Comparison of interface pressures with pin and suction suspension systems

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Abstract—A common mode of limb suspension for transtibial amputees is the pin liner/shuttle lock system. Despite its popularity, some clinicians question its use because of observed daily and chronic changes to the residual limb. For this study, we measured limb interface pressures during ambulation with pin and suction suspension systems. No pressure differences were seen between the modes of suspension during stance phase. However, during swing phase, pin suspension maintained an average occlusive compressive pressure of 6.7 kPa on the proximal tissues, as compared to the subocclusive pressure of 1.1 kPa with suction suspension. Simultaneously, pin suspension elevated the peak magnitude of suction to –39.5 kPa at the distal residual limb, compared to –26.1 kPa with suction suspension. During swing phase, the pin liner squeezes proximally while creating a large suction distally on the residual limb and is the likely cause of daily and chronic skin changes observed in pin users.

Key words: interface pressure, pin suspension, prosthesis, residual limb, suction suspension, transtibial amputee, urethane liners, verrucous hyperplasia.

INTRODUCTION

Prosthetists attempt to fit transtibial amputees with sockets that provide a firm connection to the artificial limb without causing skin disorders or limb pain. The challenges lie in the large loads placed on the previously non-weight-bearing tissues of the residual limb. As a result, all socket designs place undue stress on the residual limb. The traditional patellar-tendon-bearing (PTB) socket is designed to impose high pressures on the patellar tendon and medial tibial flair, which can reach peak pressures of 300 to 400 kPa [1–3]. In contrast, total contact PTB sockets without gel liners and total surface-bearing sockets with gel liners attempt to distribute more evenly the pressures across the residual limb with peak pressures less than 200 kPa [4–6].

Evidence suggests that skin adapts to these stresses [7–9] but also that skin health is clearly compromised. Ulcers [10–11], epidermoid cysts [8,10], Kaposi-like sarcoma [12–13], and verrucous hyperplasia [10,14–15] are skin conditions that are attributed to external pressures applied to the residual limb. Sustaining proper circulation and fluid exchange in the soft tissues is imperative for maintaining a healthy residual limb. Pressures applied to the limb by socket systems, chiefly during ambulation, complicate this task. Therefore, clinicians need to be aware of the pressures applied to the residual limb when prescribing socket systems to patients, particularly physically active amputees or those amputees with compromised circulation.

Pin and suction suspension prostheses are commonly used by amputees. Both systems use gel liners within undersized total surface-bearing sockets, although their

modes of suspension are quite different. Pin suspension uses a metal pin extending distally from the liner that locks into a receptacle at the bottom of the socket. Suction suspension does not use a pin. Instead, suction develops in the slight air space between the gel liner and socket when the liner attempts to slide proximally relative to the socket during swing phase of ambulation. The air space is sealed by a gel sleeve covering the proximal socket and liner along with a one-way valve at the distal expulsion port of the socket.

The pressures associated with pin suspension have yet to be reported in the literature, despite its prevalent use. This lack of pressure data is of some concern because of an apparent link between observed limb changes and pin use. The symptoms most commonly seen in amputees who use a locking pin system for suspension are daily reddening and swelling of the distal residual limb. Long-term changes with pin use include general thickening and discoloration of the distal tissues [16]. This condition can sometimes develop into verrucous hyperplasia in long-time pin users, which is a hyperplastic disease of warty papules (10,14–15,17).

Prosthetists attribute these symptoms to the liner being stretched during swing phase, thus squeezing the limb proximally and creating a heavy localized suction distally. Manufacturers of pin liners have attempted to reduce this effect by reinforcing the pin liner with various stiffening materials to supplement the support already provided by the fabric covering. These stiffeners extend from the pin toward the proximal end of the liner. Despite these attempts and regardless of the type of liner material (silicone, thermoplastic, or urethane), daily distal swelling and discoloration of the residual limb continue to be observed with pin suspension.

