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Interface pressure profile analysis for patellar tendon-bearing socket and hydrostatic socket

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Conventionally, patellar tendon-bearing (PTB) sockets, which need high dexterity of prosthetist, are widely used. Lack of chartered and experienced prosthetist has often led to painful experience of wearing prosthesis and this will in turn deter the patients to wear the prosthesis, which will further aggravate stump shrinkage. Thus, the hydrostatic socket which demands relatively lower level of fabricating skill is proposed to replace the PTB socket in order to produce the equivalent, if not better, quality of support to the amputee patients.

Both sockets' pressure profiles are studied and compared using finite element analysis (FEA) software. Three-dimensional models of both sockets were developed using MIMICS software.

The analysis results showed that hydrostatic socket did exhibit more uniform pressure profiles than that of PTB socket. PTB socket showed pressure concentration near the proximal brim of the socket and also at the distal fibula. It was also found that the pressure magnitude in hydrostatic socket is relatively lower than that of PTB socket.

Key words: *finite element analysis, patellar-tendon-bearing socket, hydrostatic socket, interface pressure*

1. Introduction

It is estimated by World Health Organization (WHO) that about 1.39 to 2.77 millions (5–10%) Malaysians are people with disability (PWD), though there were only 229,325 PWDs registered with the National Welfare Department till May 2008. More worryingly, amputations among Malaysia citizens are increasing by 46% annually. Thus, more emphasis should be put in this field in order to help amputee to achieve better living conditions. Besides restoring the ambulation ability, lower-limb prosthesis is used to restore the cosmetic appearance of the patient [12]. The prosthesis socket design, in particular, is challenging regarding to the requirement needed to fulfill. The socket should be able to provide suspension of prosthesis, comfortable weight-bearing in the socket and also the protection of residual limb tissue.

As such, the socket interface designs can be divided into three basic categories according to their respective weight bearing characteristics, which are patellar tendon bar (PTB), total-surface bearing (TSB), and also hydrostatic (HST) design [13]. PTB applies the principle of specific area weight bearing as it uses patellar tendon, popliteal fossa and medial flares for weight bearing. TSB, however, uniformly distributes the weight over the entire residual limb in order to deliver minimum amount of skin pressure. Gel sleeve is used to help redistribute notorious pressure areas in the residual limb. Lastly, hydrostatic design, also known as pressure cast, manipulates specific principles of fluid mechanics and a compression chamber to achieve a uniform fit.

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There are significant physical, volumetric and mechanical differences between the PTB and PCast sockets [13]. The major difference is that the hydrostatic socket is not indented proximally at the patellar tendon area and the posterior aspect of the socket [6]. While the PTB socket biomechanics had been defined for each of the progression phases of gait, the hydrostatic socket makes no accommodation for such dynamic forces. Instead, the hydrostatic socket assumes that pressure at one point will simply be transferred by the fluid principle to other accommodating soft tissues [6].

The aims of this study are to produce a model from Computed-Tomography (CT) graphic data using three-dimensional image reconstruction software. Pressure data obtained from previous researcher [1] are applied to the inner wall of PTB socket and PCast socket using Finite Element Analysis (FEA) software in order to obtain the pressure profile of both types of sockets. Lastly, both pressure profiles are compared to identify which prosthetic socket offer better comfort and more benefit to the trans-tibial amputee patients.

2. Methodology

The methodology used in this study is divided into several parts. The whole process is summarized in flow chart shown in figure 1.

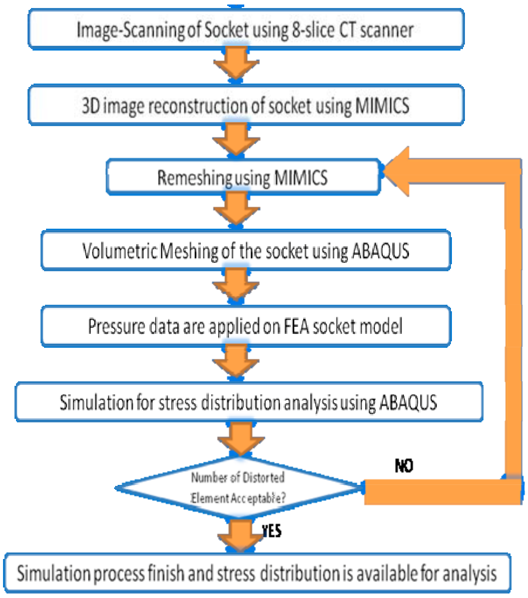
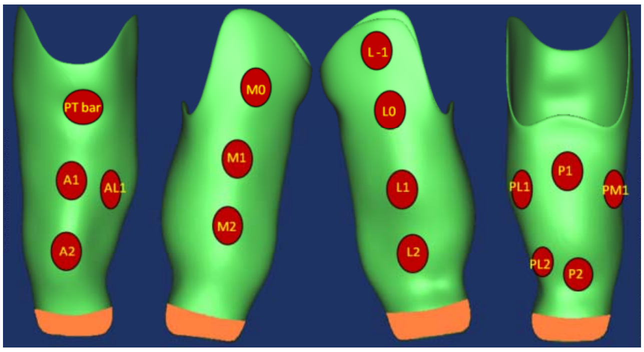


