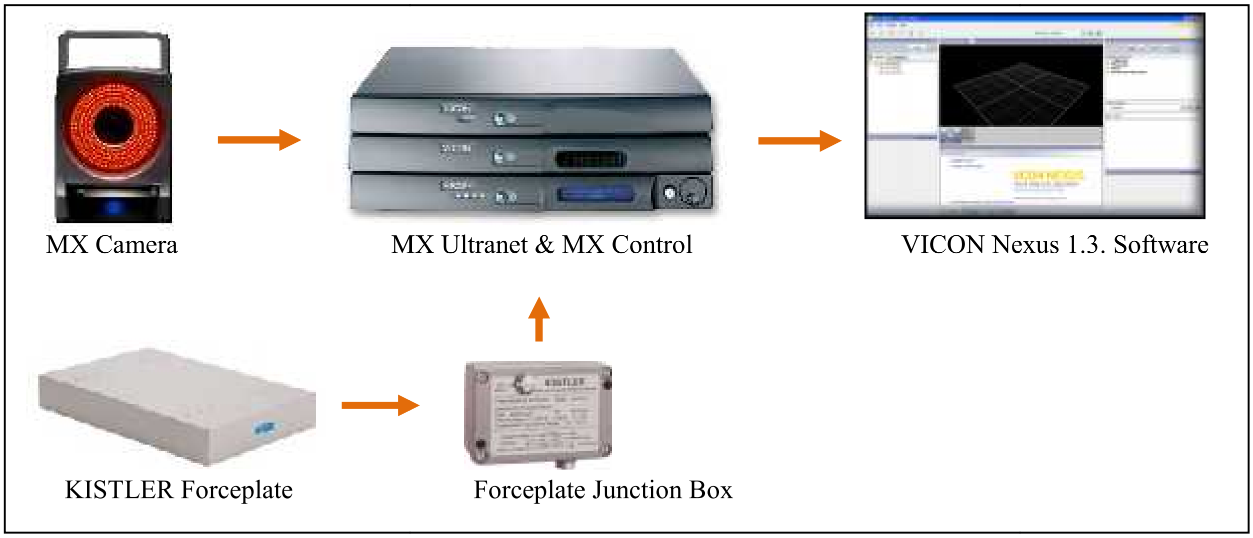


Figure 3.18: VICON Motion Systems architure. From left: The MX camera and Force plate were connected to the Nexus software through MX Ultranet and MX Control.

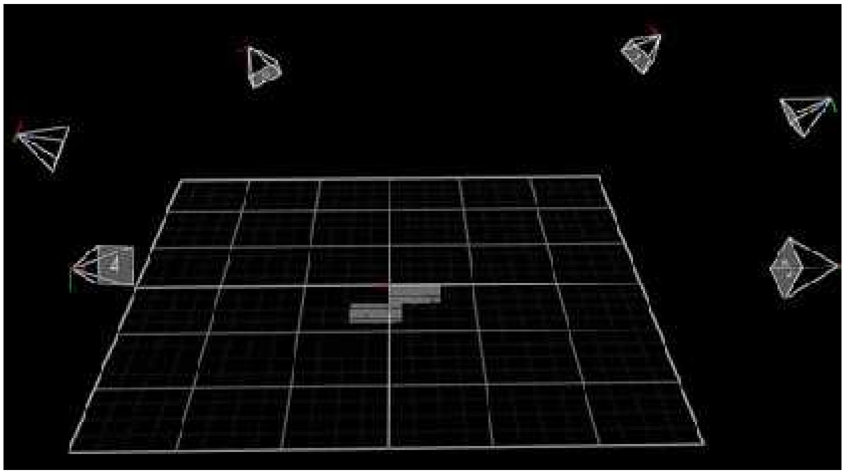


Figure 3.19: Cameras and force plates placement in the motion analysis system.
Note: This placement and volume scale were obtained after the system calibration

The integrated VICON Systems ® calibration was performed prior to gait trial began for each participant. Two types of calibration were done in the study; dynamic and static calibration. Both calibrations used special VICON calibration wand (Figure 3.20). Dynamic calibration worked through an algorithm to establish the scale of the experiment volume by knowing the distance between wand markers. It involved movement of a calibration wand which also known as 'wand dance' throughout the whole volume and allowed the system to calculate the relative positions and orientations of the cameras. This method enabled the system to reconstruct 3D position of one captured marker from 2D MX camera images. Apart from this, static calibration was used to establish an absolute reference of origin (0,0,0) and axes orientation (X,Y,Z). The global origin (0,0,0) represented the center of the capture volume, and the global axes (X,Y,Z) represented the horizontal, vertical and rotation axes of the capture volume. The KISLTER force platform calibration was completed by the manufacture during the device installation. In this study, the force platforms just need to be zeroed each time before a subject step.

Figure 3.20: Calibration wand placed on top of KISTLER force plates for static calibration. Note: Force plates were embedded in floor and covered with rug.

3.3.2.2 Stump/socket interface pressure

F-Socket System® from Tekscan Inc. provided the pressure distribution and forces acting on the interface between the residual limb and the prosthetic socket. The system instantly detected displays and recorded the pressure without disturbing the normal gait of the respective participant. F-Socket sensors, #9811 measured residual limb' pressure distribution using a thin disposable sheet composed of an array of pressure sensing elements or sensels. The sensor was resistive sensor whose electrical resistance was the result of its contact resistance of the pressure sensitive ink. In the study, two F-socket sensors were each slotted in two PCI cuffs (Figure 3.21) which acted as a data transmitter. The PCI cuffs were connected into 2 ports in PCI interface card of a host PC. Data from stump/socket interface pressure was then captured and analysed by using Tekscan Research Software v6.51. The software used a map to convert the pressure detected by the socket sensors into the pressure data displayed in the Real-time window.

Equilibration and calibration were carried out to F-socket sensors prior to the clinical assessments. These two methods were completed by using an air bladder. The air bladder was consisted of an aluminum frame, and thin flexible membrane that was pressurized against the sensor. The purpose of equilibration was to eliminate the variations of output between sensels. As each sensel was unique and might respond slightly different, equilibration was important for data accuracy. In equilibration, an air bladder (Figure 3.22) applied a highly uniform pressure across the entire sensor and each individual sensel to compensate for differences in outputs. Pressure used to equilibrate a sensor was about 100 – 200 kPa. A faulty sensor could be detected during the equilibration step; it showed in the Real-time window map display; a different output between its sensels. After equilibrating the sensor, the calibration procedure was carried out. The calibration was done in the same technique of that equilibration but instead of using a high uniform load, the calibration loaded the sensor with a known weight, which was the respective participant's body mass. This step when observed in the Real-time window would convert the raw digital output of the sensor to actual pressure units, Pascal.

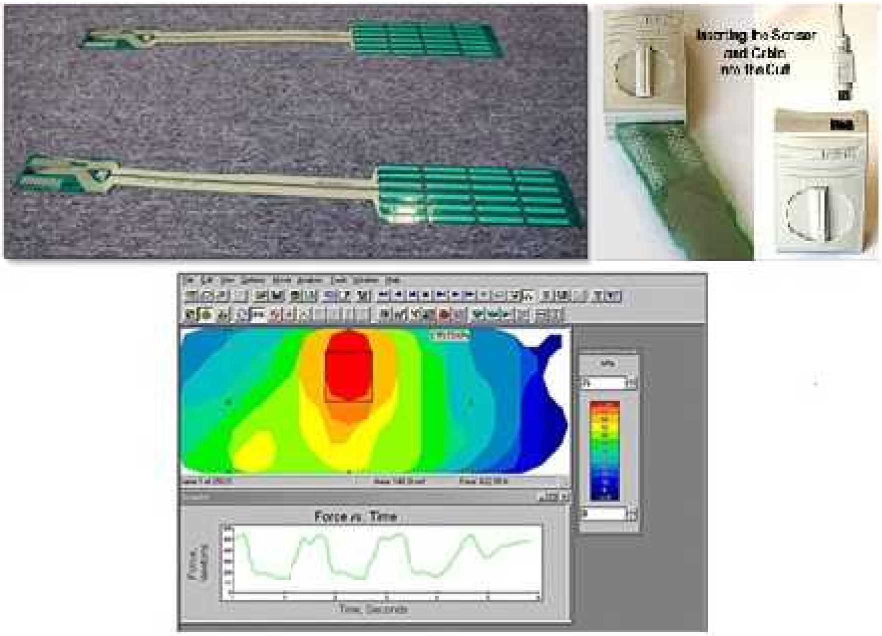


Figure 3.21: From top Left: F-socket sensors #9811 used in the study. PCI cuff held the sensor; it was connected to computer via PCI cable. The bottom picture shows Tekscan Research Software v6.51.

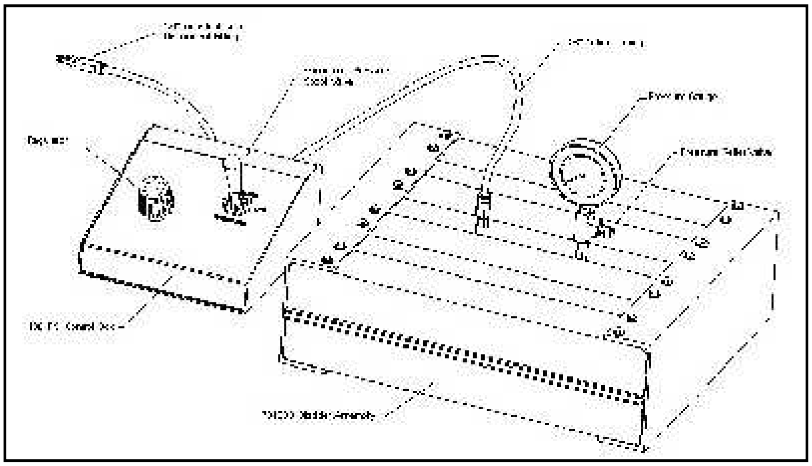


Figure 3.22: Air bladder with its components as equilibration/calibration device in the study.

3.3.3 Subjects

A total of five amputee patients from Department of Rehabilitation Medicine, University of Malaya Medical Centre (UMMC) were enlisted for the clinical experiments. The inclusion criteria of the enrolled subjects were healthy transtibial amputees, which were able to walk independently for at least 15 metres without complication. Subjects with neurological or orthopaedics impairments and walking with support of gait aid were excluded from the trial. Table 3.2 will describe the demographics data of the subjects.

The clinical study of bamboo pylon was approved by the Medical Ethics Committee, UMMC. Prior to participating in the study, the participants were given a verbal and written explanation of the study's protocol by the researcher. They were also explained about the instrumentation used in the study. After the description, participants had the option to continue in the study or drop out at any time. Those that decided to continue signed the University of Malaya (UM) approved consent form (Appendix 2). All subjects were scheduled for clinical evaluations at the Motion Analysis Laboratory four weeks after they got the bamboo prosthetic leg. The four weeks interval was served as their adaptation period and to familiarise themselves with the use of the new prosthetic leg.

Table 3.2: Subjects' Parameters.

Subject	**Age (year)**	**Body mass (kg)**	**Height (m)**	**Years since amputation**	**Amputated side**	**Reason for amputation**	**Prosthetic shank length (cm)**
S1	35	108	1.76	1	Right	Diabetes	25.4
S2	62	55	1.49	4	Right	Diabetes	19.3
S3	57	86	1.72	5	Right	Diabetes	23.7
S4	45	79	1.57	4	Right	Diabetes	22.1
S5	64	100	1.63	7	Right	Diabetes	24.5

3.3.4 Clinical Assessment Protocol

Data acquisition of integrated VICON System® and F-Socket System® were done simultaneously in the study. The goal of the clinical assessments was to evaluate the difference on gait and socket interface pressure distribution between Bamboo prosthetic leg and Stainless Steel prosthetic leg.

First of all, anthropometric parameters of the respective subject were taken. Appendix 3 shows the descriptions of anthropometric parameters and how to measure them. These measurements were entered into the VICON Nexus 1.3 software to assist in the 3D model processing. After being introduced to all the apparatus, F-Socket sensors and motion reflective sphere markers were placed on the participant. F-socket sensors were firstly trimmed to allow good intact and further conformity on top of stump curved surfaces. When trimming a sensor, the red lines within the non-conductive rows and columns on it were carefully cut, avoiding the sensels area. If any of the sensels were cut, they would not be usable, and would not produce any readings. Four F-socket sensors were placed on the subject's residual limb to gain pressure reading from all sides; anterior, posterior, medial and lateral. Pressure from the distal part of the residual limb was not taken. In order to prevent sensor movement, the sensor were sprayed with non-aggressive 3M Spray Mount Repositionable Adhesive before applied it on subject's stump. The sensor was then wrapped with a thin, flexible skin sock before putting the prosthetic leg on (Figure 3.23). The advantage of putting the sensors on subject's stump instead of the inner of hard socket, was that they did not have to be removed and would be re-used when the subject changed to the other set of prosthetic leg. Sensors would only be changed if faulty was detected at the Real-time window display.

With a two-PCI Cuff F-Socket System, the data from anterior-posterior part was recorded concurrently before recording the data from medial-lateral part. The cuffs were fastened with Velcro straps onto the subject's thigh and cables for PCI cuffs were handled by a research assistant when subject walked. This step was carried out to minimise interference during gait trials. There was no need to remove the prosthetic socket when the two sensors exchanged as they were simply removed from the cuff units and then reattached to the sensors from medial-lateral positions.

Figure 3.23: F-socket sensor placement. It covers anterior, posterior, medial and lateral part of subject's residual limb and secured by skin sock.

After the subject had put on the prosthetic leg, sixteen 14 mm motion reflective markers were placed on the subject's lower limb body to mark bone segments (Figure 3.24). Table 3.3 describes the placements of the markers used for the study. A diagram for full body marker placements with label is shown in Appendix 4. Markers were adhered to the subject's body with hypoallergenic double-sided tape. VICON system was completely passive and required no cables to be attached to the subject.

Figure 3.24: Marker placements at front and back of a subject. PCI cuffs were fastened to subject with Velcro strap. Cables of F-Socket system were handled by a research assistant during gait trial.

Table 3.3 Markers placements description

Marker label	Definition	Position
LASI/RASI	Anterior superior iliac spine/ASIS	Placed directly over the ASIS
LPSI/ RPSI	Posterior superior iliac spine/PSIS	Placed directly over the PSIS
LTHI/ RTHI	Thigh	Placed over the lower lateral 1/3 surface of the thigh
LKNEE/ RKNEE	Knee	Placed on the lateral epicondyle
LTIB/ RTIB	Tibia	Placed over the lower 1/3 of shank
LANKL/ RANKL	Ankle	Placed on lateral malleolus
LTOE/ RTOE	Toe	Placed over the 2nd metatarsal head
LHEEL/ RHEEL	Heel	Placed on the calcaneous bone

Note: L and R in front of all the labels indicate left and right side respectively.