We designed the current study on transtibial amputees to measure and contrast pressures applied to the residual limb when using two methods to anchor the gel liner to the socket:

1. Distal pin.
2. Suction created between the socket and liner during unweighting with a sealing suspension sleeve.

We conjectured that the positive (compressive) pressures during the stance phase of walking will be the same with both modes of suspension. However, during swing phase, we hypothesized that the pin-anchored liner will maintain compressive pressures on the proximal tissues, creating a squeezing effect while increasing the magnitude of the negative pressure distally. In contrast, we theorized that suction suspension will relieve compressive pressures on proximal tissues and decrease the magnitudes of the negative pressures distally during swing phase, as illustrated in **Figure 1**.

METHODS

To compare the effects of two modes of suspension, we outfitted urethane liners with pressure sensors such that limb and liner interface pressures could be measured during ambulation. Instrumentation consisted of five force-sensing resistors (Model 402, Interlink Electronics, Camarillo, CA) that measured positive pressures through contact and one air pressure sensor (Model 8515c, Endevco, San Juan Capistrano, CA) that measured the negative pressure at the distal end of the limb with a full bridge configuration.

We conducted calibration of the 0.6 mm-thick, 18 mm-diameter contact sensors by applying pressure with an inflatable air bladder while the sensor was placed on a flat piece of Shore® type OO durometer urethane. Pressures from 0 to150 kPa were randomly applied twice
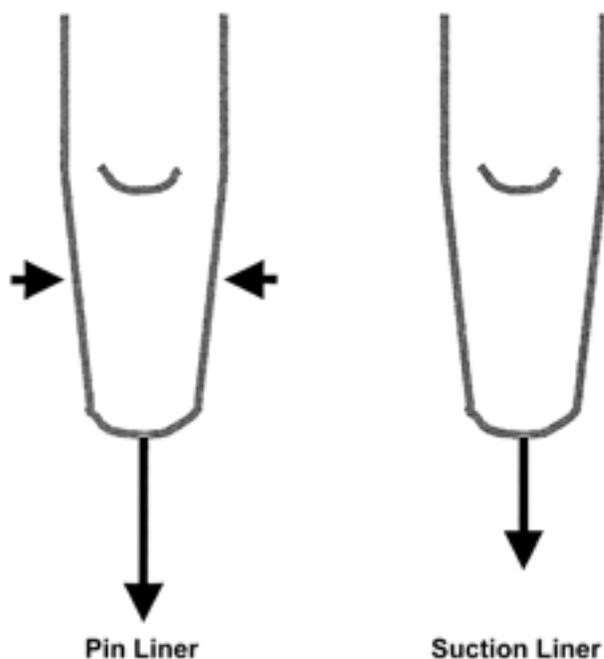

Figure 1.
Illustration on left shows pressure application of pin suspension during swing phase as compared to suction suspension of illustration on right. The pin effect created by pin suspension is a squeezing of proximal tissues while suctioning distal tissues.

in increments of 10 kPa while the voltage output was recorded for each sensor. A piecewise regression was fitted to the data in which an exponential equation was applied from 0 to 30 kPa, and an equation of the fourth power was fitted from 30 to 150 kPa. The curvilinear output resulted in decreasing precision with increasing pressure. From 0 to 80 kPa, the average residual was ±0.95 kPa (0.40–2.63) and ±2.45 kPa (1.0–4.07) from 80 to 150 kPa.

We used a sealed chamber attached to a syringe to calibrate the air pressure sensor. The syringe was drawn to create pressures in 10 kPa increments from 0 to –80 kPa. A linear regression equation was fit to the output voltages with an average residual of ±0.12 kPa (0.04–0.26).

To ensure sensors would be flush with the inner liner wall, we attached five contact sensors to the liner mold prior to pouring. Tubes containing sensor wires were molded within the liner wall from the sensor out through the proximal edge of the liner. Thus, an air vent was maintained for proper sensor function and amputee discomfort was avoided, since the wires were not in contact with the skin.