Fig. 1. Work flow of preparation of FEA socket model

The very first step is to take the scans of PTB and hydrostatic sockets using 8-slice CT scanner (Lightspeed, GE Company) in the Department of Radiology, University Malaya Medical Center (UMMC) to obtain two-dimensional socket images.

Three-dimensional socket images will be reconstructed using MIMICS software which is available in Motion Analysis Laboratory in the Department of Biomedical Engineering, the University of Malaya. A profile line is drawn across the socket wall to visualize an intensity profile of the Hounsfield unit (HU), which can aid in the quick pre-defining of a threshold value for the socket. After manual editing and some smoothing operation on the socket surface to produce acceptable three-dimensional (3D) image, the sockets will be remeshed to reduce the number of triangular elements of the socket to a reasonable amount. The bad edge and bad contour can be eliminated using manual remeshing tools.

After the volumetric meshing in ABAQUS software, the prosthetic socket model consists of a lot of tetrahedral elements. According to ABU OSMAN et al. [1], in the measurement of the pressure at the socket–residual limb interface, four types of transducer are used, i.e. patellar tendon (PT) transducer, bioengineering shear transducer (B.E.S.T.), pressure load cell device and electrohydraulic transducer. The total number of transducers used in the pressure measurement are 14 for PTB socket and 15 for hydrostatic socket. The distal end transducer is also included.



Anterior Medial Lateral Posterior

Fig. 2. Example of transducer placement on the PTB socket

The annotation for the abbreviations used to represent every location of the transducer (see figure 2) is shown below:

- PT bar – patellar tendon bar,
- P – posterior,
- A – anterior,
- PL – posterior lateral,
- PM – posterior medial.

In order to make things easy while applying pressure in later module, surface sets are created to locate every transducer sites in the inner wall of socket. This is accomplished in *Part Module*. Since the transducer diameter is small in size (5.6 mm), each surface set consist of one element only, which approximates the size of 5.6 mm. The material properties of socket wall and pylon interface are assigned to the socket model in this module under section assignment part.

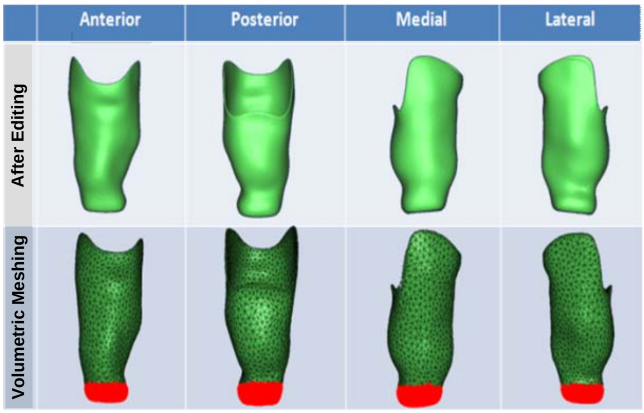


Fig. 3. Example of PTB prosthetic socket model condition after editing and after volumetric meshing

There are only two materials used in both hydrostatic and PTB sockets, namely polypropylene and stainless steel. From the literature review done, the two material properties used in this thesis project are shown in table 1. After setting the two material properties, they are assigned to two sections created, which are pylon interface and socket wall. In this study, the socket wall and pylon interface are assumed to be homogeneous solid, which was the common assumption in the previous study done. After that, both sections can be assigned to the socket model in *Part Module*.

