EFFECTS OF PROSTHETIC SOCKET SUSPENSION ON KNEE PROPRIOCEPTION
AND DYNAMIC BALANCE IN TRANSTIBIAL AMPUTEES

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ABSTRACT

Background

Prosthetic socket suspension offers a critical means to intimately integrate the prosthetic device with the human body. Effects of vacuum assisted socket system (VASS) on residual limb volume and skin health have been reported, however, little is known about its effects on joint proprioception and dynamic balance in lower limb amputees. The objective of this study was to quantitatively investigate the effects of VASS on knee proprioception and dynamic balance in transtibial amputees in comparison to suction and locking-pin suspension systems.

Methods

We recruited a group of unilateral transtibial amputees and placed them in three groups according to the suspension types: 1) locking pin (n = 10); 2) suction (n = 9); 3) VASS (n = 7). We assessed knee joint proprioception using target position matching method on both sound and affected sides, with and without weight bearing and across five target knee joint positions ranging from 5 to 25 degrees with 5 degrees of increment. Local dynamic stability was assessed using a wearable wireless accelerometer and nonlinear analysis (i.e. largest Lyapunov exponent) while participants were walking on a treadmill.

Results

Knee joint proprioception was comparable across suspension types. Participants showed overall better performance of joint proprioception with weight bearing. In addition, the performance was target position dependent and the smallest error was found under 5 degrees of knee flexion while the largest matching error was shown under 10 degrees of knee flexion. The locking-pin suspension showed the best local dynamic stability in the anteroposterior direction.
Conclusion

Socket suspension does not appear to influence knee joint sense and locking-pin is superior to other means particularly suction in local dynamic stability. The benefits of using VASS are hence not supported by this study.

Key words: Amputee, local dynamic stability, prosthetic socket suspension, suction, VASS, locking-pin, proprioception.
Introduction

Prosthetic socket suspension offers a critical means to intimately integrate the prosthetic device with the human body. A wide range of suspension systems exist including but are not limited to suction, locking-pin and vacuum assisted socket system (VASS). Each type of suspension has its pros and cons. For example, locking-pin suspension is reported to significantly reduce the pistioning movement between the stump and the socket \(^1\). However, during swing phase the locking-pin suspension could cause significantly larger negative pressure at the distal end of the limb than suction, which likely leads to skin problems \(^2\). When compared to suction, VASS applies a significantly higher yet more uniform negative pressure on the residual limb, which helps to reduce volume fluctuation and promote wood healing in residual limb \(^3-5\). In addition, VASS is reported to improve gait symmetry \(^5\). The effects of aforementioned suspensions on residual limb volume, socket interface pressure and skin problem have been investigated. Though several studies highlighted the benefits of using VASS, some pointed out that the benefit was only marginal and/or amputee dependent \(^6\). The mixture of inconsistency in outcomes measures and relatively meager scientific evidence fails to justify its clinical necessity. VASS is hence still treated as experimental and investigational and not covered by insurance.

Proprioception, a collective neural afferent inputs from mechanoreceptors in the joint capsule, ligaments, muscles, tendons and skin, allows us to sense the position of the limbs subconsciously. The distal joints (e.g. foot and ankle) tend to have higher density of sensory input than proximal ones \(^7,8\). Reduction or loss of proprioception is a debilitating condition particularly in lower limb amputations. For example, when compared to the sound limb, the knee joint proprioception was reported significantly worsened in the threshold detection test in below-knee amputees \(^9\). Furthermore, it could jeopardize the dynamic balance in gait, which in turn could lead
to increased risk of fall. Effects of VASS on residual volume and skin health have been reported in the literature, however, little is known about its effects on proprioception in lower limb amputees. In addition, the proprioception was assessed without weight bearing. Earlier study showed that weight bearing had enhanced perception of proprioception than non-weight bearing. In a complete gait cycle stance (weight bearing) and swing (non-weight bearing) phases are constantly alternating and it will be reasonable to evaluate proprioception under both conditions. Furthermore, degradation in proprioception might worsen dynamic balance in gait and it remains unknown if VASS will benefit dynamic balance. Dynamic balance in amputees has been successfully quantified with non-linear dynamics approach. Particularly, the largest Lyapunov exponent has been reported to be a valid metric for assessing gait variability and/or predicting risk of fall.