We gathered data in the current experiment in conjunction with a companion study that dictated the sensors be placed on soft tissue areas [4]. A pentagon pattern was used for sensor placement to provide a sample of pressures covering the entire posterior aspect of various sized and shaped residual limbs. The first contact sensor was centered on the gastrocnemius approximately 3 cm below the brim of the socket and was referred to as the proximal sensor. A contact sensor was placed on each side of the proximal sensor at the distal end of the liner avoiding the acute curvature, which was approximately 2 cm from the end of the limb. These were labeled *distal medial* and *distal lateral*, accordingly. The final two contact sensors were placed on the medial and lateral aspects of the liner at a height midway between the proximal and distal contact sensors and identified as *midmedial* and *midlateral*. No sensors were placed on the anterior aspect of the residual limb because of bony prominences. The general pattern and relative size of the contact sensors is shown in **Figure 2**.

The air pressure sensor was placed in a 1 cm^3 cavity at the distal end of the liner during testing. Extra space in the cavity was filled with cloth and held in place with a thin piece of urethane tape. The thin (0.6 mm), flat sensor wire was run along the limb and out the proximal edge of the liner. Vaseline was placed around the wire from

where it exited the liner to prevent air from being drawn in during ambulation.

Each subject was provided custom pin and suction socket systems manufactured by TEC Interface Systems, Inc. (Waite Park, MN). Liners and sockets were constructed by the same practitioner with digitized limb dimensions and computer-aided design and machining technology. Liners were of Shore® type OO durometer urethane and undersized by 10 percent. The total surface weight-bearing check sockets were undersized by 4 percent.

The pin system consisted of a pin liner, stretchable fabric bonded to the outside of the liner, check socket with a shuttle lock, pylon, and solid ankle cushion heel (SACH) foot. A suspension sleeve was not worn with the pin system. The suction system consisted of a urethane sealing suspension sleeve worn over the proximal half of the socket and distal three-fourths of the thigh. The sealing sleeve created a thin sealed air space between the liner
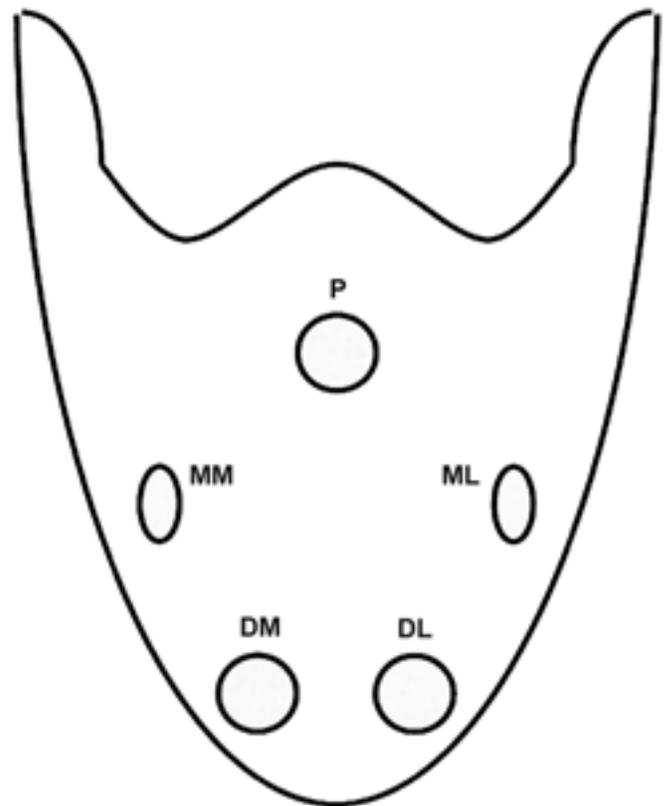

Figure 2.
Illustration of placement of five contact sensors as viewed from posterior of limb. Sensor locations are described as *proximal* (P), *midmedial* (MM), *distal medial* (DM), *midlateral* (ML), and *distal lateral* (DL).

and socket, enabling suction to suspend the prosthetic limb. The system was completed with a 0.3 mm-thick nylon sheath over the urethane liner, a check socket with one-way valve, pylon, and SACH foot.