Table 1. Summary of mechanical properties of the materials used in socket model

	Polypropylene	Stainless steel
Mass density	850 kgm^{-3}	7800 kgm^{-3}
Young modulus	1500 MPa	200 GPa
Poisson ratio	0.3	0.3

After proper set-up in *Step Module*, the pressure data obtained from the previous study done by ABU OSMAN et al. [1] are inputted and applied in the socket model according to the surface sets created previously in *Part Module*. The pressure distribution is assumed to be uniform. Boundary conditions are also applied in the four specific locations at the pylon interface that are meant to be screwed with pylon shaft.

After that, an analysis job is created in the *Job Module* using the socket model created. Once the job is submitted for analysis, the warning message must be checked for the number of distorted elements in the meshed model of socket. Too high the number of distorted elements will cost much longer simulation time and worse still, fail the whole simulation process.

After the simulation succeeded, the result of stress distribution on inner wall of socket can be analyzed in *Visualization Module*. Since the analysis used in this study is dynamic, there will be 20 frames of output produced and care should be taken to standardize the scaling used in each frame so that the output can be better compared.

3. Results

The summary of the details of the two socket models developed is presented in table 2. It should be noted that the finite element used in default was linear tetrahedral element (C3D4). Both pressure profiles are successfully developed and presented in the interface pressure profile shown in figure 4.

Table 2. Summary of the details of the two socket models developed

	PTB socket	Hydrostatic socket
Number of nodes	26719	34681
Number of elements	14463	19079

4. Discussion

The difference in interface pressure distribution in the wearing of different types of prosthetic socket is studied. The two prosthetic sockets involved, i.e. PTB and hydrostatic sockets, were fabricated by ABU OSMAN et al. [1] and the effect of the prosthesis alignment and the foot/ankle system used on the interface pressure is not under consideration in this study. The pressure data used here is actually the average of ten-subject trials of pressure measurements. Thus, it was already proven that the pressure measurement process and pressure data were reproducible.

The pressure data used in the project had been normalized into 100% of gait cycle. Basically, gait cycle can be divided into two phases, namely stance phase (60%) and swing phase (40%). The focus in this study will be put on the former since the weight bearing process occurs in the stance phase of gait cycle. The whole stance phase is done through flexion–extension–flexion of knee and it is generally divided into five stages, which are initial contact, loading response,