Prior to data acquisition, subject calibration was carried out for the VICON System® based on the VICON Skeleton Template (.vst file) from the manufacturer. In the capture volume, subject stood in a stationary neutral pose, to enable the VICON System® to determine the location of all sixteen markers. Nexus then automatically displayed sixteen nodes in the 3D Perspective view pane from the detected markers. By labelling all the nodes, the system would generate 3D skeletal frame of the respective subject (Figure 3.25). All calculations of range of joints motions and joints' forces were calculated based on this vst file.

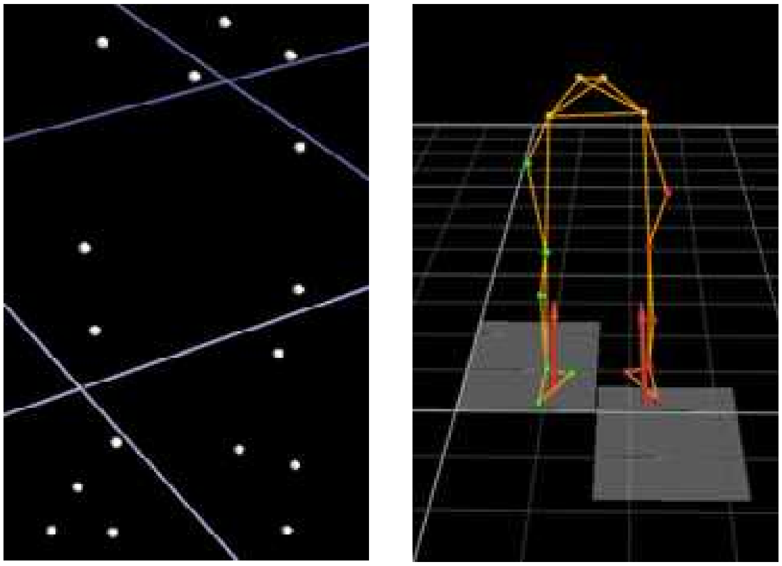


Figure 3.25: 3D skeletal frame was generated from nodes after subject calibration was done in the Nexus software.

Once the systems and the subject were ready, the subject was acquired to walk several times across the two embedded KISTLER force plates before the gait trials started. This was done to familiarise the subject with the set-up, minimise discomfort and observe any fault in the system set-up. Ten gait trials with self selected speed were captured for the analysis and each one would produce about five to six gait cycles. The researcher would obtain socket interface measurements from anterior-posterior part of residual limb at the first five gait trials and medial-lateral on the other five trials. Subject was also ascertained to step on both KISTLER force plates without being informed of the locations.

All data were tracked simultaneously and in Real-time windows by using two side by side hosts PC for each system. Post experiment evaluations will produce kinetic and kinematic data of the subject; range of joints motions, Ground Reaction Forces and socket interface pressure distribution which were all processed and analysed through the F-Scan 6.11 and Vicon Nexus 1.3 software.

3.4 Statistical Test

T-Test and a single factor analysis of variance (ANOVA) were used to determine statistical significance between subjects walking using bamboo and stainless steel proshetic legs. The parameters analyzed were bamboo mechanical strengths, spatio-temporal parameters, GRF, joint angles and socket interface pressure. Statistical difference between prosthetic and sound leg for both pylon materials used in gait were also analysed. The statistical analysis was performed in SPSS ® software version 12.0. Significant level was set at 0.05.

Chapter 4

Results and Discussions

Chapter 4 features the results of the mechanical tests and the outcome of clinical evaluations obtain from the preceding experiments. The chapter interprets the experimental results in order to reflect the objectives of the study, which is to evaluate the mechanical strength of bamboo pylon whether it is appropriate as a prosthesis component and to compare the efficiency of gait between the Bamboo prosthetic leg (BPL) and Stainless Steel prosthetic leg (SPL).

4.1 Variables

There were six sets of data discovered from the mechanical and clinical assessments. Table 4.1 shows the list of all variables used within the study. Three variables were chosen as key data to support the final research outcome and categorized as follow:

- Primary data : Mechanical strength properties; tensile, compressive and flexural modulus.
- Secondary data : Ground Reaction Forces (GRF) of vertical, anterior-posterior (A/P) and medial lateral components from the gait trials.
- Tertiary data : Range of motion (ROM); hip, knee and ankle flexion-extension (F/E) from the gait trials.

Table 4.1: List of variables

Outcome Category	Variable	Units
Mechanical Strength	Tensile	
	Max. tensile strength	σ, MPa
	Tensile modulus	*E,* Gpa
	Compression	
	Max. compressive strength	σ, Mpa
	Compressive modulus	*E,* Gpa
	3-Point Bending	
	Max. bending strength	σ, Mpa
	Bending modulus	*E,* Gpa
FEA	Max. Stress	Mpa
	Max. Displacement	mm
Spatio-Temporal	Cadence	Step/min
	Step length	m
	Step width	m
	Walking speed	m/s
GRF	Vertical GRF	
	Force normalised	N/kg
	Percentage of stance time	%
	A/P GRF	
	Force normalised	
	Percentage of stance time	N/kg
		%
ROM	Hip, knee and ankle; flexion-extension	Degrees
	Minimum	Degrees
	Maximum	
Residual Limb Pressure	Anterior, posterior, medial and lateral areas	
	Minimum	kPa
	Maximum	kPa

4.2 Mechanical Strength

Bambusa Heterostachya is found in all states of Peninsular Malaysia, which has about 70 different species of bamboo. Bamboo culm is strong and has found various applications; from basket making to house construction. The length of the internodes varies appreciably along the tree, while the wall is up to 20 mm thick. This plant has a wide ecological tolerance, able to withstand severe harvesting and was chosen for the study because of its plentiful supply. Bamboo is known to possess good strength to weight ratio and a fast growth rate. It takes only about one quarter of the time taken by trees to reach maturity and with present rate of deforestation, bamboo may become an increasingly important substitute for timber in the near future (Ali, 1984).

In this project, mechanical properties of dried bamboo and bamboo pylon of *Bambusa Heterostachya* were investigated to demonstrate whether it was suitable as a new low-cost pylon material. Fifty samples from each dried bamboo and bamboo pylon category were tested under tensile, compression and 3-point bending experiments. Generally, it was observed that the mechanical strength was lower for the cases with nodes within the specimen length compared to the cases where there were no nodes within the specimen length (Subrahmanyam, 1984; Lee et al., 1994). Therefore, all the specimens within the study were prepared without the nodes. Specimens of bamboo pylon had an average specific gravity of 0.52 and the average moisture content was 12 percent. The average percent shrinkages of the specimens from green to bamboo pylon were 18.21%, 9.25% and 0.02% in radial, tangential and longitudinal directions, respectively. The results of mechanical tests are presented in Table 4.2.

Table 4.2: Mechanical properties of dried bamboo and bamboo pylon

Mechanical Properties	**Units**	**Dried Bamboo**	**Bamboo Pylon**
Tensile Yield	σ_t ,MPa	200.5 ± 3.1	230.3 ± 6.2
Tensile Modulus	E_t , GPa	43.0 ± 6.2	49.5 ± 6.9
Compression Yield	σ_c , MPa	120.0 ± 4.6	132.6 ± 3.3
Compressive Modulus	E_c , GPa	26.2 ± 4.0	30.7 ± 4.7
Flexural Yield	σ_b , MPa	192.8 ± 8.2	220.6 ± 3.5
Flexural Modulus	E_b , GPa	23.1 ± 5.5	27.2 ± 4.5

No. of samples, N = 50
Values are mean ± standard deviation
No significant difference for both groups ($p > 0.05$)

The mean strength, σ_t of the dried bamboo was 200.5 MPa (SD ±3.1 MPa) and 230.3 MPa (SD ±6.2MPa) for the bamboo pylon. Modulus tensile, E_t for dried bamboo and bamboo pylon were 43.0 GPa (SD ±6.2 GPa) and 49.5 GPa (SD ± 6.9 GPa) respectively. Tensile specimens that were tested under ASTM D 143-94 showed similar stress-strain curves between both categories (Figure 4.1 and Figure 4.2). Basically, the tensile loads increased linearly with the increasing strain until the point of ultimate load; when bamboo fibres underwent breakage and exhibiting brittle fracture. The stress-strain curves showed sharp, staggered decreases beyond the rupture points. Tensile fracture of bamboo was mainly longitudinal cracking in the same orientation of the fibres. The tensile curves pointed that bamboo was a brittle material which had no strain-harden property. Rosler et al. (2007) explained that the breaking strength and the ultimate strength of one brittle material were equal. In this type of material, tensile strength was normally negligible and the use of the material was mostly utilized on other kind of mechanical strength.

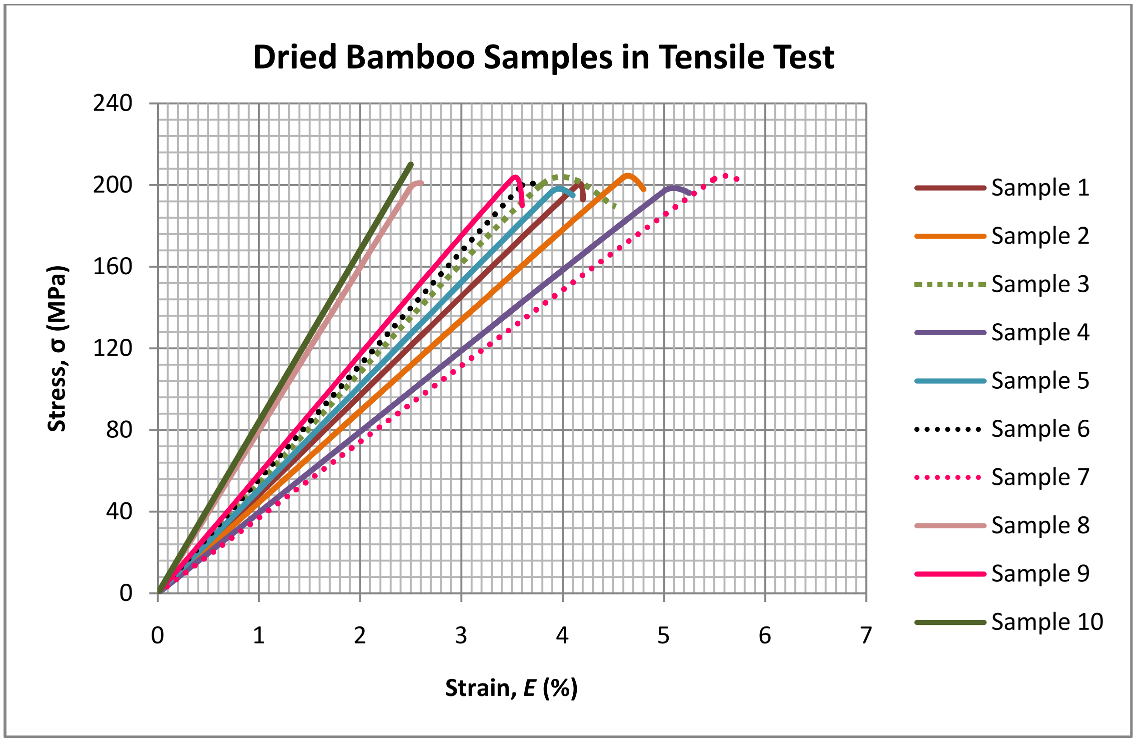


Figure 4.1: Stress-strain curves for ten dried bamboo samples under tensile load.

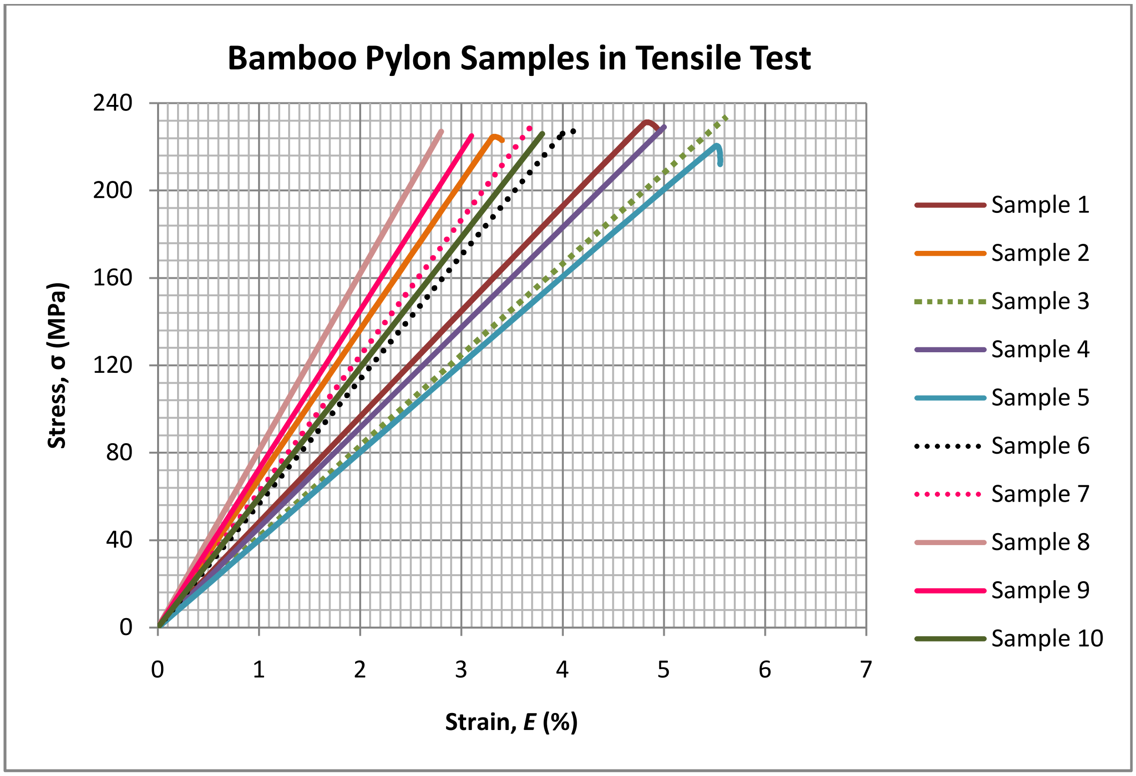


Figure 4.2: Stress-strain curves for ten bamboo pylon samples under tensile load.

Compressive properties were investigated by using ASTM D 3410 standards. To ensure that fractures occurred in the middle portion of the test laminate, the two ends of a sample were clamped with pylon adapters with diameter of 30 mm (SD ±4.5 mm). The sample was then aligned to the Universal Testing Machine with the help of a pair of longitudinal strain gauges attached to the sides, the position adjusted until the gauges showed identical strain to guarantee the absence of bending moment. Mean compressive strength, $\boldsymbol{\sigma_c}$ observed in dried bamboo, being 120 MPa (SD ±4.6 MPa). Its compressive modulus, $\boldsymbol{E_c}$ was 26.2 GPa (SD ±4.0 GPa) which was less than its tensile modulus. Figure 4.3 shows the stress-strain curves for dried bamboo samples under compression stress.