Eight unilateral, transtibial amputees who regularly used a urethane liner and total surface weight-bearing socket completed the study. Mean age was 46 yr (33–65), mean limb maturity was 18 yr (6–32), and none of the subjects were amputated because of vascular conditions. All testing procedures were approved by the institutional review board. Upon arrival on the testing day, the prosthetic limb was dynamically aligned with standard alignment procedures.

Because this experiment was conducted concurrently with another study, all subjects completed the three suction system trials before the three pin system trials. A trial consisted of a subject walking over level ground for 20 m next to a target that was controlled at 4 km/h. We collected data for five steps once the subject had reached a steady-state walk to avoid times of acceleration or deceleration. Pressure data were collected with a 12-bit analog-to-digital (A/D) board (Keithley Instruments, Cleveland, OH) at 100 Hz for eight seconds per trial.

Toe-off and heel strike were identified as the rapid fall and rise in pressure measured by the distal air pressure sensor. Its output, as opposed to the five contact sensors, was more sensitive to the vertical movement of the limb within the liner that occurred at these critical events. The greatest negative and positive slopes were calculated for each trial. Toe-off and heel strike were defined to occur when the slope reached a value that was half the maximum negative or positive slope of that trial.

We calculated a pressure impulse value for stance and swing phases by finding the area under the respective positive and negative pressure curves. An average pressure was calculated for each of the five contact sensors during stance and swing phases, and an average pressure for the air pressure sensor was calculated for the swing phase. Peak positive and negative pressures were identified for each step at each sensor. As a precaution to avoid false peaks, we smoothed data with a 0.1 s floating average before identifying the peak.

Three two-factor repeated measures analyses of variance (ANOVAs) (a = 0.05) were used to determine if a difference existed between the suspension systems in pressure impulse values, average pressures, and 0.1 s peak pressures for the five contact sensors during stance phase. Pressure impulse values and average pressures of the contact sensors during swing phase were also analyzed with two-factor repeated measures ANOVAs (a = 0.05). Three single-factor ANOVAs (a = 0.05) were run to test for significant differences between conditions in pressure impulse value, average pressure, and 0.1 s peak pressure of the air pressure sensor during swing phase.

RESULTS

During the stance phase of ambulation, pressures with the pin system were not significantly different from those in the suction system (p = 0.76). Average pressures during stance phase were 68.6 kPa (15.0–152.1) and 66.4 kPa (23.1–114.7) with pin and suction suspension, respectively.

During the swing phase, several pressure indicators were significantly different between the two modes of suspension. The positive pressure impulses (3.5 kPa·s versus 0.5 kPa·s, p = 0.008) and average positive pressures (6.7 kPa versus 1.1 kPa, p = 0.004) of the contact sensors were significantly greater with pin suspension than suction suspension and are presented in **Tables 1** and **2**. The difference in positive pressures applied to the limb is illustrated in **Figure 3** with a comparison of sample pressure curves from one subject under each condition.

The distal negative pressures measured during swing phase were also significantly different between conditions. The magnitudes of the negative pressure impulses and peak negative pressures were larger with pin suspension than suction suspension: –16.0 kPa·s versus –10.3 kPa·s (p = 0.053) and –39.5 kPa versus –26.1 kPa (p = 0.026), respectively. The negative pressures for each subject are listed in **Table 3**.

DISCUSSION

Pin suspension has raised concerns among a number of prosthetists who regularly observe daily swelling and dark red discoloration of the distal end of the residual limb. These symptoms generally subside by the next morning in most pin users. More permanent changes observed in long-term pin users include a distal bulbous shape, darkening and thickening of the distal skin, and occasionally, verrucous hyperplasia. These residual limb changes are most likely associated with the elongation of the liner, which generates a squeezing of the limb proximally and suctioning of the limb distally during the swing

Table 1.
Pressure impulse values in kilopascal seconds for the five contact sensors during swing phase.

