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Vacuum Suspension and its Effects on the Limb

Since its inception in 1999 (Board et al., 2001), vacuum suspension has proven to be a major innovation. Vacuum suspension provides the amputee with unmatched linkage. This linkage alters the pressures that the limb experiences, which in turn prevents daily limb volume loss and improves limb health. The purpose of this paper is to review what is known about vacuum suspension and its effects on the limb.

Vacuum Suspension

A vacuum pump removes air molecules from the thin, sealed air space (sheath) between the total surface weight bearing socket and liner as shown in Fig. 1. The vacuum created by the removal of these air molecules holds the liner firmly and globally to the socket wall as shown in Fig. 2a.

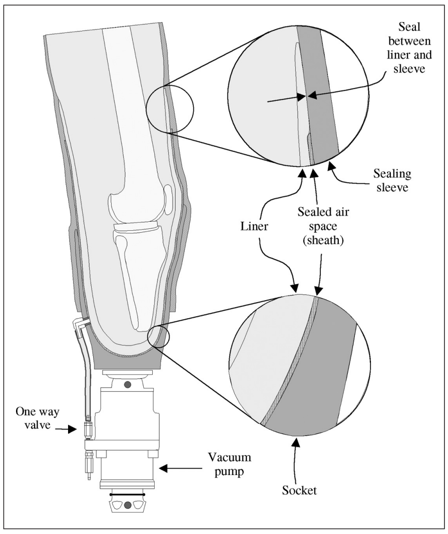

Fig. 1 *Cross section of vacuum suspension system showing sealed air space (sheath). Note that the sealed air space does not extend to the thigh. The seal between the top of the liner and sealing sleeve isolates the limb from the vacuum.*

Note that the limb is completely isolated from the vacuum. This raises the question: How can this vacuum that is completely isolated from the limb affect it in any way? The answer to this question is addressed in detail later in this paper. However, the essence is that the liner, and therefore skin, are no longer able to separate from the socket. This lack of separation of the liner and limb from the socket is thought to explain why vacuum suspension prevents volume loss and improves limb health.

As shown in Figure 2b, the sum of the axial components of the liner anchoring forces creates an exceptionally large suspension force; ~70 kg for the average size limb (33 cm proximal circumference) and vacuum (-78 kPa) (Street, 2006). This means that it would take an extraction force of ~70 kg to cause any separation between the liner and socket. Since extraction forces during daily activities seldom exceed 5-10 kg, vacuum suspension prevents separation between the liner and socket (Board et al., 2001). This is in sharp contrast to all other modes of suspension where the liner separates from the socket as soon as even a small extraction force (<0.25 kg) is applied to the socket.

Proprioception and Prosthesis Control

Eliminating separation between the liner and socket improves the patient's spatial awareness of (proprioception) and control over the prosthetic leg. Amputees new to vacuum suspension typically express surprise at how the prosthesis feels more a part of the limb. The prosthetic leg is more responsive; as the amputee moves his/her limb there is a corresponding, immediate movement of the prosthetic leg. The following unsolicited quote from an amputee that switched to vacuum suspension illustrates the functional significance of the improved linkage.

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"The second major bonus is how well your device stays 'glued' to my leg, making the prosthesis feel much lighter and allowing me to wear work boots again. The previous system that locked the liner to the socket with a pin always felt heavy, and made work boots unbearable. Managing my horse farm with tennis shoes was often a challenge, particularly in the muddy months. Now work boots feel light, and are easy to walk in."

Limb Volume

Vacuum suspension further improves proprioception and control of the prosthesis by preventing the limb from losing volume during the day. Unlike all other modes of suspension where the limb loses volume each day and causes a sloppy fit, the limb stays hydrated and positively keyed to the socket.

The first trans-tibial amputees to use vacuum suspension in 1999 reported that their limbs no longer lost volume during the day. This unanticipated effect of vacuum suspension has since been confirmed in two studies (Board et al., 2001; Goswami et al., 2003) and patients continue to consistently identify daily volume maintenance as a major advantage of vacuum suspension.

A study comparing daily limb volume loss between valve and vacuum suspension showed that limbs of trans-tibial amputees lost an average 6.5% in volume during 30 minutes of walking with valve suspension. On a separate day, the same subjects in the same sockets, except with vacuum applied to the expulsion port (vacuum suspension), gained 3.7% in volume while walking. In a separate study (Goswami et al., 2003), it was again shown that vacuum suspension prevents daily volume loss or results in a slight gain.

Limb volume fluctuates as pressure fluctuates (Guyton, 2000). In the morning before donning the socket, with one atmosphere of pressure (1 atm), limb volume is stable. As limb pressure increases, for example after donning the undersized socket or during stance, the limb loses volume. Volume is lost because elevated (>1 atm) pressure increases the amount of interstitial fluid being driven back into the bloodstream and lymphatic vessels, and out of the limb. In contrast, as pressure drops below 1 atm, such as when the tibia extracts and causes the soft tissues to elongate during swing, the limb gains volume. Volume is gained because low (<1 atm) pressure increases the amount of fluid being drawn out of the blood stream and into the limb's tissues.