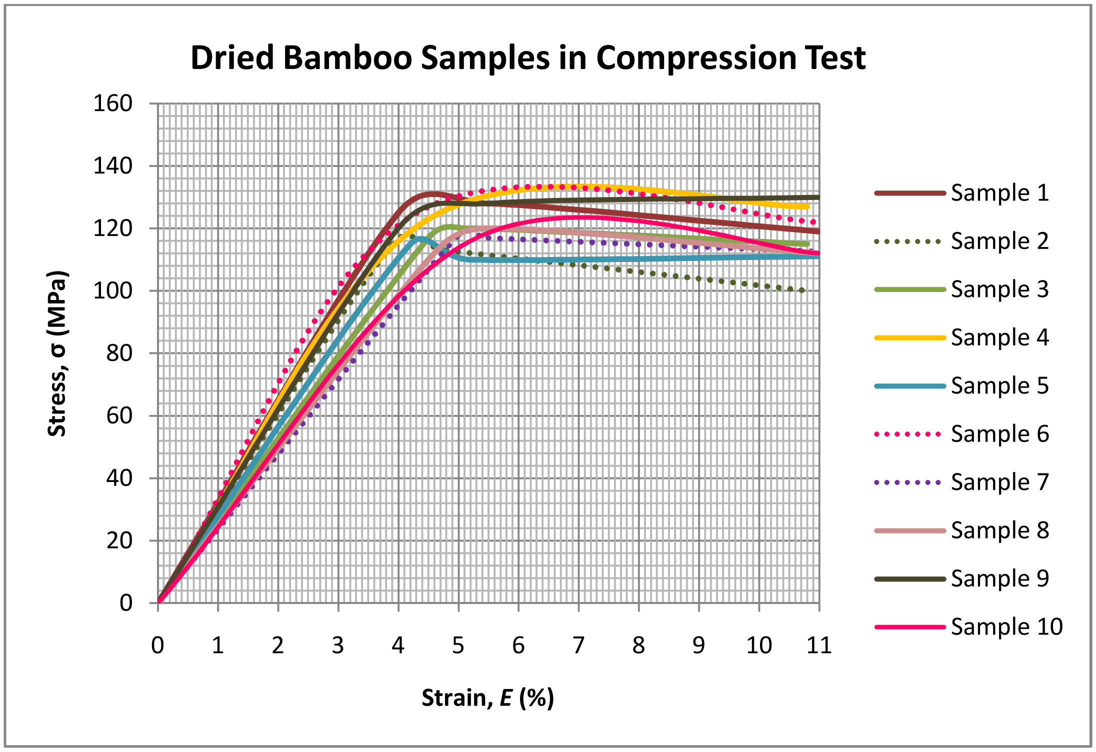


Figure 4.3**:** Stress-strain curves for ten dried bamboo samples under compression load.

In bamboo pylon the compressive strength, $\boldsymbol{\sigma}_c$ and modulus, $\boldsymbol{E}_c$ were 132.6 MPa (SD ±3.3 MPa) and 30.7 GPa (SD ±4.7 GPa) respectively. Even though dried bamboo and bamboo pylon had lower compressive strength than the tensile strength, the stress-strain curves showed that both bamboos had better physical property under compression loads with appearance of strain-hardening region (Figure 4.4).

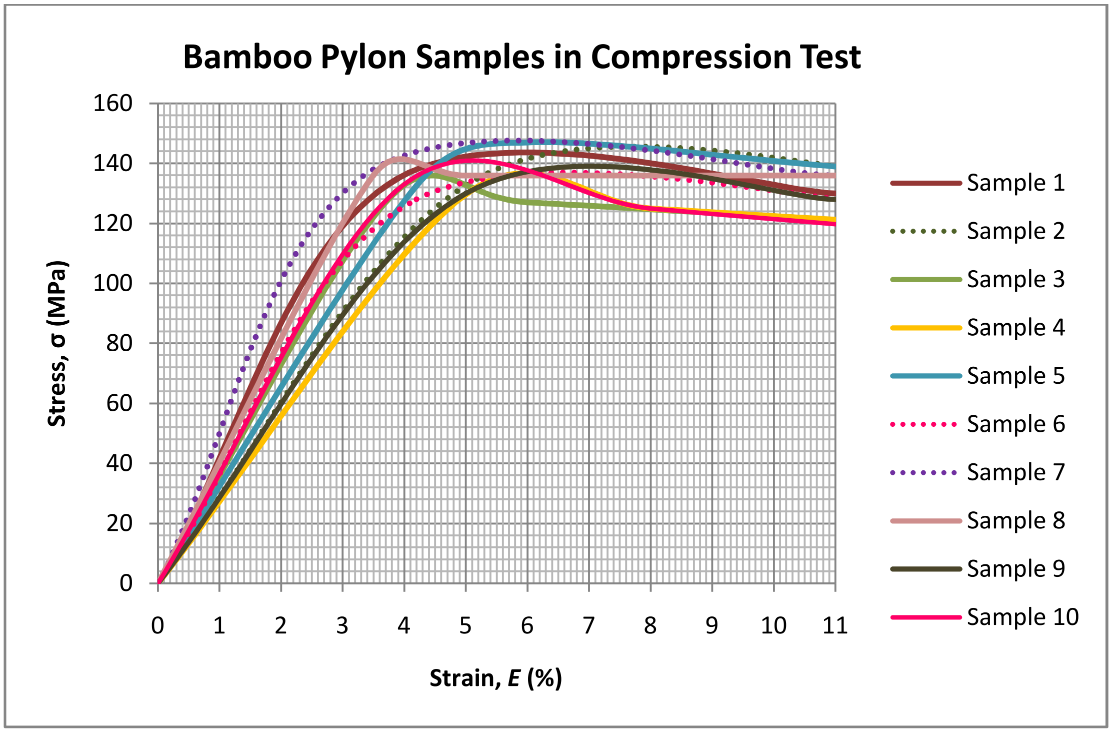


Figure 5.4: Stress-strain curves for ten bamboo pylon samples under compression load.

A material with strain-hardening region will not rupture at the ultimate strength due to its plastic-deformity property (Verterra, 2007). This shows that the bamboo, when applied under compression load would behave like steel and any other ductile materials; which was different when it was applied under tensile load. The difference between these was possible as bamboo is not a homogenous substance unlike the industrial materials as Stainless Steel and Titanium. These industrial materials may possess equal strength under compressive and tensile stress as result of their homogeneity design.

The 3-point bending test was performed by using ASTM D 3043 – 95 standards. The mean flexural strength, **σ_b** was 192.8 MPa (SD ±8.2 MPa) and the flexural modulus, **E_b** 23.1 GPa (SD ±5.5 GPa) for dried bamboo while mean flexural strength, **σ_b** was 220.6 MPa (SD ±3.5 MPa) and the flexural modulus, **E_b** 27.2 GPa (SD ±4.5 GPa) for bamboo pylon. Stress-strain curves for 3-point bending test of both categories are shown in Figure 4.5. Bending fractures concentrated in the middle of the sample where load was applied. The stress-strain curve in this study showed an early linear segment, followed by a non-linear segment beyond 50% of fracture load until ultimate strength was applied. Following that, an irregular, staggered decrease in load was observed.

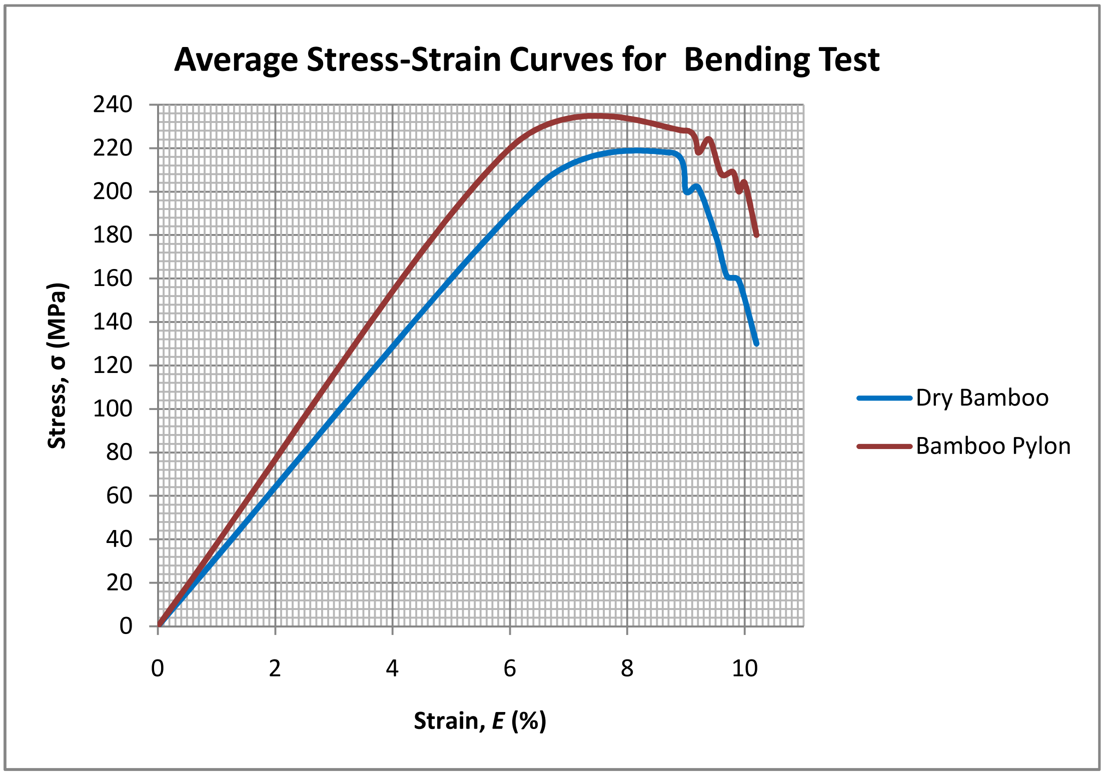


Figure 4.5: Stress-strain curves for 3-point bending test of dried bamboo and bamboo pylon. Graphs are average value of 50 samples (N=50).

The bamboo pylon in this study was treated with hot oil. The oil treatment has been used for various wood products to improve their dimensional stability and durability against bio-deterioration. Different types of oil treatment process has been investigated and it was found that process conditions, such as wet or dry application and types of oils and their temperatures were major parameter influencing overall properties of the treated products.

Sulaiman et al. (2006) had evaluated influence of treatment process on adhesion of laminated bamboo by using vinyl urethane adhesive. Pre-treatments of the test specimens were conducted before mechanical test that included hot soaking. Analysis of oil absorption was done by using Weld emission scanning electron microscope. The results showed that as oil treatment was more severe, over 200^{o}C for more than 120 minutes, the delamination would increase thus reducing the mechanical properties. The reason for the lower mechanical strength might be the presence of oil in the cell which also contributed to the weight gained. The presence of oil could be seen as the weight of samples increased after treatment indicating a gain in weight after heat treatment. The presence of oil could be seen in FESEM micrographs as shown in Figure 4.6.

Treated oil penetrated in the cell wall as well as in the cell lumen. The penetration of oil in the cell wall and lumen interfered with interfacial surface of bamboo and this reduced the adhesion. Thus, the bamboo pylon for the trantibial prosthesis was treated at 120^{o}C to 180^{o}C for less than 90 minutes to avoid the circumstance.

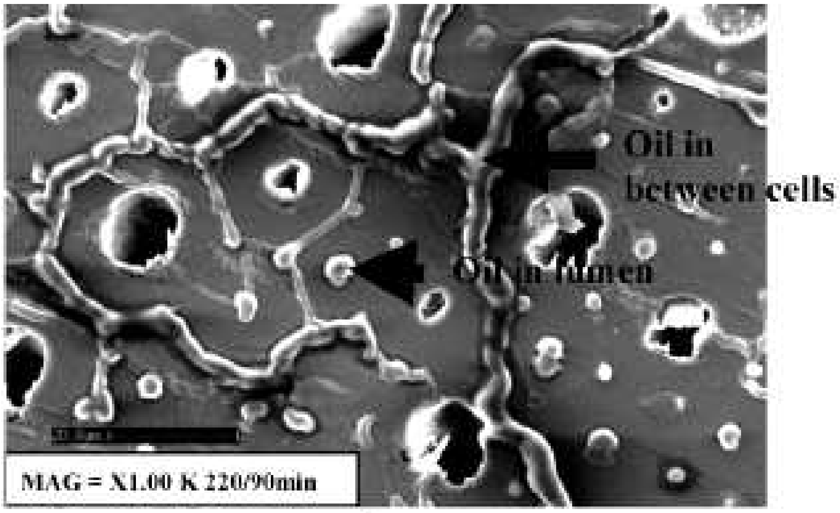


Figure 4.6: Cross section of bamboo showing location of oil in between the cell wall and in the lumen of the cell. Reproduced from Sulaiman et al., 2006.

Generally, the mechanical properties of bamboo pylon under tensile, compressive and flexural loads were higher when compared to dried bamboo. However, there was no significant difference ($p > 0.05$) when comparing the means of both groups with T-Test. No difference was found when comparing mechanical properties between different culms' coordinates too ($p > 0.05$) which was differ than Ahmad (2000). This was probably due to different bamboo species used in the study. The author used Calcutta Bamboo which was reported to have significant different in culm diameters between the coordinates. Bamboo, being a biological material like timber, was subjected to greater variability and complexity, due to various growing conditions as moisture, soil, culm coordinates, fibre bundles and the manner of their scattering. The percentage of fibres increased from the bottom to the top of the culm. These fibres played major role in determining the bamboo hardness (Abullah, 1983).

Stainless Steel and Aluminum are widely used in conventional trantibial pylon. In annealed state, the mechanical strength of Aluminum is 48 MPa (Shasmin et al., 2008). Other material that recently use in prosthetic pylon is fibre reinforced plastic which has Young's modulus at 12.23 GPa (Hahl et al., 2000). Comparing to these two conventional substances, bamboo is expected to be a good alternative for the new pylon material in transtibial prosthesis. With yield compressive stress and Young's modulus of 132.6 MPa (SD ± 3.3 MPa) and 30.7 GPa (SD ± 4.7 GPa) respectively, bamboo pylon is three times stronger than fibre reinforced plastic and two times stronger than Aluminum. Figure 4.7 shows the Young's modulus for various materials to compare with bamboo pylon.