To further extend our current existing knowledge base on the effects of VASS, studies addressing aspects closely related to amputee’s functional performance when using VASS are strongly needed. The objective of this study was hence to quantitatively investigate the effects of VASS on knee proprioception and dynamic balance in transtibial amputees. We hypothesized that VASS will improve the knee proprioception in transtibial amputees in position target matching tasks at the knee joint with and without weight bearing as well as dynamic balance in comparison to suction and locking-pin suspension systems.

Methods

Subjects
Sixteen unilateral transtibial amputees, who have amputations due to either trauma, infection or Peripheral Vascular Disease (PVD) for more than a year without neuromuscular disorders and can walk independently (K level ≥ 2, 15 male and 1 female; mean (std); age: 63.4 (7.9) yrs; body mass: 85.5 (22.4) kg; body height: 1.77 (0.10) m), participated in the study. With one-way expulsion valve and/or vacuum pump, we were able to obtain two other types of suspension (i.e. suction and VASS) for five participants who originally used locking-pin suspension. Participants were placed in three groups according to the suspension types used: 1) locking pin (n = 10); 2) suction (n = 9); 3) VASS (n = 7). The study was approved by the local Institutional Review Board. All participants were recruited from the prosthetics and orthotics clinic at UT Southwestern Medical Center and signed informed consent form before the test. Detailed demographic information is summarized in table 1.

Instrumentation

A custom electrical goniometer (Bourns AMS22U non-contacting analog rotary position sensor, linearity: 0.5%; supply voltage: 5VDC) was used to measure knee joint position. The goniometer had two arms which were secured on the thigh and lower leg using elastic bandage on the lateral side of the knee. A custom LabVIEW GUI was used for data acquisition and signals were collected via an NI PCIe6363 data acquisition card at a rate of 100 Hz (National Instrument, Inc., Austin, TX, USA). A three-dimensional wireless IMU sensor (YEI Technology, 3-Space Sensor Wireless 2.4 GHz) was used to register the acceleration (at a range of ±2 g) of the center of mass of the body during treadmill walking. The signal was streamed to a desktop PC at a rate of 100 Hz. A NordicTrack™ treadmill was used for walking trial. For the five participants who originally used locking-pin suspension, a battery-powered air-pump (vacuum level up to 25 inHg) was used to convert the test suction socket to VASS.
Protocol

Knee position sense test

Knee position sense was tested with (WB) and without weight bearing (NWB) for both sides with joint target positions set at 5, 10, 15, 20 and 25 degrees of knee flexion. Participants were instructed to stand upright between parallel bars (Figure 1a). For each test condition, a baseline condition was collected at the beginning when participants kept the knee of the tested sided fully extended. The target positions were randomly selected. Participants were allowed to practice with visual feedback of their knee joint position shown on the computer screen to ensure that they were comfortable with the target positions. Visual feedback was removed once they were ready for joint position matching test. Participants attempted to match the target positions and held at the target position for at least 3 seconds. Six trials were conducted for each test condition.

Dynamic balance test

Participants walked on the treadmill at their self-selected speeds. The tri-axial accelerometer was attached to the low back region (close to L5/S1)\(^{17}\) (Figure 1b). The accelerometer was oriented in such a way that X, Y and Z axes corresponded to anteroposterior (AP), mediolateral (ML) and vertical (VT) directions. Participants were instructed to stand upright for 10 seconds for baseline recording and the data were used for accelerometer tilt calibration\(^{18}\). A three-minute walking session was conducted after participant’s walking was stabilized.

Data analyses
The knee joint position signals collected during the joint sense test were first low-pass filtered with a zero-lag 4th order Butterworth digital filter with a cut-off frequency set at 5 Hz. The position matching error was calculated as the difference between the target position and the average of attempted joint position with a window size of 100 data points (i.e. 1 second of recording, figure 2). The position matching error was further obtained by averaging across the six trials.