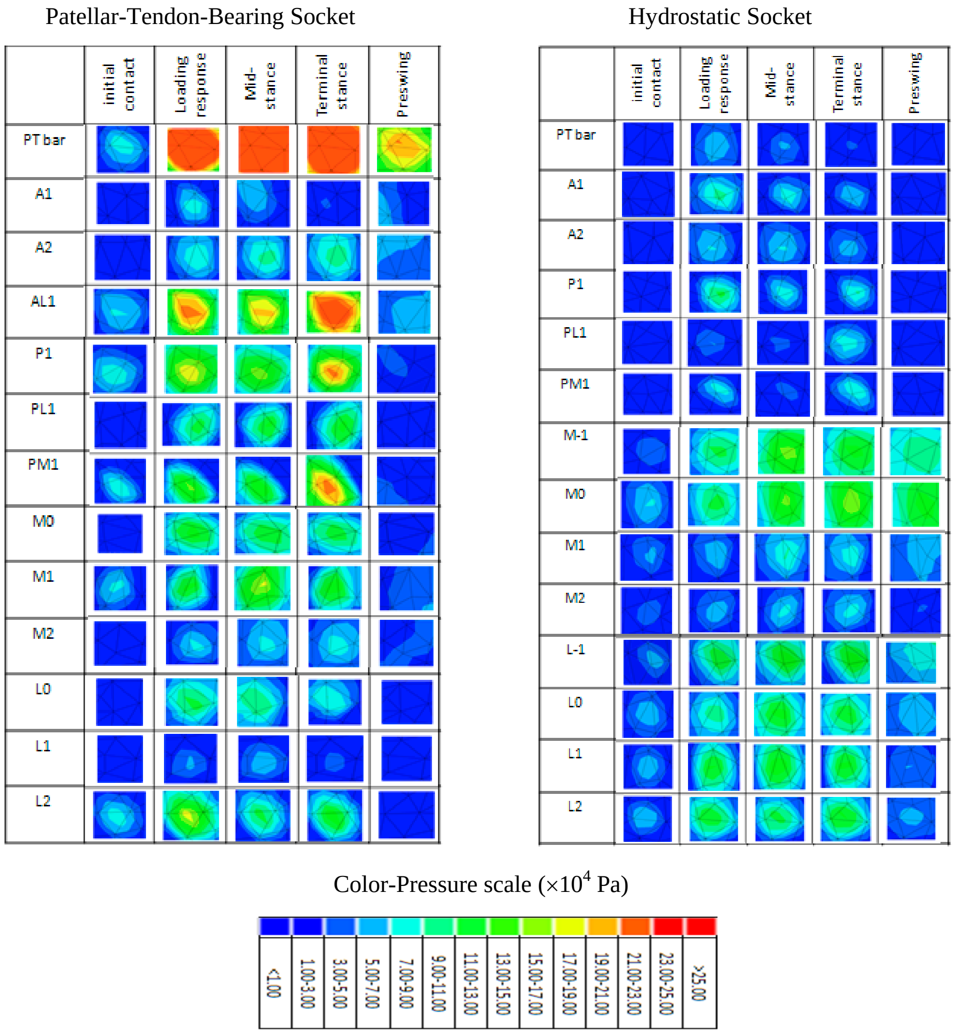


Fig. 4. Interface pressure profiles of PTB socket and hydrostatic socket

mid-stance, terminal stance and pre-swing. Since the active function of ankle joint cannot be restored with the current technologies, active ankle plantar flexion in the heel strike and push-off phase and the contribution of the ankle to the initiation of knee flexion must be lost. Therefore, the gait is different from stance phase of normal person.

The pressure profile from ABAQUS simulation results will be studied on four sides of the socket, which are anterior, posterior, medial and posterior sides.

i. Anterior Pressure Profiles

On the anterior side, *PTB socket* exhibits irregular pressure distribution with the highest pressure in PT bar region and AL1 region and relatively low pressure in A1 and A2 regions (tibial crest). PT bar exhibits peak pressure up to around 502–551 kPa while AL1 peak pressures reach up to around 207–257 kPa. This is in conformity with the Radcliffe criterion as these two sites are in pressure tolerant area of residual limb. In A1 and A2 regions, the peak pressure is around 50–90 kPa as they are in pressure sensitive region. As regards the gait cycle, the peak pressure at PT bar occurs at mid-stance, AL1 at terminal stance, A1 at loading response and A2 at terminal stance.

In *hydrostatic socket*, however, the pressure distribution is relatively uniform, i.e. around 50–90 kPa over PT bar, A1 and A2 areas. There is also no sharp change of pressure during every stage in stance phase.

ii. Posterior Pressure Profiles

On the posterior side, PTB socket exhibits high pressure in P1 (proximal popliteal fossa) and PM1 (posterior medial flare), in which their peak pressures are up to about 210–230 kPa. PL1, though relatively lower than P1 and PM1, still have peak pressures around 110–130 kPa. All of P1, PM1 and PL1 show peak pressure at terminal stance stage during stance phase.

Hydrostatic socket, like on the anterior side, also shows relatively low pressure with more uniform pattern. PL1 and PM1 show peak pressures of about 70–90 kPa while P1 shows slightly higher peak pressures, which is at about 90–110 kPa. P1 shows peak pressure during loading response stage while both PL1 and PM1 show peak pressures during terminal stance stage.

iii. Medial Pressure Profiles

On the medial side, peak pressures of PTB socket are relatively lower than on both anterior and posterior sides. M1 shows higher peak pressure (170–190 kPa) than M0 (110–130 kPa) and M2 (70–90 kPa). The pressure applied is reasonable, considering that they are in medial tibial flare region, which is pressure tolerant. There is no significant difference in pressure during each stage of stance phase.

As for the medial side of hydrostatic socket, in contrast with its relatively low pressure at anterior and posterior sides, it shows higher pressure, especially at proximal brim (M1, M0). The peak pressures of M1 and M0 are at around 150–170 kPa. M1 and M2 show lower peak pressure, which is at 70–90 kPa. Also, the pressures on each site exhibit a uniform pattern without significant change when going through different stages of stance phase.

iv. Lateral Pressure Profiles

On the lateral side of PTB socket, the highest peak pressure occurs at L2 (distal fibula), which is around 150–170 kPa. Besides, L0 (fibula head) also shows considerable peak pressure, which is at 150–170 kPa. In this case, L1 is lower in peak pressure, which is at around 50–70 kPa. The peak pressure of L0 occurs during loading response and mid-stance, while peak pressure of L2 occurs during loading response stage.

As for hydrostatic socket, the pressure distribution at lateral sides follows a uniform pattern, being at about 90–110 kPa. Besides, the pressures also show no significant difference during each stage of stance phase.