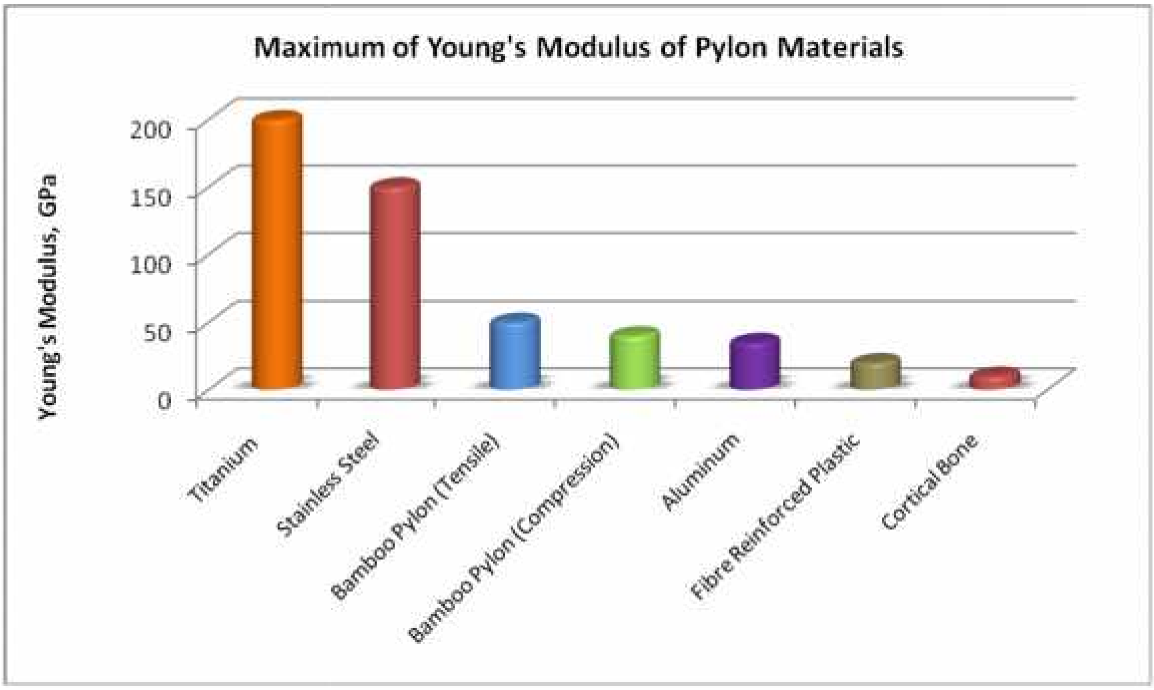


Figure 4.7: Young's modulus for conventional pylon materials, bamboo pylons and bone. Bamboo pylon has higher Young's Modulus than Aluminum and Fibre reinforced plastic. Reproduced from Rho (1993)

4.3 Finite Element Analysis

The FEA was performed to simulate the actual condition for transtibial amputee when walking with the BPL. Failure criteria of the BPL were made based on two criteria; Von Mises stress test and the displacement of the model due to the applied loading condition. The von Mises stress was used because this stress values "allow the most complicated stress situation to be represented by a single quantity" (Shigley et al., 2004). In essence, the von Mises stress values are a combination of all of the stress components present in the bamboo pylon model into one value. This is a good measure of the overall reaction of the BPL to the loading condition, because it takes all of the stress components and outputs one stress value. This value was compared to the Yield Strength to ensure that the material did not exceed the stress limit presented from the experimental tests.

As load of 100 kg was applied directly on the top part of the bamboo pylon with inclination of 15^o as socket to feet alignment, the maximum stress produced from the condition was 15.6 MPa and the maximum displacement resultant from the condition was 5.66 cm. Figure 4.8 and Figure 4.9 show the diagrams from the Patran FEA software of the Von Mises stress and displacement distribution. Since the maximum stress was lower than the Yield compressive strength which was 132.6 MPa and the 5.66 cm was considered as a very minimal displacement (Richardson, 2008), the bamboo was considered as safe and would make an adequate pylon material.

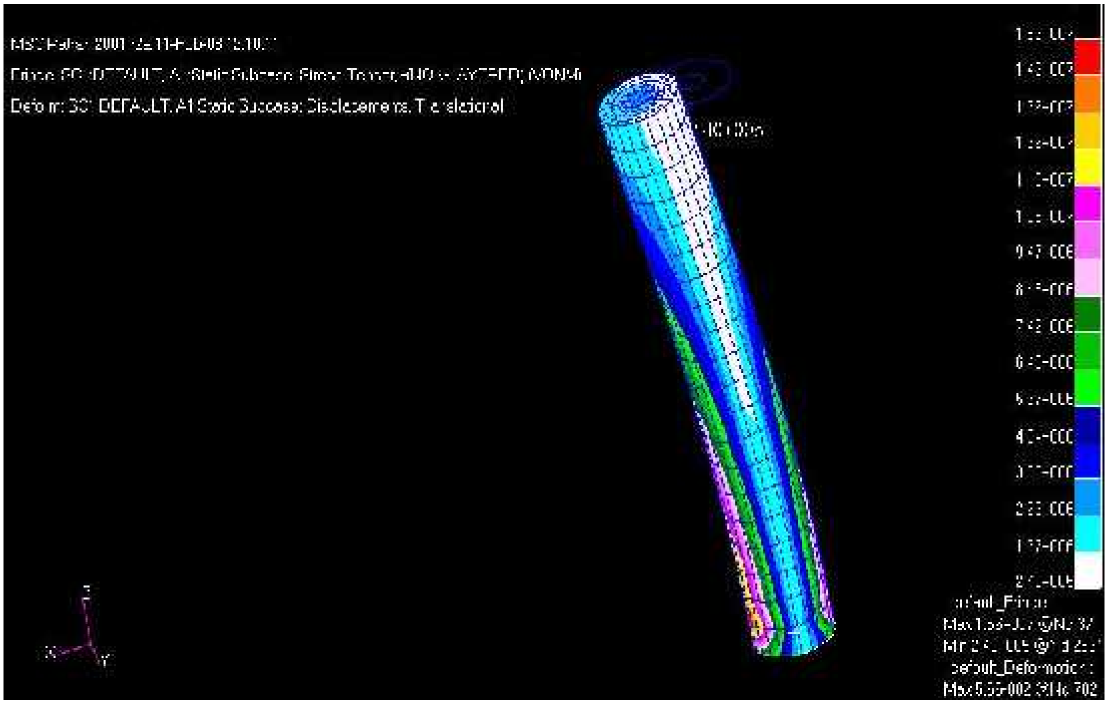


Figure 4.8: Von Mises stress for bamboo pylon under 100 kg loads.

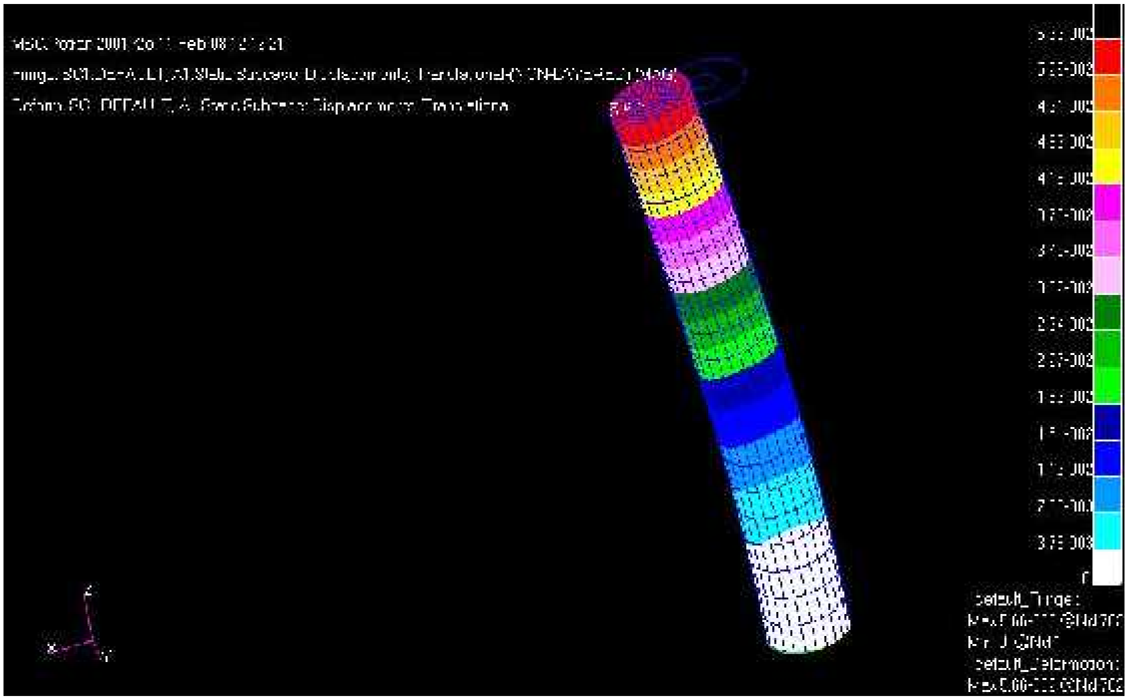


Figure 4.9: Maximum displacement for bamboo pylon under 100 kg loads.

4.4 Spatio-Temporal Parameters

Six subjects with unilateral transtibial amputation were enrolled in this study. Their average age was 52.60 years (SD ±12.30 years). Their average height and mass were 163.00 cm and 75.40 kg, respectively. The subjects were on average 4.20 years since amputation and walked without an assistive device. Analyses for spatio-temporal parameters were categorized into 4 components; prosthetic and sound side from both prosthetic legs. Data was averaged from at least three gait cycles from each subject. Statistical test was performed by using one-way ANOVA, with significant level set at 0.05.

For the spatio-temporal parameters tabulated in Table 4.3, there was no significant difference ($p > 0.05$) found between prosthetic and sound side when subjects walking with either BPL or SPL. Values for all sound sides were slightly higher than prosthetic side except for step length and step width for BPL which slightly higher from the sound side. Significant difference between BPL and SPL category was found in the step width ($p = 0.01$). Cadence, step length and walking speed of BPL were comparable to SPL ($p > 0.05$). All values from walking with SPL showed higher values compared to BPL. Figure 4.10 shows the box plots for cadence. Cadence for sound side with SPL was the highest value among all while cadence for prosthetic side with BPL being the lowest. The cadence value between sound side of BPL and prosthetic side of SPL was almost equal.

It has not been shown that the use of lightweight prosthesis is beneficial for amputees. None of the previous studies (Godfrey et al., 1977; Skinner and Mote, 1989; Hale, 1990; Czerniecki et al., 1994) evaluating the effect of prosthetic weight on gait in amputees has shown an improvement in subject preference, walking speed or energy expenditure with a lighter prosthesis.

Table 4.3: Temporospatial data for subjects.

Variables	**Units**	**BPL**		**SPL**	
		Prosthetic Side	**Sound Side**	**Prosthetic Side**	**Sound Side**
Cadence	steps/min	73.59 ± 4.55	76.79 ± 4.33	76.80 ± 6.91	81.52 ± 9.05
Step Length	m	0.38 ± 0.08	0.37 ± 0.16	0.40 ± 0.14	0.47 ± 0.17
Step Width	m	0.25 ± 0.04	0.24 ± 0.04	0.33 ± 0.10*	0.33 ± 0.12*
Walking Speed	m/s	0.45 ± 0.13	0.48 ± 0.13	0.57 ± 0.20	0.59 ± 0.18

Values are mean ± standard deviation from (N=6)

*Significant difference ($p < 0.05$) between category (BPL and SPL)

No significant difference was recorded between legs within same category ($p > 0.05$)

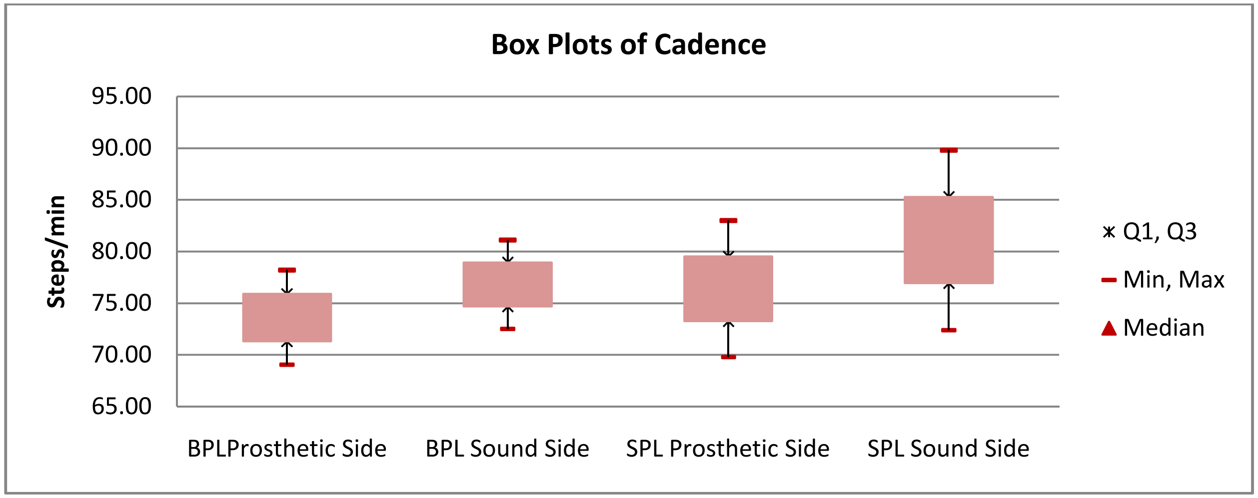


Figure 4.10: Box Plots of subjects' cadence.

Meikle et al. (2003) indicated that short-term intervention with increased prosthetic mass had no significant adverse affect on gait speed. Therefore, there was no different in spatio-temporal parameters detected when subjects wore BPL which was lighter than SPL during the gait analysis.

4.5 Ground Reaction Forces

Although GRF were collected in the three directions, only the vertical and A/P directions were analysed. Medial-lateral forces are important forces, but were left out in order to focus on the forces where greater effects were identified. Figure 4.11-4.14 compares the prosthetic and sound side mean vertical and A/P GRF curves for both the BPL and SPL used for one subject (S3), normalized by the body weight. When S3 walked with SPL, the vertical GRF of sound side produced classic curve (Figure 4.11) as a normal subject walked barefoot (Whittle, 1996) and the prosthetic side showed some asymmetrical curve from the time of initial contact to the loading phase (Figure 4.12). Apart of this, when S3 walked with BPL, the vertical GRF was asymmetrical on the sound leg while producing flat curve between loading to terminal stance phase on the prosthetic leg. A/P GRF for S3 displayed relatively identical curves on the sound side when walking with BPL and SPL (Figure 4.13). On the other hand, breaking force was lower on the prosthetic side when walking with BPL than SPL. The propulsion forces on the prosthetic side were equal for both prosthetic legs (Figure 4.14). These observations were similarly noted across all subjects (Table 4.4).