The acceleration signals collected during treadmill walking were first compensated for initial tilt and then low-pass filtered with a zero-lag 4th order Butterworth filter with cut-off frequency set at 20 Hz. For each walking trial, gait cycles were identified according to the acceleration signal in the AP direction. The AP acceleration was first low-pass filtered at 2 Hz and the peaks right before the sign of signal switching from positive to negative were treated as heel strikes. A consecutive 100 complete gait cycles were identified. Data series were resampled to 10,000 data points. The largest Lyapunov exponents (LLE) for both short-term (0-1 stride, ST) and long-term (4-10 strides, LT) were obtained with a time delay of 15 and an embedding dimension of 5 for each of the three directions (Figure 3). The embedding dimension and time delay were obtained by using Global False Nearest Neighbors (GFNN) analysis and Average Mutual Information (AMI) function respectively. All data analyses were conducted using custom MATLAB programs (MathWorks Inc., Natick, MA, USA).

Statistical analyses

One-way ANOVA with repeated measure was conducted. Dependent variables included knee joint matching error, ST LLE and LT LLE. Independent variables include weight-bearing
(WB v.s. NWB), side (affected v.s. sound), target position (5, 10, 15, 20 and 25 degrees) and suspension type (locking-pin, suction and VASS). All statistical analyses were done in SPSS with significance level set at P< 0.05. Post-hoc comparisons with Bonferroni correction was conducted if ANOVA showed statistical significance.

Results

Knee joint proprioception

The performance of knee joint proprioception was assessed using joint target position matching error. The matching errors of knee joint position are 2.02±0.57 deg, 2.20±0.60 deg and 2.02±0.68 deg (mean±SE) for locking-pin, suction and VASS respectively and there is no statistical difference between suspensions (P=0.97). The matching errors of knee joint position are 2.63±0.44 deg and 1.53±0.35 deg for non-weight-bearing and weight-bearing respectively (P=0.004). Target position shows significant effect and the matching errors are 1.50±0.32 deg, 2.78±0.46 deg, 2.50±0.37 deg, 1.74±0.33 deg and 1.87±0.66 deg for target positions of 5, 10, 15, 20 and 25 degrees respectively (P= 0.004). In addition, sound side shows slightly better performance than affected side (1.82±0.29 deg v.s. 2.35±0.52 deg) though the difference does not reach significant level.

Dynamic balance

No significant effect is revealed on long term LLE. The short term local dynamic stability in the anteroposterior direction are 0.38±.04, 0.52±0.04 and 0.44±0.04 (mean±SE) for locking-pin, suction and VASS respectively. The effect of suspension shows statistical significance.
(P=0.047) only in the AP direction and the AP short-term LLE of locking-pin is significantly less than that of suction (P=0.036).

**Discussions**

Our hypothesis that VASS will improve knee proprioception is not supported by the findings of the study. Among different prosthetic socket suspension, suction showed the largest matching error when compared to either locking-pin or VASS while the performance of locking-pin and VASS is fairly comparable. At this point, we cannot compare our results to the literature due to a lack of study on knee joint proprioception using all three suspension types.

The outcome of this study indicates that prosthetic socket suspension does not influence knee joint sense. Proprioception could be attributed to a wide range of sources including mechanoreceptors in the joint capsule, ligaments, muscles, tendons and/or skin. In addition, joint proprioception could be enhanced by using other cues. For example, patellar taping has been reported to improve knee joint proprioception in healthy population with poor proprioceptive ability \(^{21}\). Though VASS or suction was expected to enhance the sensory input, particularly through the skin and/or soft tissue of the residual limb due to an intimate contact interface between the residual limb and the socket, locking-pin seems to provide similarly intimate interface via the gel liner and a more secure attachment at the distal end. Collectively, the overall sensory input when using locking-pin is not much different from that when using other types of suspension.