Subject	Pin					Suction				
	P	**MM**	**DM**	**ML**	**DL**	**P**	**MM**	**DM**	**ML**	**DL**
1	5.7	17.4	4.9	7.2	3.2	0.2	0.2	0.2	0.2	0.3
2	3.9	1.1	0.2	0.5	0.0	2.7	0.0	0.0	2.8	0.0
3	6.5	9.9	1.0	9.5	1.1	0.3	0.3	0.2	0.3	0.2
4	1.8	7.0	2.1	3.1	1.8	0.7	0.9	0.0	0.3	0.0
5	6.5	5.0	0.6	3.6	3.0	2.2	0.9	0.0	0.8	0.0
6	7.9	5.9	0.5	2.2	1.0	0.2	1.3	0.2	0.3	0.2
7	3.7	0.7	0.0	0.2	0.2	0.5	0.3	0.0	0.0	0.0
8	5.4	4.0	0.2	2.1	0.2	0.1	0.3	0.0	0.7	0.0
Average	5.2	6.4	1.2	3.5	1.3	0.9	0.5	0.1	0.7	0.1
Overall Average	—	—	3.5	—	—	—	—	0.5[*]	—	—

[*]$p < 0.05$
P = proximal, MM = midmedial, DM = distal medial, ML = midlateral, DL = distal lateral

Table 2.
Average positive pressure in kilopascals for five contact sensors during swing phase.

Subject	Pin					Suction				
	P	**MM**	**DM**	**ML**	**DL**	**P**	**MM**	**DM**	**ML**	**DL**
1	8.6	26.7	7.3	10.8	4.7	0.5	0.6	0.4	0.4	0.6
2	7.7	2.3	0.4	1.2	0.0	6.2	0.1	0.0	6.4	0.0
3	11.5	16.7	2.1	17.4	2.0	0.8	0.8	0.4	0.8	0.6
4	3.3	13.6	4.2	6.1	3.5	1.6	2.0	0.0	0.8	0.0
5	13.3	10.2	1.4	7.5	6.2	5.3	2.3	0.0	2.0	0.0
6	16.1	12.1	1.2	4.5	2.5	0.7	3.0	0.5	0.9	0.5
7	6.6	1.2	0.1	0.3	0.3	1.3	0.8	0.0	0.1	0.1
8	11.1	8.2	8.2	4.4	0.5	0.2	0.9	0.0	1.7	0.1
Average	9.8	11.4	3.1	6.5	2.5	2.1	1.3	0.2	1.6	0.2
Overall Average	—	—	6.7	—	—	—	—	1.1[*]	—	—

[*]$p < 0.05$
P = proximal, MM = midmedial, DM = distal medial, ML = midlateral, DL = distal lateral

phase (**Figure 1**). In support of the notion of a pin effect, some transtibial amputees have reported proximal tightness and discomfort distally because of the suction [18].

In contrast, these symptoms are rarely observed with suction suspension socket systems [19–20]. In fact, when users switch from pin to suction suspension, the symptoms are alleviated. During our observations of pin users who discolor and swell daily, the distal limb reverts to its normal color within 30 min of wearing a total surface-bearing, suction suspension prosthesis, and the bulbous end is lost within a few days. In the majority of long-time pin users, the thickening and darkening of distal skin gradually return to normal after switching to a

total surface-bearing, suction suspension prosthesis. These symptoms are likely alleviated because liner stretch is avoided with suction suspension. The same pulling force of swing phase is distributed more evenly to the liner and to the suspension sleeve, as opposed to only the distal end of the liner as with pin suspension.