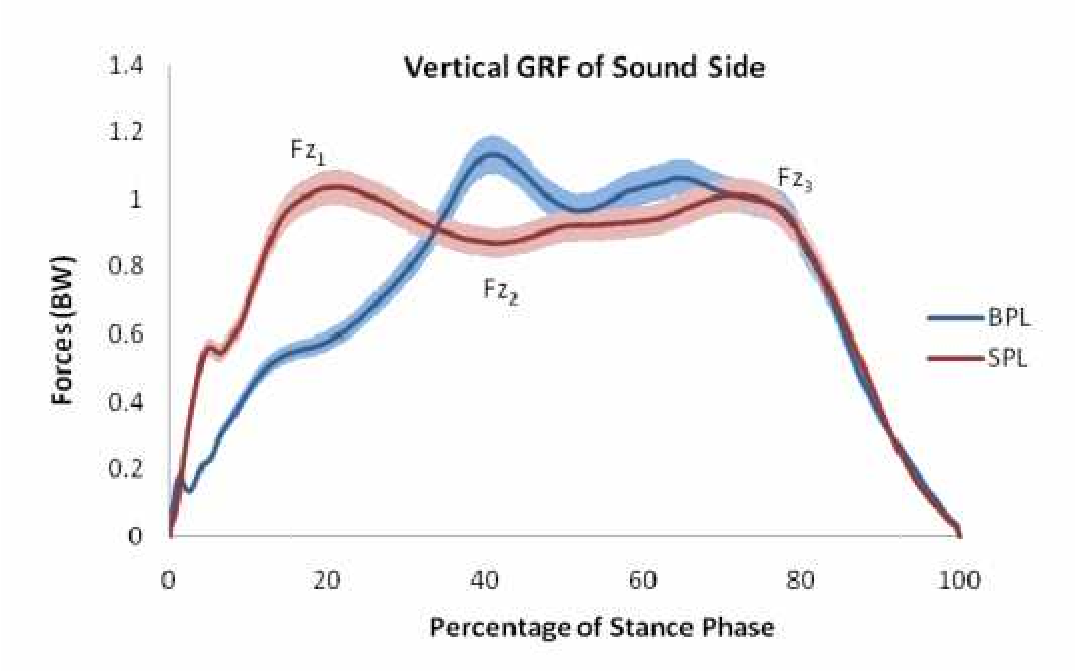


Figure 4.11: Vertical GRF of sound side for one subject walking using the BPL and SPL at self-selected speed. GRFs were normalized by body weight (BW). Shaded area represents standard deviation.

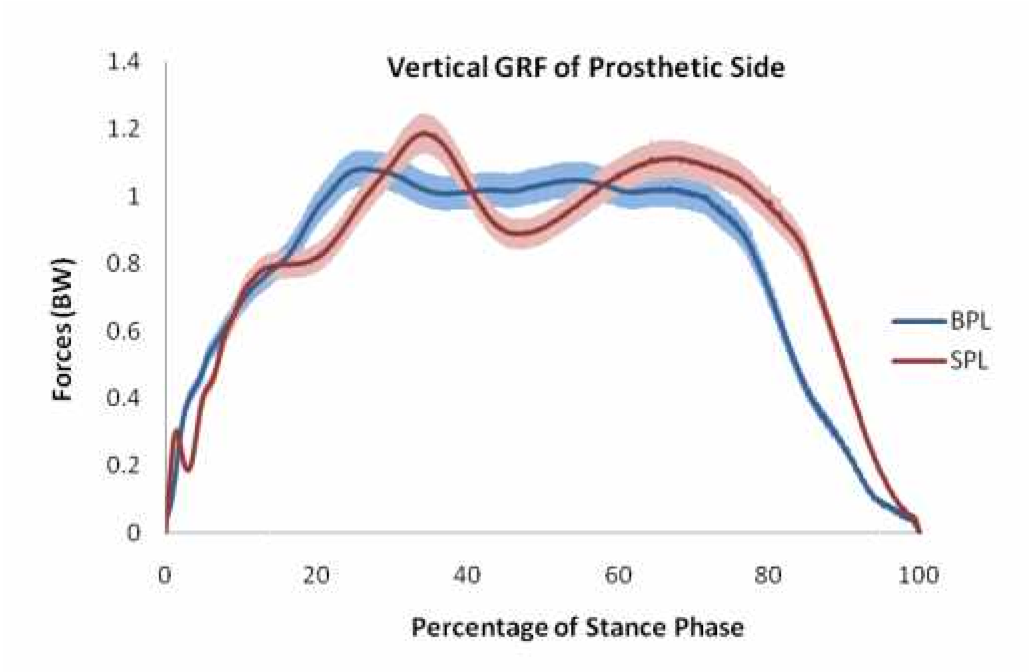


Figure 4.12: Vertical GRF of prosthetic side for one subject walking using the BPL and SPL at self-selected speed. GRFs were normalized by body weight (BW). Shaded area represents standard deviation.

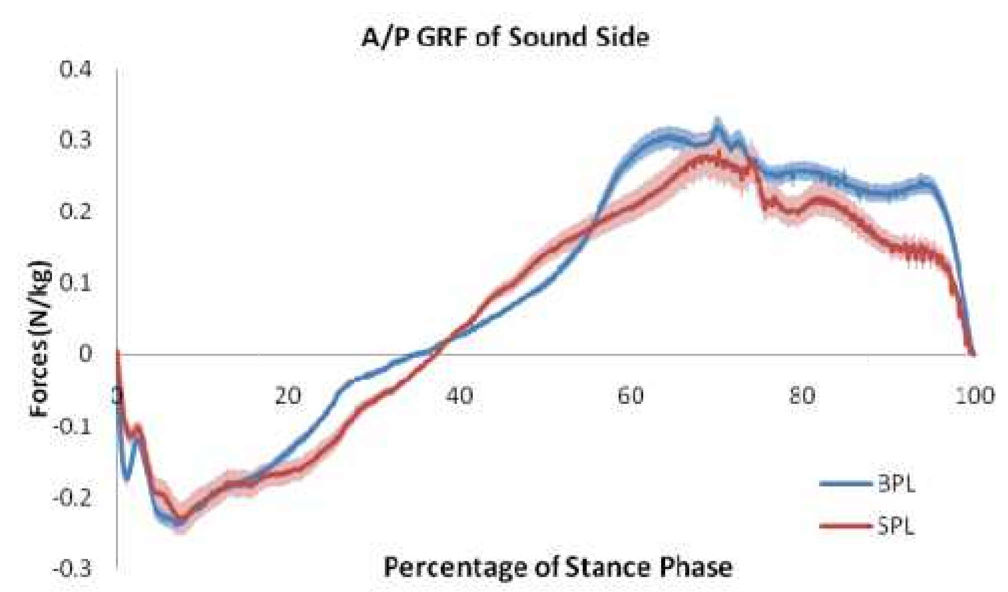


Figure 4.13: A/P GRF of sound side for one subject walking using the BPL and SPL at self-selected speed. GRFs were normalized by body weight (BW). Shaded area represents standard deviation.

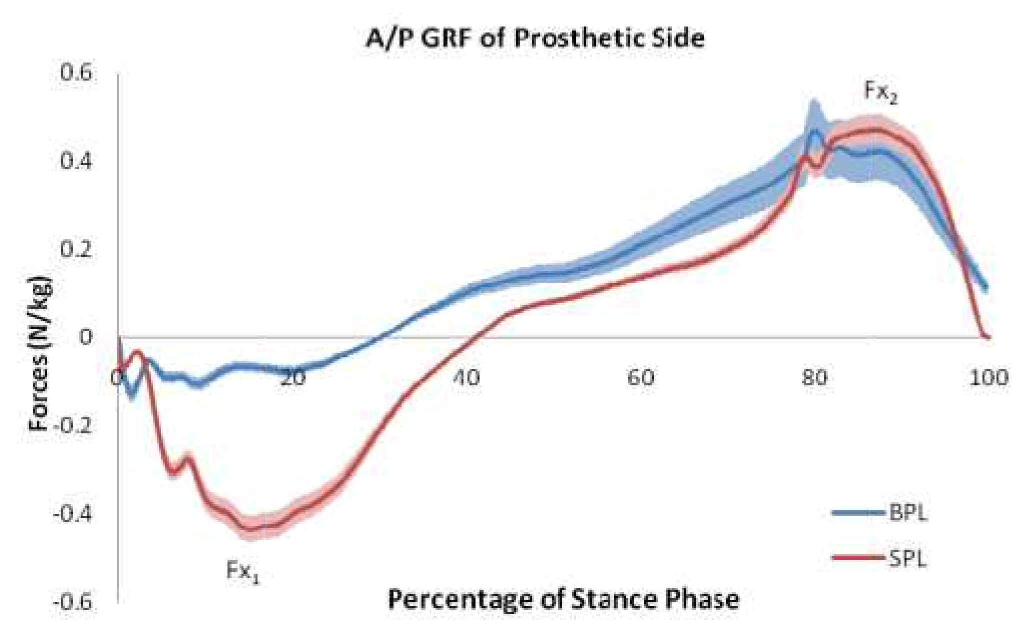


Figure 4.14: A/P GRF of prosthetic side for one subject walking using the BPL and SPL at self-selected speed. GRFs were normalized by body weight (BW). Shaded area represents standard deviation.

The highest peak on the force curve was defined as the maximal force amplitude. Vertical GRF represented by three maximal forces (Figure 4.11). Fz_1 was maximum vertical force during the loading phase. Fz_2 was vertical force during mid-stance and Fz_3 was maximum vertical force in late terminal stance. In A/P GRF, two forces were identified for analysis purposes which were Fx_1 as the maximum breaking force and Fx_2 as the maximum propulsion force (Figure 4.14). The time is measured in seconds and represents the time between the start of the stride, to the moment the force reaches the maximal amplitude indicated by the peak. All the force data were normalized to body mass.

The magnitude of the first peak of the vertical GRF typically indicates the capability of the locomotor system to absorb shock during gait. Previous studies of persons with unilateral transtibial amputations reported that the first peak of the vertical GRF on the prosthetic limb was about 5 to 15 percent higher than the sound limb (Power et al., 1994; Snyder et al., 1995). Contrary to these finding, there was no significant difference ($p > 0.05$) found in the vertical GRFs between the prosthetic and sound side. The vertical GRFs when walking with BPL or SPL was comparable ($p > 0.05$).

A/P GRF values would show if the alignment in prosthesis was properly done. Significant difference for A/P GRF was found ($p < 0.05$) in Fx_1 of SPL prosthetic side which had greatest value among all breaking force. This showed that the ability of the subjects to control their breaking forces when wearing the SPL. Fx_1 for prosthetic and sound side of BPL were comparable ($p > 0.05$) with the sound side of SPL. No significant difference was found in Fx_2 ($p > 0.05$) for sound and prosthetic side of BPL and SPL.

Table 4.4: Mean ± standard deviation of GRFs for six subjects walking using the BPL and SPL.

		BPL Prosthetic Side	BPL Sound Side	SPL Prosthetic Side	SPL Sound Side
GRF (N/kg)					
Vertical	Fz_1	1.05 ± 0.45	1.13 ± 0.34	1.17 ± 0.31	1.02 ± 0.33
	Fz_2	1.01 ± 0.67	0.97 ± 0.52	0.89 ± 0.50	0.87 ± 0.45
	Fz_3	0.95 ± 0.34	1.06 ± 0.23	1.11 ± 0.32	1.01 ± 0.30
A/P	Fx_1	-0.20 ± 0.03	-0.23 ± 0.05	-0.43 ± 0.01*	-0.22 ± 0.01
	Fx_2	0.43 ± 0.07	0.31 ± 0.04	0.47 ± 0.03	0.26 ± 0.02
Range Of Motion, Degree (°)					
Hip Angle	Maximum Extension	5.25 ± 0.26	0.02 ± 0.00*	4.79 ± 0.24	14.17 ± 0.71*
	Maximum Flexion	37.97 ± 1.90	32.12 ± 1.65	29.27 ± 1.45	28.75 ± 1.45
Knee Angle	Maximum Extension	10.00 ± 0.50	7.38 ± 0.21	8.92 ± 0.45	10.15 ± 0.51
	Maximum Flexion	60.26 ± 3.05	58.41 ± 2.92	45.68 ± 2.28	39.19 ± 1.96
Ankle Angle	Maximum Plantar Flexion	17.93 ± 0.89	19.80 ± 0.99	28.44 ± 1.42*	19.80 ± 0.99
	Maximum DorsiFlexion	4.60 ± 0.23	3.92 ± 0.09	4.84 ± 0.24	4.02 ± 0.20

Values are mean ± standard deviation from (N=6)

*Significant difference ($p < 0.05$)

4.6 Range of Motions

Table 4.4 shows average results for hip, knee and ankle joint kinematics for all subjects. Significant differences were found ($p < 0.05$) in the maximum hip extension for both sound sides when subjects wore either BPL or SPL. Magnitudes for sound side of SPL were highest compared to other groups (Figure 4.15). Clearly, subjects felt better stability during gait when their body weights were supported by the sound leg.

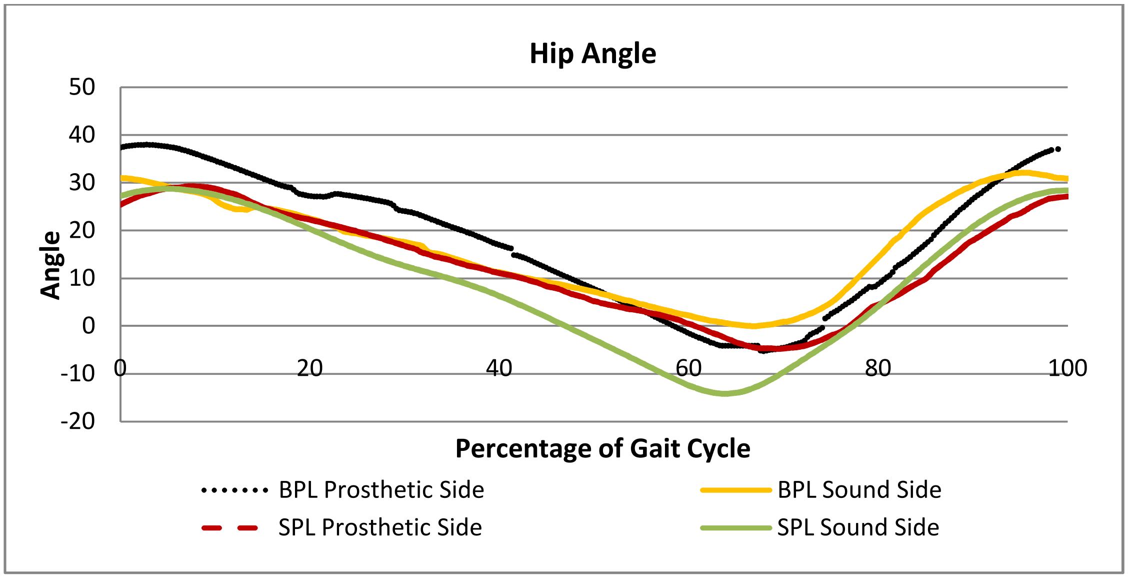


Figure 4.15: Hip joint angular position for all subjects (N=6). Positive values indicate flexion and negative values indicate extension.

Walking with BPL did not show any significant difference ($p > 0.05$) with SPL in the knee flexion and extension of both limbs. The subjects in this study walked with 15 percent less knee flexion and 10 percent more extension than the normal individual (Su et al., 2007). The subjects might reduce the knee flexion to minimise relative motion between the residual limb and the prosthetic socket. Figure 4.16 shows knee joint angular position for both limbs when wearing BPL and SPL. Ankle joint angular values were comparable (p

> 0.05) between BPL and SPL for the maximum dorsi flexion values. Significant difference ($p < 0.05$) was only found in prosthetic side of SPL for maximum plantar flexion. In addition, the prosthetic side of SPL produced the highest magnitudes for both dorsi flexion and plantar flexion among all limbs (Figure 4.17).