In summary, the pressure distribution in inner wall of hydrostatic prosthetic socket is far more uniform than that in PTB prosthetic socket. Besides being more scattered in pressure distribution, PTB socket also exhibits higher pressure, in general, than that of hydrostatic pressure at the measurement sites. This may be due to the fact that hydrostatic socket is fabricated using the Pascal principle of fluid dynamics, first proposed by MURDOCH [21], in which the body weight of the amputee will be transmitted equally to every point of the stump due to the transmissibility of the fluid pressure [21]. In this case, the pressure applied to the stump will be the body weight divided by total area of stump, making the overall pressure lower and more uniform. Thus, hydrostatic pressure is indeed "letting the nature dictate the most realistic and achievable pressure distribution" [17]. However, it is noted that the pressure distribution in hydrostatic socket is not in absolutely uniform state. In fact, the ideal condition for the Pascal principle to apply is that the system must be a closed system. This implies that the volume of soft tissues in the residual limb must be contained in the same volume in socket, which is impossible in real situation as the stump of amputee will keep changing according to his/her daily activity level. This is verified by SCHUCH [29] who states that residual limb is not a closed fluid system at all [29]. Therefore, in this non-ideal condition, it is impossible for the pressure distribution in the hydrostatic socket to be exactly uniform.

In contrast, PTB socket is fabricated according to the Radcliffe criterion, who advocated that the stumps can be divided into pressure-tolerant and pressure-sensitive areas and that more pressure should be applied to pressure-tolerant area by rectification of prosthetic socket [23], [25]. The rectification of socket would end up applying more pressure over bony anatomy and less pressure over delicate soft tissue. Therefore, a certain area in the socket will sustain more body weight than others, making the pressure higher since the surface area for load-bearing is relatively lower than that of hydrostatic socket. Thus, distinct non-uniform pressure distribution is observed in PTB prosthetic socket, where proximal area of PTB socket shows higher pressure than other regions.

The results of this study, which are the interface pressure profiles, are also compared with those of CONVERY and BUIS [4] who used 0.017-mm thick mylar/resistive ink (9810) F-socket transducer developed by Tekscan Inc. to undertake the interface pressure measurement. There are some deviations of pressure value in the current study if compared with study done by CONVERY and BUIS [4]. The deviation may be due to the usage of different pressure sensor and the different coverage area for pressure measurement. In CONVERY and BUIS [4], Tekscan F-socket transducers were used to measure pressure over a large surface of area whereas the pressure data in this thesis project were obtained using high-precision pressure load cell (model ELFM-B1-5L) that covered small area of 5.6-mm diameter. However, Tekscan F-socket transducer sensor is susceptible to errors due to hysteresis, drift, surface curvature and sensitivity to loading rates, whereas high-precision pressure load cell is more capable of producing accurate results [2], [20]. Besides, the coverage area for Tekscan F-socket sensor is much larger and can represent each side of socket more convincingly rather than that of high-precision pressure load cell which could only measure at discrete points. As a whole, however, the interface pressure obtained in this study conforms fully to that of CONVERY and BUIS [4].

The limitation in the pressure profiles developed in this study is that the locations of analysis are constrained to transducer of small diameter (5.6 mm), which means the coverage area for analysis is not big enough to produce overall view of the pressure acted upon the stump. Besides, more subjects should also be used in order to produce pressure profiles that are more representative of the whole Malaysian amputee population.

5. Conclusions

From the results of this study, it is concluded that hydrostatic prosthetic socket has more uniform interface pressure profiles than that of PTB socket. PTB socket, as expected, shows pressure concentration on pressure-tolerant sites and lower pressure at pressure-sensitive area. Besides, the magnitude of pressure in hydrostatic socket is relatively lower than that of PTB socket. Though the subject had good acceptance of both sockets, it is believed that hydrostatic prosthetic socket provides better comfort due to its pressure profiles. Besides, hydrostatic socket is most advocated in country, especially in Malaysia that lack chartered prosthetists, as it can be easily fabricated using pressure tank without the intervention of specialist. Though relatively easier-fabricated and offer comparable quality of comfort as that of PTB socket, hydrostatic prosthetic socket cannot completely solve the problems of chartered prosthetist shortage in Malaysia. It is known that besides socket shape, there are other factors that cannot be neglected such as ground reaction force, alignment and thigh muscle strength [3], [8]. All of these factors necessitate an expert in prosthetics and orthotics to better develop functional modular endoskeleton prosthesis for Malaysian amputee.

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