No difference in pressures between pin and suction suspension was measured during stance phase. This is quite understandable, since in both conditions, the same subject weight was applied over the same surface area in the two sockets. Pressures recorded in the current study are of similar magnitude to those reported in other interface studies of total contact sockets [1,5–6]. The pressures
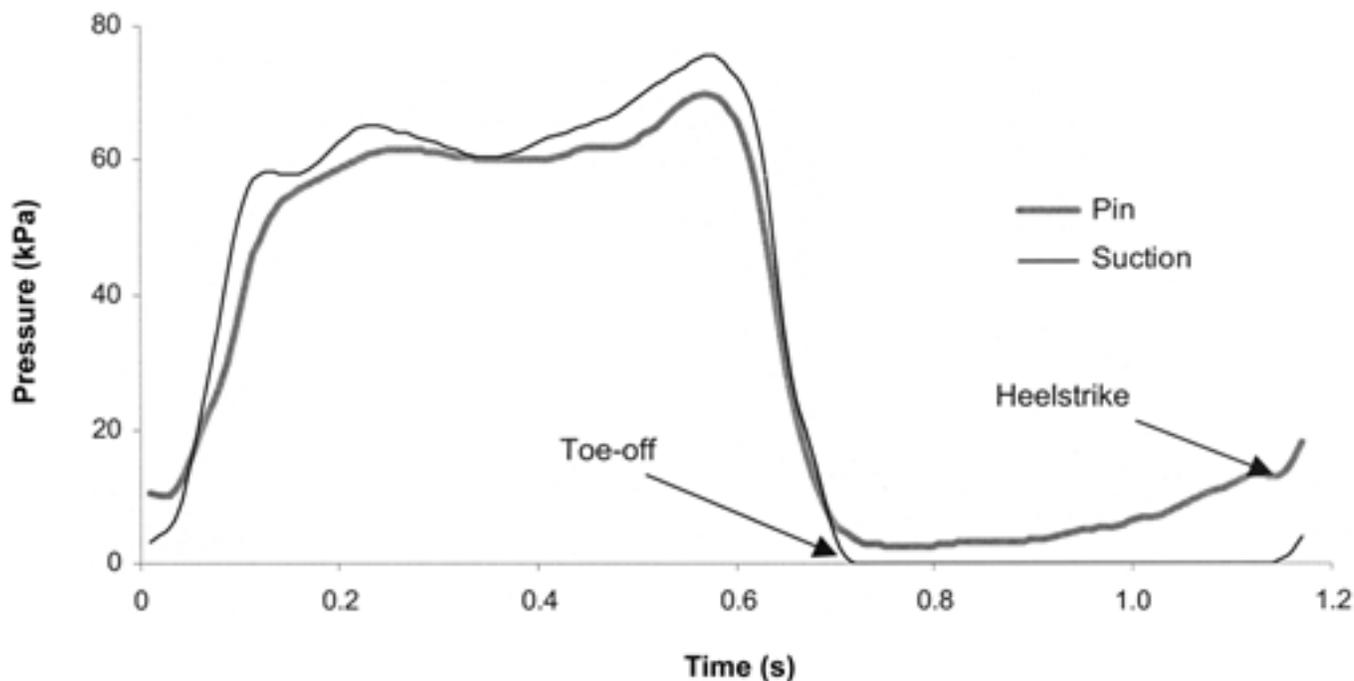
Figure 3.
Sample pressure curves from one contact sensor midmedial (MM) with pin and suction suspension for one complete step for Subject 8.

measured at the various sensor locations were of very different magnitudes between individuals. For example, the midlateral sensor had a range of 51.8 to 108.1 kPa of average pressure during stance phase. This difference between individuals is expected and can be attributed to many factors, including liner and socket fit, limb shape and length, prosthesis mass, and gait.

Pressures measured in this study support the notion of a pin effect during swing phase as illustrated in **Figure 1**.

Table 3.
Negative pressure impulse values in kilopascal seconds and peak negative pressure values in kilopascals attained during swing phase.