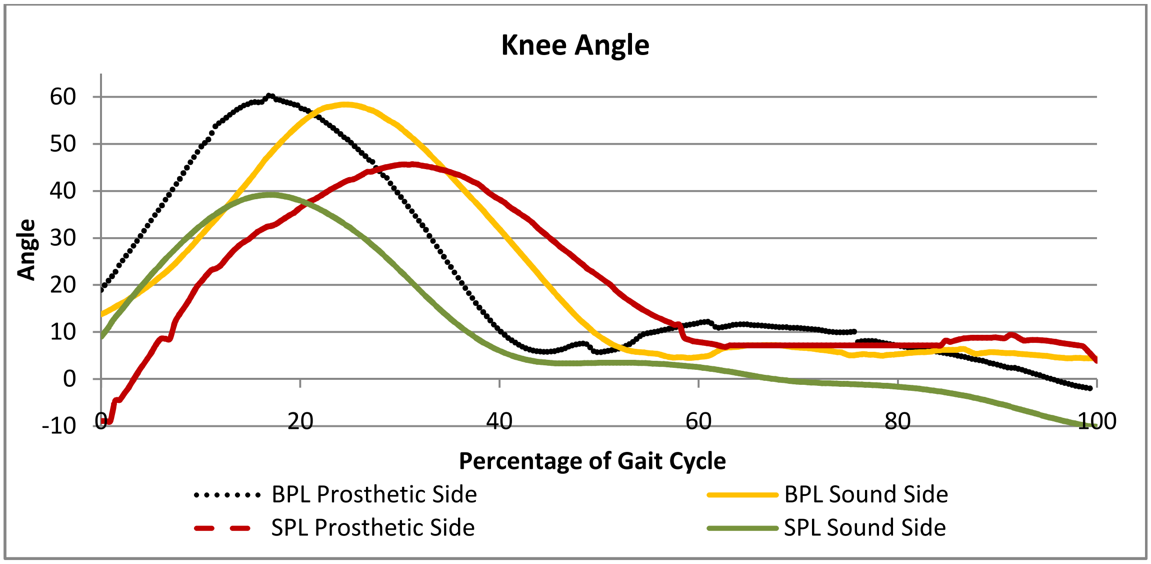


Figure 4.16: Knee joint angular position for all subjects (N=6). Positive values indicate flexion and negative values indicate extension.

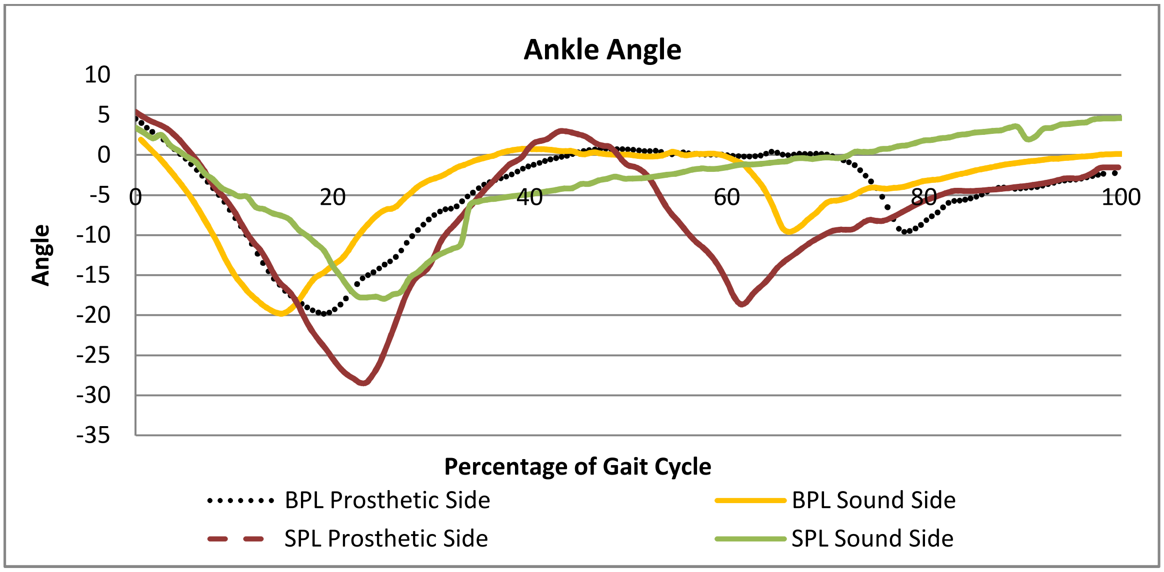


Figure 4.17: Ankle joint angular position for all subjects (N=6). Positive values indicate dorsiflexion and negative values indicate plantarflexion.

4.7 Socket Interface Pressure Analysis

The residual limb interface pressure was the supporting data of this study to confirm that there was no high stress pressure or pain occurred on subjects' residual limbs. Socket interface pressure analyses were made based on anterior, posterior, medial and lateral sensor groups. The length of the sensor was divided into three boxes; the top, medial and distal regions of the respective areas. Figure 4.18 shows colour codes used to indicate the pressure values. The upper and lower values however did not act as a threshold that limited the displayed pressure.

Figure 4.19 and Figure 4.20 shows the maximum pressure produced in S1's stance phase when wearing BPL and SPL. Maximum pressure for each box is displayed at the top right corner of the respective boxes. Based on the diagrams and Table 4.5, SPL had higher values in residual limb interface pressures for most of the areas when compared to BPL. The reason for this was that the socket for BPL was newly made for every subjects based on their present residual limb shapes and skin-bone profiles. Subjects possibly felt more convenient and less pain when wearing the new socket from BPL.

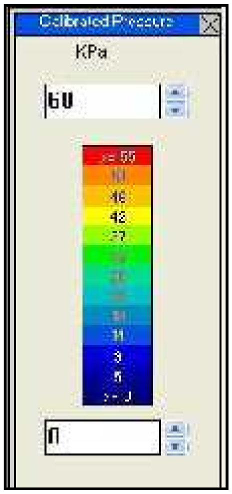


Figure 4.18: Colour bar for stance pressures.

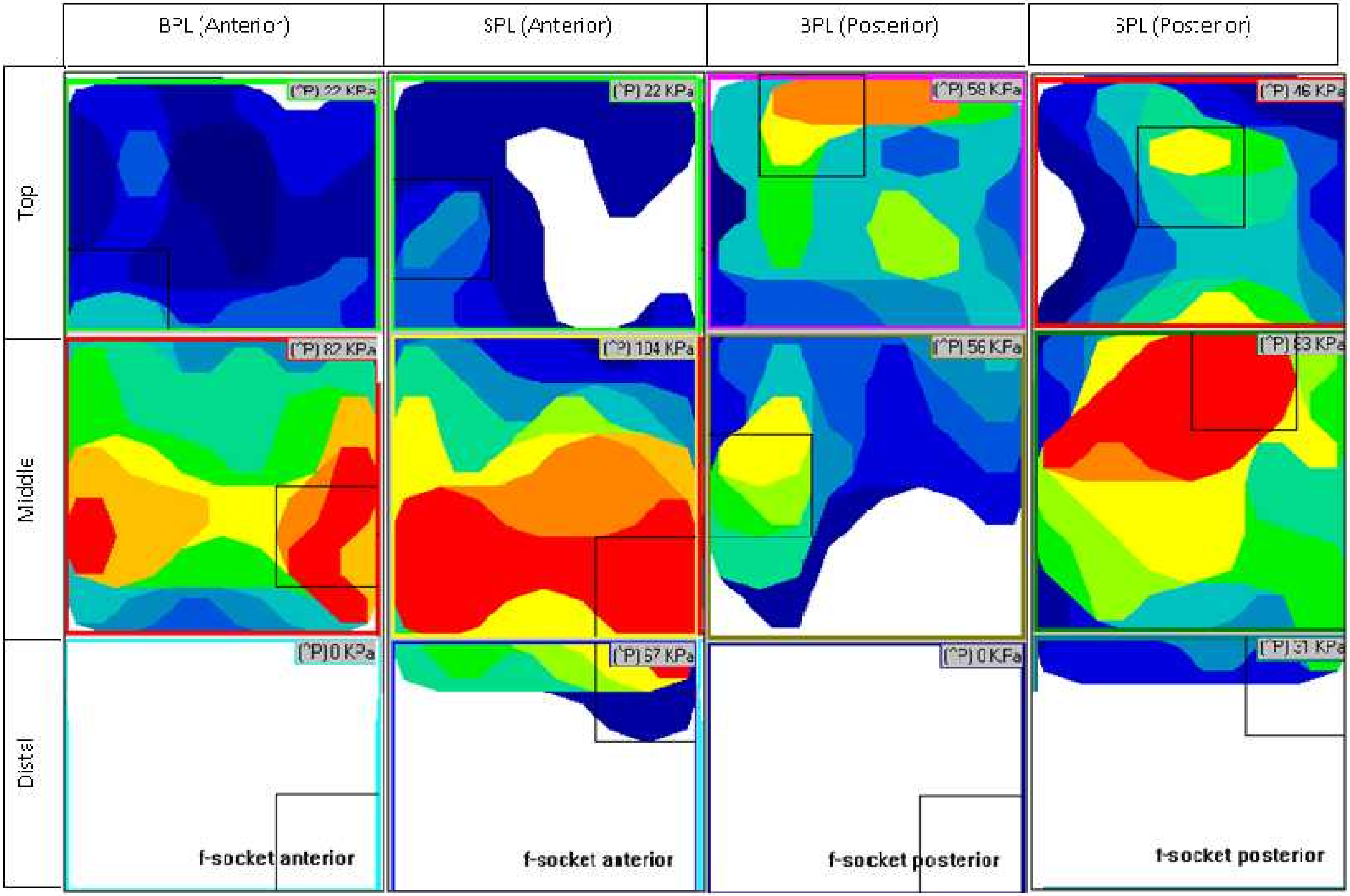


Figure 4.19: Maximum stance pressures for BPL and SPL at anterior and posterior residual limb's area.

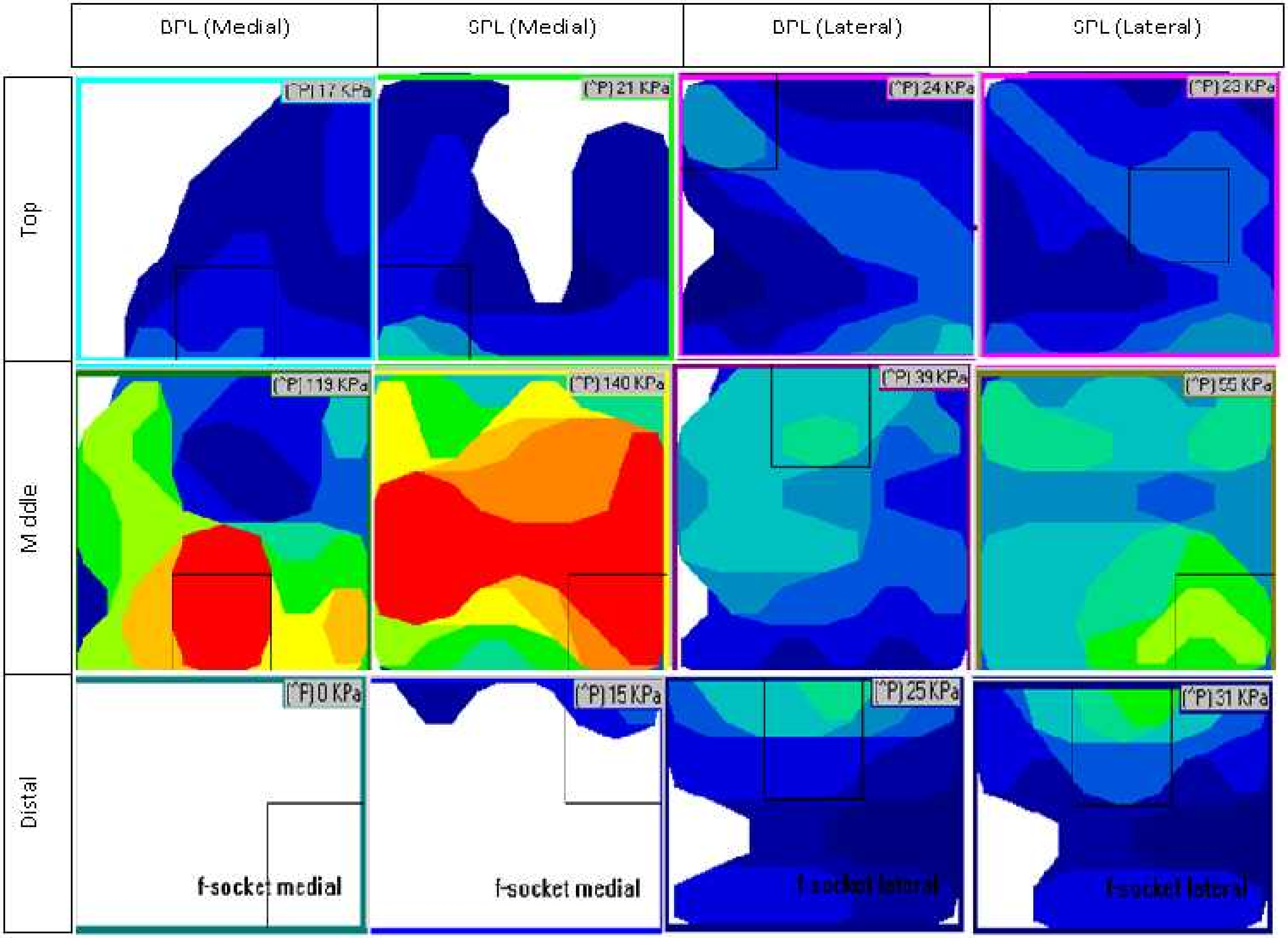


Figure 4.20: Maximum stance pressures for BPL and SPL at medial and lateral residual limb's area.

Table 4.5: Mean ± standard deviation of residual limb interface pressure for six subjects when walking using BPL and SPL.

	BPL	**SPL**
Maximum pressure, kPa		
Anterior	61.34 ± 32.23	62.31 ± 44.26
Posterior	31.14 ± 17.81	60.64 ± 14.53*
Medial	55.16 ± 26.55	63.75 ± 31.89
Lateral	51.96 ± 15.32	59.06 ± 15.43
Values are mean ± standard deviation		
*Significant difference ($p < 0.05$)		

In the above diagrams and Figure 4.21, pressure interface were high on anterior and medial area especially for SPL which were 104 kPa and 140 kPa respectively. These areas mark the patellar tendon and tibial tuberosity which had high pressure tolerant. Zhang and Lee (2006) reported that the pain threshold for patellar tendon was 1.00 MPa while pain threshold for tibial tuberosity was 0.89 MPa. Lowest pain threshold recorded in their study was 0.45 MPa for distal end of fibula.