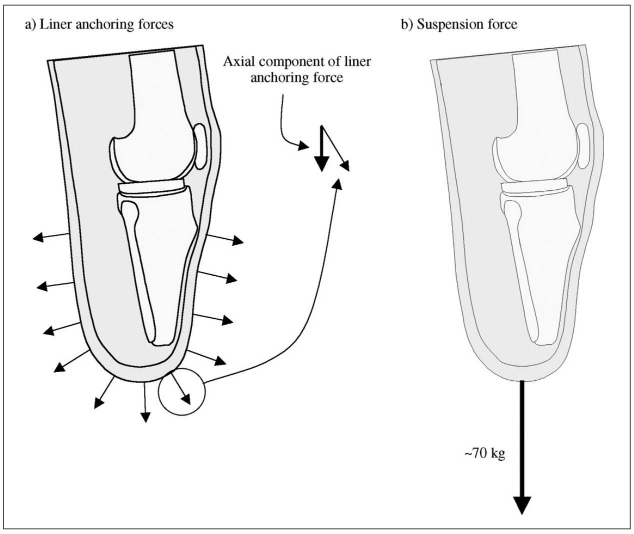

Fig. 2 *The vacuum creates forces that: a) anchor the liner to the socket. The sum of all the axial components of the axial forces creates a large: b) suspension force of ~70 kg. The suspension force prevents the liner/limb from extracting out of the socket.*

Hence, there are three possible explanations for why vacuum suspension prevents daily volume loss in ambulating amputees: 1) less fluid is driven out of the limb because of a reduction in positive pressure during stance, 2) more fluid is drawn into the limb because of a decrease in pressure during swing or 3) both. Beil et al. (2002) found that both changes occur with vacuum suspension. Compared to valve suspension, vacuum suspension 1) reduces the external positive pressure by ~4-7% during stance and 2) increases the drop in pressure an additional ~27% during swing. So, vacuum suspension shifts the fluid balance in the limb to one of maintenance or slight gain by driving less fluid out of the limb during stance and drawing more fluid in during swing. Of these two, Beil et al. (2002) proposed that drawing more fluid in because of the additional 27% drop in pressure is probably most responsible for volume maintenance.

We hypothesize that this additional 27% drop in pressure is a result of the liner staying anchored to the socket and the skin staying in close contact with the liner. With the liner globally anchored, as the tibia extracts from the soft tissues during swing, the tissues elongate and tissue pressure drops to a greater extent than with other modes of suspension (Beil et al., 2002). With valve suspension, the liner/limb separate from the socket (Street, 2006); resulting in less tissue elongation, smaller drop in pressure and less fluid being drawn into the limb. With pin suspension, there is an interesting paradox. During swing, there is an even larger pressure drop than with vacuum suspension; an additional 9% at the distal end of the limb (Beil et al., 2002, Beil and Street, 2004).

The paradox is that while pin suspension is even more forceful in drawing fluids into the limb, it is only at the distal end of the limb while the proximal portion of the limb is squeezed. So, with pin suspension, instead of moderate (valve suspension) to strong (vacuum suspension) global filling of the limb, there is strong distal filling, with a predisposition for congestion of these fluids and volume loss proximally because of the simultaneous proximal squeeze.

Limb Health

There is considerable anecdotal evidence from amputees that shows vacuum suspension improves limb health. A few clinical studies, yet to be published, are underway to document this effect. A nearly universal observation with vacuum suspension is the reduction or elimination of minor skin problems such as folliculitis and recurring cysts. More impressive are the cases where open wounds heal and remain healed upon switching to vacuum suspension. It should be emphasized that this healing occurs while the amputee wears the vacuum suspension prosthesis. In contrast, other modes of suspension normally require the limb be out of the prosthesis for healing to take place. The following unsolicited quote illustrates a typical experience of an amputee with chronic wounds after switching from pin to vacuum suspension.

"I have been a left below knee amputee for 3 years, and for most of that time struggled with pressure sores. Late last summer I developed two pressure sores on my distal stump that progressed into full-thickness erosions. I suffered with these painful sores for over 3 months before my doctor recommended that I have plastic surgery to resect them. Before I was able to make that appointment, I was called in by my prosthetist to try something new…your device. Within 2 weeks of wearing the [vacuum suspension] system, the pressure sores had completely healed. For the first time I can wear my leg all day in comfort. I used to go to bed for 2 hours as soon as I got home from work to give my stump a much needed break from the pressure. Last evening, after a 12-hour day at work, I stood in the kitchen and made supper for my family, and then did some work before calling it a night. Your innovation is nothing short of miraculous."