Subject	Pin		Suction	
	Impulse	Peak	Impulse	Peak
1	−20.9	−49.1	−8.4	−23.7
2	−26.6	−58.1	−11.1	−28.5
3	−10.5	−31.0	−8.3	−35.2
4	−17.4	−39.7	−15.1	−19.6
5	−5.9	−16.8	−8.8	−22.3
6	−10.8	−39.0	−6.7	−16.8
7	−26.0	−25.1	−13.4	−26.3
8	−10.1	−56.9	−10.9	−36.5
Average	−16.0	−39.5[*]	−10.3	−26.1[*]

[*]$p < 0.01$

Compared to suction suspension, pin suspension elevated the average proximal compressive pressures by 5.6 kPa (500%) and the magnitude of the peak distal negative pressures by −13.4 kPa (51%) during the swing phase. One previous interface study recorded negative pressures in suction suspension and found similar values to what was found in the current study [19]. Suction suspension nearly completely relieved the limb of compressive pressures, only 1.1 kPa, during the swing phase.

Applying external pressures to the residual limb invariably affects circulation. Understanding the effects in detail is difficult, given that most pressure studies applied pressures much smaller than those typically applied by sockets and applied them for sustained durations [21–24]. Those that did apply cyclic pressures did not use a high enough frequency to mimic the pressure application during ambulation [25–27]. One study was found that applied both positive and negative pressures in a cyclic manner at 10 s intervals [28]. The study concluded that the cyclic application of positive and negative pressure might have a small effect on increasing circulation. The applicability of this notion to the pin liner is complicated by the pin liner concurrently applying positive and negative pressure during swing phase.

Pin suspension applied an average compressive pressure of 6.7 kPa to the proximal tissues during swing phase. Some estimates indicate that an external compressive pressure greater than 4.3 kPa occludes circulation in capillaries [29]. Therefore, during ambulation with pin suspension, no relief is given from proximal occlusive pressures. In contrast, suction suspension should allow normal circulation to resume during swing phase, because it applied only 1.1 kPa.

Shear pressure is also an important factor in blood flow and occlusion [30–31]. Bennett et al. estimated that with the addition of shear, the amount of positive pressure required to occlude blood flow is halved [30]. While shear pressure was not measured in the present study, almost certainly, the skin experienced shear proximally with both modes of suspension during the swing phase. The stretch of pin liners during swing phase likely creates larger shear values than suction suspension, further raising concern over the pin liner's occlusive effects.

Negative pressure or suction externally applied to skin has been shown to increase the amount of fluid drawn into soft tissues [32]. Both modes of suspension apply high suction to the distal end of the residual limb during swing phase. The key difference between the two modes is that pin suspension also potentially impairs the free flow of fluids into and out of the limb by squeezing the midportion of the residual limb. This combination of pressures likely causes distal edema and venous stasis, which have been thought to be the main contributing factors to verrucous hyperplasia [10–11,14]. With extended use of the pin suspension, it is common for the skin to thicken and darken in pin users. In some cases, this progresses into verrucous hyperplasia. Although verrucous hyperplasia is typically a benign condition, cases have been found in which verrucous hyperplasia became malignant [16,33].

Our study only looked at pressures at five regional locations on the limb on a limited number of individuals. Because of large variations in limb length and geometry, these locations only lend insight into the interaction of the socket system and the limb. Ideally, pressures should be mapped at an infinite number of locations on the limb, so a complete understanding of the effects of the pin liner on the limb could be gained.

In summary, pin suspension elevates the magnitude of the negative distal pressure and maintains a proximal squeeze during swing phase. Pin suspension pressures and its observed effects on the limb lead one to question the efficacy of the fairly widespread use of pin suspension. With the majority (50%–70%) of transtibial amputees suffering from diabetes and circulatory conditions independent of the prosthesis [34], complications imposed by pin suspension can be debilitating. This is particularly true for amputees who experience frequent and/or large socket extraction forces, including those who are physically active or wear heavy prostheses. Fortunately, alternative modes of suspension exist, such as suction, that do not create pressure distributions that are likely to disturb normal circulation and soft tissue fluid balance as drastically as pin suspension.

CONCLUSION

During the swing phase of ambulation, pin liners maintain compressive pressure on the proximal tissues of the residual limb while creating large suction at the distal end. This pressure combination is the likely cause of the daily and chronic skin changes often observed in pin liner users.

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