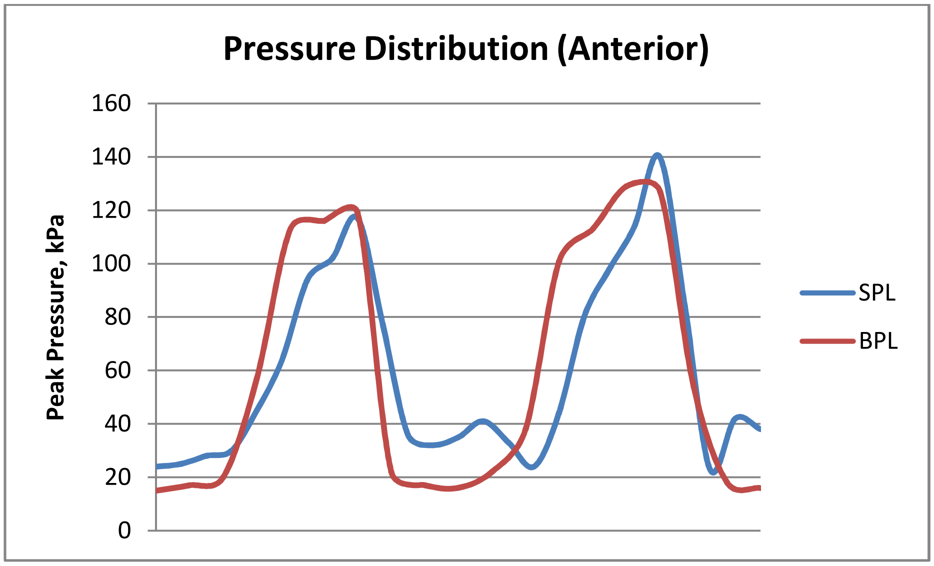


Figure 4.21: Average peak distribution at the anterior area of residual limbs for 6 subjects when walking using BPL and SPL for 2 consecutive steps.

Chapter 5

Conclusions and Recommendations

Bamboo pylon was tested under three mechanical tests and evaluated under finite element model. The results showed that bamboo was three times stronger than fibre reinforced plastic and two times stronger than Aluminum. Fibre reinforced plastic and Aluminum are widely used as the transtibial pylon material.

Despite the strength, bamboo had physical limitation on water resistance and durability. These limitations were overcome through lamination process and oil treatment that enhancing its anatomical structures. The total cost to develop bamboo pylon was RM10 with minimal manufacturing processes involved. Apart of this, evaluation on bamboo pylon durability was not made in this study. This evaluation could be done through dynamic test under Universal Testing Machine for further study.

Clinical assessment was carried out to determine the efficiency of bamboo transtibial pylon in amputees' gait. There was no significant difference found in vertical and A/P GRF ($p > 0.05$) in BPL compared to SPL. Joint kinematics for BPL was also comparable to joint kinematics for SPL ($p > 0.05$) except for the hip extension ($p < 0.05$). In spatio-temporal parameters, cadence, step length and walking speed of BPL were comparable to SPL ($p > 0.05$).

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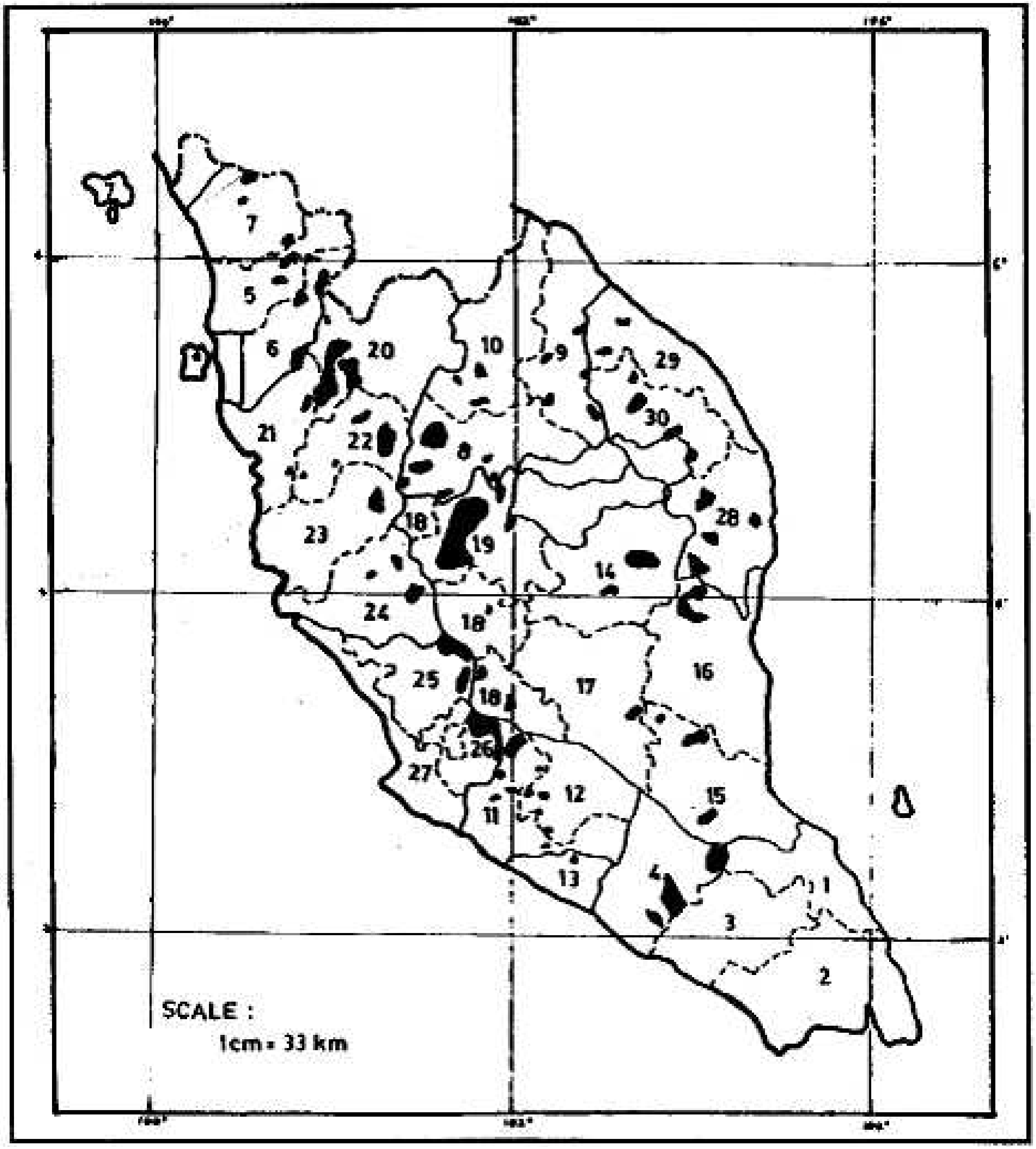
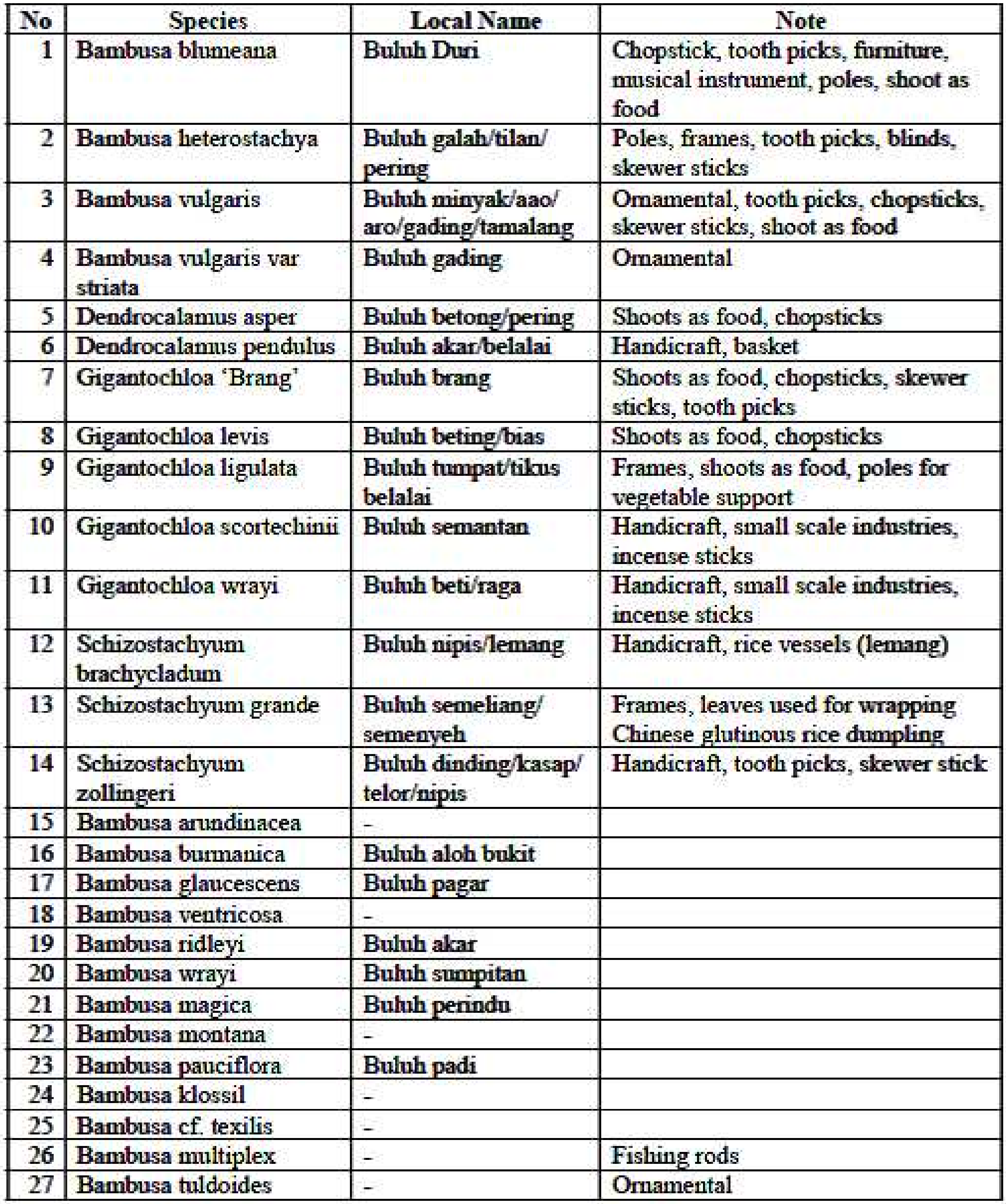
Appendix I

Distribution of Bamboo by Forest District in Peninsular Malaysia (The number indicates the species shown in Table below).



Bamboo Species of Malaysia (Kiam et al, 2005)



No	Species	Local Name	Note
1	Bambusa blumeana	Buluh Duri	Chopstick, tooth picks, furniture, musical instrument, poles, shoot as food
2	Bambusa heterostachya	Buluh galah/tilan/ pering	Poles, frames, tooth picks, blinds, skewer sticks
3	Bambusa vulgaris	Buluh minyak/aao/ aro/gading/tamalang	Ornamental, tooth picks, chopsticks, skewer sticks, shoot as food
4	Bambusa vulgaris var striata	Buluh gading	Ornamental
5	Dendrocalamus asper	Buluh betong/pering	Shoots as food, chopsticks
6	Dendrocalamus pendulus	Buluh akar/belalai	Handicraft, basket
7	Gigantochloa 'Brang'	Buluh brang	Shoots as food, chopsticks, skewer sticks, tooth picks
8	Gigantochloa levis	Buluh beting/bias	Shoots as food, chopsticks
9	Gigantochloa ligulata	Buluh tumpat/tikus belalai	Frames, shoots as food, poles for vegetable support
10	Gigantochloa scortechinii	Buluh semantan	Handicraft, small scale industries, incense sticks
11	Gigantochloa wrayi	Buluh beti/raga	Handicraft, small scale industries, incense sticks
12	Schizostachyum brachycladum	Buluh nipis/lemang	Handicraft, rice vessels (lemang)
13	Schizostachyum grande	Buluh semeliang/ semenyeh	Frames, leaves used for wrapping Chinese glutinous rice dumpling
14	Schizostachyum zollingeri	Buluh dinding/kasap/ telor/nipis	Handicraft, tooth picks, skewer stick
15	Bambusa arundinacea	-	
16	Bambusa burmanica	Buluh aloh bukit	
17	Bambusa glaucescens	Buluh pagar	
18	Bambusa ventricosa	-	
19	Bambusa ridleyi	Buluh akar	
20	Bambusa wrayi	Buluh sumpitan	
21	Bambusa magica	Buluh perindu	
22	Bambusa montana	-	
23	Bambusa pauciflora	Buluh padi	
24	Bambusa klossil	-	
25	Bambusa cf. texilis	-	
26	Bambusa multiplex	-	Fishing rods
27	Bambusa tuldoides	-	Ornamental

No	Species	Local Name	Uses
28	Dendrocalamus hirtellus	Buluh kapur	
29	Dendrocalamus elegans	-	
30	Dendrocalamus dumosus	-	
31	Dendrocalamus sinuatus	Buluh akar	
32	Dendrocalamus strictus	-	
33	Dendrocalamus giganteus	Buluh betong	
34	Gigantochloa balui	-	Handicrafts, sailing masts
35	Gigantochloa latifolia	Buluh pahit	
36	Gigantochloa apus	-	
37	Gigantochloa maxima	-	
38	Gigantochloa rostrata	-	
39	Gigantochloa holttumiana	-	
40	Gigantochloa hasskarliana	-	
41	Gigantochloa ridleyi	-	
42	Racemobamboo setifera	-	
43	Racemobamboo gibbsiae	-	
44	Racemobamboo glabra	-	
45	Racemobamboo hepburnii	-	
46	Racemobamboo hirsute	-	
47	Racemobamboo pairinii	-	
48	Racemobamboo rigidifolia	-	
49	Schizostachyum blumei	-	
50	Schizostachyum gracile	Buluh repen/akar	
51	Schizostachyum aciculare	Buluh padi	
52	Schizostachyum jaculans	Buluh sumpitan	
53	Schizostachyum latifolium	-	
54	Schizostachyum terminale	-	
55	Schizostachyum lima	-	
56	Schizostachyum pilosum	-	Flooring and basketry
57	Thyrsostachys siamesis	-	
58	Yushania tessellata	-	
59	Dinochloa scandens	-	
60	Dinochloa darvelana	-	Pests species
61	Dinochloa obclavata	-	Pests species
62	Dinochloa prunifera	-	Pests species
63	Dinochloa robusta	-	Pests species
64	Dinochloa scabrida	-	Pests species
65	Dinochloa sipitangensis	-	Pests species
66	Dinochloa sublaevigata	-	Pests species
67	Dinochloa trichogona	-	Pests species

Appendix II

CONSENT BY PATIENT FOR CLINICAL RESEARCH

I, ………………………………………………………Identity Card No……………………………………………
(Name of Patient)

of ………...
(Address)

hereby agree to take part in the clinical research (clinical study/questionnaire study/drug trial) specified below:

Title of Study:
…...……

the nature and purpose of which has been explained to me by Dr. ……………………………… *(Name & Designation of Doctor)* and interpreted by ………………………………………………………… *(Name & Designation of Interpreter)* …………………………………….. to the best of his/her ability in ……………………………………. language/dialect.