The current study also shows that there is no difference in knee joint proprioception (i.e. target position matching) between the affected side and the sound side though the affected side shows slightly better performance. There are very limited studies on knee joint proprioception in
lower limb amputees and to the best knowledge of the authors, there is only one study in which the knee joint proprioception was assessed using threshold detection method and showed that the affected side had significantly poorer performance. In the current study, we used joint position matching (or duplication) method, which has been reported to have good reliability. Both methods have been extensively used in evaluating joint proprioception and each has its own pros and cons. However, the threshold detection method typically needs more sophisticated setup (e.g. a motorized device to move the joint at slow speed), which makes it impractical in clinical practice.

Weight-bearing does improve the performance of joint proprioception. Our results are in agreement with a previous study in which a significantly higher accuracy was reported with weight bearing. This finding, however, is not surprising because during weight-bearing, the socket interface is more involved which significantly increase the sensory input from mechanoreceptors. Another interesting finding of the study is that the performance of knee joint position sense is target position related. For example, our results showed that target position at 10 degrees had the largest matching error while target positon at 5 degrees showed the least error. One interpretation is the tension of the gel liner is closely related to knee joint position. It is likely that at 10 degrees the tension reaches the lowest level and increases at other positons particularly at target positon of 5 degrees. Without weight bearing, gravity may play a major role at different knee configurations. This finding might have clinical implication and indicate that knee joint proprioception training could be focused on fewer target positons (i.e. those with larger errors). In addition, the hypothetical reasoning regarding the gel liner contribution (i.e. tension level) could be useful in developing more effective gel liner with enhanced joint proprioception.
Similar to joint proprioception, the second hypothesis is also not supported. On the contrary, locking-pin suspension showed the best performance in local dynamic stability (i.e. short term LLE) in the anterior-posterior direction. We believe that locking-pin suspension offers a more secure attachment of the prosthetic leg (i.e. due to the distal pin engagement) than others and significantly improves the confidence of the amputees during ambulation, which in turn reduces the stride to stride variability. Among the few studies on comparing locking-pin with suction/VASS, suction/VASS was reported to improve gait symmetry and socket fit but with poor satisfaction when compared to locking-pin. Nonlinear analysis has been shown to be a useful and sensitive means, which allows the researchers/clinicians to assess dynamic balance and is also highly related to the perception of prosthetic devices of the amputees. For example, local dynamic stability has been used to assess the effects of torsion adaptor in transtibial amputees when walking straight-line or making turn. A more recent study also indicated that the level of vacuum when using VASS is critical and 15 inHg is recommended to achieve optimal gait performance.

There are a couple of limitations we would like to acknowledge and hopefully address in future studies. First, the study is limited by a relatively small sample size and the fact that some of the participants have not used other suspensions (i.e. suction or VASS) before. In addition, the accommodation period is brief. The cohort tested in the study are older and have relatively low level of activity. Participants were tested with their own prosthetic feet and footwear. When converting the test suction socket to VASS, a single vacuum level of 25 inHg was used.

**Conclusion**
This is the first study which systematically assessed the effects of prosthetic socket suspension on knee joint proprioception and dynamic balance in transtibial amputees. Our findings indicate that socket suspension does not influence knee joint sense and locking-pin is superior to other means particularly suction in dynamic stability. The benefits of using VASS are not supported by this study.

**Abbreviations**

Competing interests

The authors declare that they have no competing interests.

Authors’ contributions

FG conceived of the study, recruited human subjects, collected data, analyzed data, performed statistical analyses, drafted the manuscript and interpreted the findings.

Acknowledgment

This work was supported by AOPA Research Award administered by the Center for Orthotics and Prosthetics Learning and Outcomes/Evidence-based Practice.
References


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Figure 1. Experimental setup. Knee joint sense test on the sound side with weight bearing (left). Dynamic balance test on the treadmill with motion sensor attached at the low back (right).

Figure 2. Sample data for knee joint position matching test (the red line represents the target position of 25 degrees).

Figure 3. Sample divergence curve as a function of number of strides (the red lines represent the linear curve fitting and the slopes correspond to the estimates of LLE).

Figure 4. Short term LDS in anteroposterior direction (mean±SE).
Figure 2.

![Graph of Knee joint position (degree) over Data points.](image)
Figure 3.
Figure 4.

Short term LDS, anteroposterior

P = 0.036