All prostheses place the limb in an unhealthy environment. The skin is subjected to pressures and shear forces that exceed those for which it is normally designed to withstand. Furthermore, the warm, moist socket environment is conducive for microbial growth; thus challenging the limb's immune system. Vacuum suspension has reduced the peak pressures (Beil et al., 2002) and shear forces because of its superior linkage and its maintenance of limb volume. Vacuum suspension has put an end to the abusive cycle where the fit becomes sloppy as the limb loses volume, causing the limb to hammer and bell clap in the socket, which in turn causes even more volume loss and limb trauma. The warm, moist socket environment remains an unresolved problem for all modes of suspension.

Aside from less physical abuse, a second likely explanation for the observed improvement in limb health and wound healing with vacuum suspension is increased blood flow (Street, 2002). Skin blood flow was measured as simulated walking pressures were applied to the limb. The cyclic, positive and negative pressures measured in an earlier study (Beil et al., 2002) were applied to the limb to simulate vacuum suspension. A clear pumping effect was observed in all trials. During simulated stance, blood was driven out of the skin blood vessels because of positive pressure. During simulated swing, the vessels rapidly refilled as the limb was exposed to negative pressure.

As of yet, no studies have been conducted to show that the increased blood flow improves limb health. However, it would have the potential to do so since blood is the delivery system that provides the limb with its nutrients and immune cells, and removes wastes. This coupled with the knowledge that vacuum suspension enhances fluid and nutrient exchange in the soft tissues strongly suggests that circulatory changes play a role in improving limb health and wound healing. Enhanced fluid exchange is thought to exist because of the observed limb volume maintenance as previously discussed.

The potential improvements in limb health and wound healing due to the global increase in blood flow and fluid exchange are probably most important when comparing vacuum suspension to pin suspension. Pin suspension creates a relatively strong distal draw while simultaneously constricting the limb proximally during swing phase (Beil and Street, 2004). This has the potential of causing distal limb congestion. In contrast, the pumping effect seen with vacuum suspension and valve suspension (to a lesser extent) appears to increase global circulation and fluid exchange, and avoid congestion.

Importance of Proper Fit

The benefits of vacuum suspension are only realized by the amputee if the limb and liner are in total contact with the socket. Meeting this requirement depends on the actions of the prosthetist and amputee. The prosthetist must design and construct a total surface weight bearing socket that closely matches the shape of the amputee's limb, and is free of specific weight bearing structures and areas of relief.

The amputee must maintain total contact by adding fillers if the limb loses volume. If both the prosthetist and amputee meet this requirement and vacuum is maintained, the amputee will reap the benefits of vacuum suspension. If they fail to meet this requirement, the limb will experience pressure, and skin damage in extreme cases, as the liner and limb are pulled into the void.

A properly fitting vacuum suspension system is almost certainly the healthiest environment for all limbs. This is especially true for vascular amputees or those on anticoagulants ("blood thinner" medication) who are prone to internal bleeding when exposed to high or low pressures and shear forces.

Vacuum suspension minimizes these pressures and shear forces because of the limb's positive global connection with the socket; a connection that is maintained throughout the day since limb volume is maintained.

Old Idea Revisited

Removing air molecules from the air space (sheath) between the socket and liner is a new concept. Yet, having the limb staying in close contact with the socket, and observing that it improves linkage and heals wounds is not new. Grevsten and Marsh (1971) and Grevsten (1977), who used a prosthesis with trans-tibial amputees that closely mimics vacuum suspension, reported that "all of the patients feel that the prosthesis is identified more closely with the lower leg" and that "all patients who were unable to wear the ordinary PTB prosthesis because of a skin lesion and who then tried the PTB-suction model noticed healing while using the new prosthesis." Grevsten and Marsh (1971) used a total contact, undersized socket. The trans-tibial amputee's limb was pulled into the socket using a stocking. After pulling the limb into the socket, the stocking continued to be pulled out the distal port until the limb was left in total contact with the socket. The hole was sealed with a threaded plug.

Since there was virtually no air in

the socket, suction prevented any measurable separation between the skin and socket. So, as with vacuum suspension where the skin stays in close contact with the anchored liner, their suction system where the skin was held in close contact with socket demonstrated similar improvements in linkage and healing of wounds.

Summary

Vacuum suspension is simply the removal of air molecules from the sealed air space in a valve suspension system. The resulting vacuum has one direct physical effect; it anchors the liner to the socket. The large suspension force, ~70 kg, created by the axial components of the liner anchoring forces prevents separation between the liner and socket. This provides the amputee with unmatched linkage that improves his/her spatial awareness and control over the prosthesis. With this elimination of pistoning, limb pressures and shear forces are reduced, providing the limb with a healthier environment. Unlike all other modes of suspension, vacuum suspension prevents the limb from losing volume during the day. So, a healthier environment is maintained throughout the day. The global pumping effect of the cyclic positive and negative pressures during walking increases circulation and fluid exchange, and probably plays a role in improving limb health and wound healing.

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