I have been told about the nature of the clinical research in terms of methodology, possible adverse effects and complications (as per patient information sheet). After knowing and understanding all the possible advantages and disadvantages of this clinical research, I voluntarily consent of my own free will to participate in the clinical research specified above.

I understand that I can withdraw from this clinical research at any time without assigning any reason whatsoever and in such a situation shall not be denied the benefits of usual treatment by the attending doctors.

Date: ………………………….. **Signature or Thumbprint ……………………………………………**
(Patient)

IN THE PRESENCE OF

Name …………………………………………………………… **Signature**
Identity Card No. ………………………………………… **(*Witness for Signature of Patient)***
Designation ……………………………………………

I confirm that I have explained to the patient the nature and purpose of the above-mentioned clinical research.

Date ……………………………. **Signature**
……………………………………………………
(Attending Doctor)

CONSENT BY PATIENT
FOR

R.N.:
Name:

CLINICAL RESEARCH **Sex:** **Age:**

KEIZINAN OLEH PESAKIT UNTUK PENYELIDIKAN KLINIKAL

Saya,…………………………………………………..……………No. Kad Pengenalan ………………..…………………
(Nama Pesakit)

beralamat……………………………………………………………………………..………..………………………………
(Alamat)

dengan ini bersetuju menyertai dalam penyelidikan klinikal (pengajian klinikal/pengajian soal-selidik/percubaan ubat-ubatan) disebut berikut:

<u>TajukPenyelidikan</u>: **.…………………………………………………………..…………………………………………….**

yang mana sifat dan tujuannya telah diterangkan kepada saya oleh Dr……………………………………
***(Nama & Jawatan Doktor)* mengikut terjemahan ………………..……………………………………………**
***(Nama & Jawatan Penterjemah)* ………………………………………. yang telah menterjemahkan kepada saya dengan sepenuh kemampuan dan kebolehannya di dalam Bahasa / loghat………………………………………………………**

Saya telah diberitahu bahawa dasar penyelidikan klinikal dalam keadaan methodologi, risiko dan komplikasi (mengikut kertas maklumat pesakit). Selepas mengetahui dan memahami semua kemungkinan kebaikan dan keburukan penyelidikan klinikal ini, saya merelakan/mengizinkan sendiri menyertai penyelidikan klinikal tersebut di atas.

Saya faham bahawa saya boleh menarik diri dari penyelidikan klinikal ini pada bila-bila masa tanpa memberi sebarang alasan dalam situasi ini dan tidak akan dikecualikan dari kemudahan rawatan dari doktor yang merawat.

Tarikh: …………………….. Tandatangan/Cap Jari ……………………………………………….
(Pesakit)

DI HADAPAN

Nama ……………………………………………….) Tandatangan…………………………………
No. K/P……………………………………………..) *(Saksi untuk Tandatangan Pesakit)*
Jawatan ………..…………………………………..)

Saya sahkan bahawa saya telah menerangkan kepada pesakit sifat dan tujuan penyelidikan klinikal tersebut di atas.

Tarikh: ……..………………….. Tandatangan ……………………………………………………………………
(Doktor yang merawat)

No. Pendaftaran:
KEIZINAN OLEH PESAKIT UNTUK **Nama:**

PENYELIDIKAN KLINIKAL **Jantina:** **Umur:**

Appendix III

SUBJECT MEASUREMENTS

Mass (required): This is the mass of the subject in kilograms.

Height (required): This is the height of the subject in centimeters.

Inter-ASIS distance (optional): If this is not entered the model will calculate this distance based on the position of the LASI and RASI markers (recommended). If you are collecting data on an obese patient and cannot properly place the ASIS markers, place those markers laterally and preserve the level of the ASIS. Palpate the LASI and RASI points and manually measure this distance. This measurement should be entered here for this scenario.

Head Angle (Calculated): This is the absolute angle of the head with the global coordinate system.

Leg Length (required): This is the true leg length measurement. It is measured from the ASIS to the medial malleolus. In the case of a patient who can straighten their legs, the measurement should be taken in two pieces. The leg length will be the sum of the length from the ASIS to the Knee and from the knee to the medial malleolus.

Knee Width (required): This is the measurement of the knee width, about the flexion axis, in centimeters.

Ankle Width (required): This is the measurement of the ankle width, about the medial and lateral malleoli, in centimeters.

ASIS-Trochanter Distance (optional): This is the perpendicular distance from the trochanter to the ASIS point. If this value is not entered, then a regression formula is used to calculate the hip joint centre. This value will be calculated as part of this process. If this value is entered, it will be factored into an equation which represents the hip joint centre. For more details on this, please refer to the paper by Davis, et. al in the reference section. It is recommended that this value not be entered when processing the model.

Tibial Torsion (optional): Tibial torsion is the angle between the ankle flexion axis and the knee flexion axis. The sign convention is that if a negative value of tibial torsion is entered, the ankle flexion axis is rotated externally with respect to the knee flexion axis. If tibial torsion is entered while using a KAD, the ankle flexion/extension axis will be adjusted from the KAD's defined position to a position dictated by the tibial torsion value.

Thigh Rotation Offset (calculated): When a KAD is used, this value is calculated to account for the position of the thigh wand (marker). By using the KAD, placement of the thigh wand in the plane of the hip joint centre and the knee joint centre is not crucial. Please note that if you do not use a KAD, this value will be reported as zero because the model is assuming that the thigh wand has been placed exactly in the plane of the hip joint centre and the knee joint centre.

Shank Rotation Offset (calculated): The shank rotation offset is similar to the thigh rotation offset. This value is calculated if a KAD is present and removes the importance of placing the shank wand in the exact plane of the knee joint centre and the ankle joint centre. As above, if you do not use a KAD, then these values will be zero.

** A note about the foot: VCM previously treated the foot as a vector, using only two markers during dynamic trials. Plug in Gait will process the foot as a vector if the heel marker is missing during dynamic trials. If all three markers are present then Plug in Gait will treat the foot as a three dimensional segment and NOT as a vector. The following parameters are used only if the foot is treated as a vector.*

Foot Plantar Flexion Offset (calculated): Calculated as a rotation about the ankle flexion axis. This angle is measured between the line joining the heel and toe markers and the line joining the heel marker and the toe marker. This is one of the rotations performed in establishing the foot vector.

Foot Rotation Offset (calculated): This is a rotation about the foot rotation axis, which is perpendicular to the foot vector (after applying the foot plantar flexion offset) and the ankle flexion axis. This angle is measured between the line joining the heel and the toe markers and the line joining the ankle joint centre and the toe marker. This is the final rotation performed in establishing the orientation of the foot vector.

Shoulder Offset (required): This is the vertical distance from the centre of the glenohumeral joint to the marker on the acromion calivicular joint. Some researchers have used the (anterior/posterior girth)/2 to establish a guideline for the parameter.

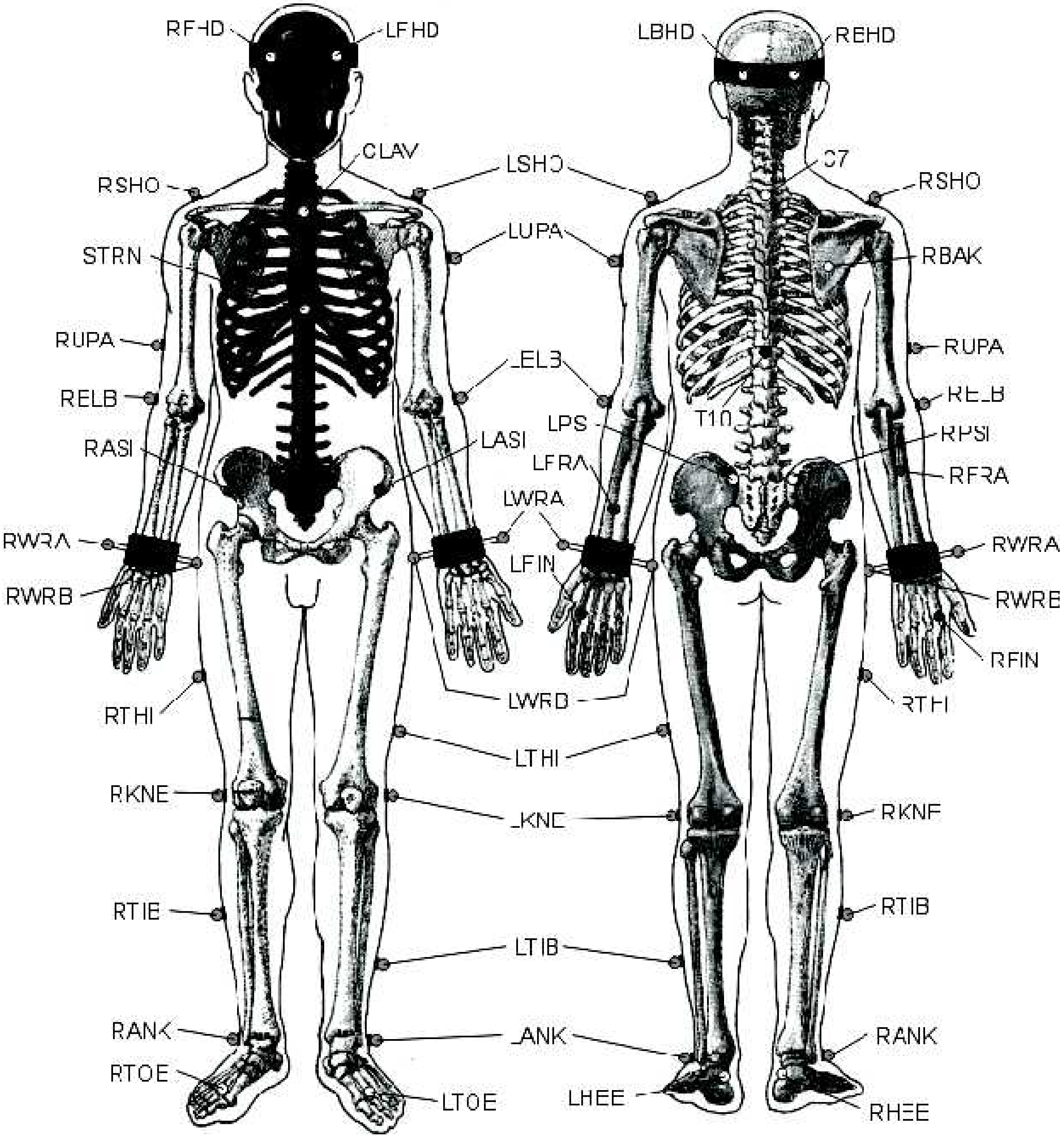
Elbow Width (required): This is the distance between the medial and lateral epicondyles of the humerus.

Wrist Width (required): This is the distance between the ulnar and radial styloids.

Hand Thickness (required): This is the distance between the dorsal and palmar surfaces of the hand. On a normal monitor the required, optional, and calculated fields will all have different colored backgrounds. Some laptops may not display these color differences.

Appendix IV

Plug-in-Gait Marker Placement



The following describes in detail where the Plug-in-Gait markers should be placed on the subject (Lower Limb). Where left side markers only are listed, the positioning is identical for the right side.

Lower Body

Pelvis

LASI	Left ASIS	Placed directly over the left anterior superior iliac spine
RASI	Right ASIS	Placed directly over the right anterior superior iliac spine

The above markers may need to be placed medially to the ASIS to get the marker to the correct position due to the curvature of the abdomen. In some patients, especially those who are obese, the markers either can't be placed exactly anterior to the ASIS, or are invisible in this position to cameras. In these cases, move each marker laterally by an equal amount, along the ASIS-ASIS axis. The true inter-ASIS Distance must then be recorded and entered on the subject parameters form. These markers, together with the sacral marker or LPSI and RPSI markers, define the pelvic axes.

LPSI	Left PSIS	Placed directly over the left posterior superior iliac spine
RPSI	Right PSIS	Placed directly over the right posterior superior iliac spine

LPSI and RPSI markers are placed on the slight bony prominences that can be felt immediately below the dimples (sacro-iliac joints), at the point where the spine joins the pelvis.

SACR	Sacral wand marker	Placed on the skin mid-way between the posterior superior iliac spines (PSIS). An alternative to LPSI and RPSI.

SACR may be used as an alternative to the LPSI and RPSI markers to overcome the problem of losing visibility of the sacral marker (if this occurs), the standard marker kit contains a base plate and selection of short "sticks" or "wands" to allow the marker to be extended away from the body, if necessary. In this case it must be positioned to lie in the plane formed by the ASIS and PSIS points.

Leg Markers

LKNE	Left knee	Placed on the lateral epicondyle of the left knee

To locate the "precise" point for the knee marker placement, passively flex and extend the knee a little while watching the skin surface on the lateral aspect of the knee joint. Identify where knee joint axis passes through the lateral side of the knee by finding the lateral skin surface that comes closest to remaining fixed in the thigh. This landmark should also be the point about which the lower leg appears to rotate. Mark this point with a pen. With an adult patient standing, this pen mark should be about 1.5 cm above the joint line, mid-way between the front and back of the joint. Attach the marker at this point.

LTHI	Left thigh	Place the marker over the lower lateral 1/3 surface of the thigh, just below the swing of the hand, although the height is not critical.

The thigh markers are used to calculate the knee flexion axis location and orientation. Place the marker over the lower lateral 1/3 surface of the thigh, just below the swing of the hand, although the height is not critical. The antero-posterior placement of the marker is critical for correct alignment of the knee flexion axis. Try to keep the thigh marker off the belly of the muscle, but place the thigh marker at least two marker diameters proximal of the knee marker. Adjust the position of the marker so that it is aligned in the plane that contains the hip and knee joint centers and the knee flexion/extension axis. There is also another method that uses a mirror to align this marker, allowing the operator to better judge the positioning.

LANK	Left ankle	Placed on the lateral malleolus along an imaginary line that passes through the transmalleolar axis
LTIB	Left tibial wand marker	Similar to the thigh markers, these are placed over the lower 1/3 of the shank to determine the alignment of the ankle flexion axis

The tibial marker should lie in the plane that contains the knee and ankle joint centers and the ankle flexion/extension axis. In a normal subject the ankle joint axis, between the medial and lateral malleoli, is externally rotated by between 5 and 15 degrees with respect to the knee flexion axis. The placements of the shank markers should reflect this.

Foot Markers

LTOE	Left toe	Placed over the second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot
LHEE	Left heel	Placed on the calcaneous at the same height above the plantar surface of the foot as the toe marker