Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement Science

Suman Paudel

Socket Residuum movements in a lower limb prosthesis using different suspension systems during different physical activities.

Master's thesis in Physical Activity and Health
Supervisor: Karin Roeleveld
February 2023

NTNU
Norwegian University of Science and Technology

Suman Paudel

Socket Residuum movements in a lower limb prosthesis using different suspension systems during different physical activities.

Master's thesis in Physical Activity and Health
Supervisor: Karin Roeleveld
February 2023

Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement Science

NTNU
Norwegian University of
Science and Technology

Socket Residuum movements in a lower limb prosthesis

Is pistoning similar for every suspension system during different activities ?

Purpose of the study

To study socket residuum movement through 2 different approaches, i.e., proximal, and distal approaches in 3 different suspension systems namely Pinlock, Active vacuum, and Passive vacuum systems during activities like walking, fast walking, turning (towards both amputated and healthy side), and jumping.

Hypothesis

The vacuum suspension system has the lowest pistoning compare to non vacuum pinlock suspension systems.

Pistoning increases irrespective of the type of suspension system used when the velocity increases of activity increases.

Comfort, stability, and overall user satisfaction with the system are related to pistoning .

METHODS

Participant

An active adult prosthetic user with an unilateral transtibial amputation.

Method

Participant requires to complete 3 different activities, i,e. normal walking, fast walking, turning, and jumping using different suspension systems fitted in a transparent prosthetic socket. The socket residuum movement is recorded through a camera fitted on the socket itself. The 3D motion system is also used for the measurement of velocity, time, height, and assess gait. VAS for comfort and stability is also used.

CONCLUSION

Vacuum system combined with pinlock has lowest pistoning, thus can be a choice of suspension during any level of activity. However, lesser pisstoning can always not mean greater comfort and greater stability.

Abstract

Introduction: Movement occurring at the socket-limb interface in the prosthesis has a great influence on the lower limb prosthetic user activity and comfort of the prosthesis. Examples of such movements are rotation and pistoning. Pistoning' also called vertical displacement is the up and down movement of the residual limb inside the socket and is considered as one of the indicators for suspension system efficiency. There are several suspension systems available, but a systematic objective evaluation of the suspension systems to socket-limb interface movement for different activities is lacking.

The study aimed to investigate socket residuum movement mainly vertical displacement in 3 different suspension systems during walking, fast walking, sudden turning, and jumping. In addition, study also aimed to investigate variable like velocity of activity, time of activity during the activities and satisfaction with the suspension used with regards to comfort and stability.

Method: A unique GoPro™ camera-based measurement technique attached to a transparent socket, with a locking textile liner was used to measure prosthetic socket interface movement at the distal end of socket and residual limb interface. In addition, a 3D motion capture system was also incorporated to determine the performance of tasks. The velocity at which the activity was performed, time and height was determined with the 3D system for which the marker placements were more proximal than the camera-based technique. Displacements were calculated using synchronized values from camera records as well as the 3D motion capture system. In addition, Visual analogue scale (VAS) for comfort and stability was administered at the end of the trials for the subjective grading of comfort and stability with the suspension system used. Several trials were conducted with 3 suspension systems for 4 different activities (Normal walking, Fast walking, Turning, and Jumping). The pin-locking textile liner suspension systems tested were "non-vacuum", "sleeve-passive suction", and "sleeve-active vacuum".

Results: The highest average displacement was found in non-vacuum pin-lock suspension for every activity. An average of 1.9 mm, 2.8mm, 1.5mm and 2.2 mm displacement was seen during normal walking, fast walking, turning towards healthy side and turning towards amputated side respectively. For the vacuum system, the sleeve active vacuum showed lesser vertical displacements and less stability score. Pinlock suspension system was perceived the most comfortable system. Displacements increased in every suspension system tested with the increase in velocity of activity performed.

Conclusion: The pin lock non-vacuum suspension system had the overall highest pistoning movement among the 3 suspension systems, therefore may not be a good choice for demanding activities. Irrespective of the type of suspension system used, the pistoning also is seen to increase with the increase in the velocity at which the activity is performed. In terms of comfort, pain, and stability, the pin lock non-vacuum suspension system is observed to be the superior one.

Acknowledgements

Firstly, my sincere thanks to my supervisor Karin Roeleveld who continually guided me from the beginning of the thesis process and encouraged me to do better. My thanks go to Eivind Modalsli for his valuable contribution to this project by recruiting the participant, designing a prosthesis, and helping collect data. I thank Anne Øvreness, who trained and assisted me with gait laboratory handling and data management. Thanks also to Sindre Wold Eikevåg, Sampsa Matias, Knut Einar, and Clara Luiten from the department of mechanical and industrial engineering for meaningful discussions and contributing to the data collection. Many thanks to the participant for participating in this research study.

I would like to thank my parents for their encouragement in achieving my goal. Lastly, many thanks to my lovely wife, Laxmi Upadhyaya, for her continuous support and motivation during my master's degree.

There are no conflicts of interest

Contents

Abbreviations

CT: Computer tomography
Mm: millimeter
RL: Residual limb
TOV: Trøndelag orthopedic workshop
NM: Normal walking
FW: Fast walking
TH: Turning towards healthy side
TA: Turning towards amputated side
JU: Jumping
PL: Pinlock suspension system
AV: Active vacuum suspension system
PV: Passive vacuum suspension system

Introduction

An amputation is the surgical removal of part of the body, such as an arm or leg. It may be done due to many reasons like to prevent infection from spreading, due to peripheral artery diseases, serious trauma to the limb and many more. The limb is deformed and usually have limited movement and function. Therefore, prosthesis is usually prescribed for amputees and thorough training is given so that user can return to daily activities. This process is called prosthetic rehabilitation. Prosthetic rehabilitation after lower limb amputation has several goals, returning to highest level of function, becoming as independent as possible and improving quality of are some examples of it. However, the foremost goal is to obtain optimal functioning, i.e., to restore functional mobility and static positioning of the limb (Crowe et al., 2019; Taylor et al., 2008) . For achieving such optimal functioning, comfort, stability, and control of the prosthesis is of great concern for the users and can be greatly affected by the movements occurring inside the residual limb and socket of the prosthesis (socket-residuum movement). Prosthetic sockets which are basically the devices joining residual limb (stump) to the prosthesis remains stable if such movements can be reduced. Studies suggest that the reduction of such movements leads not only to better proprioception and socket stability but also helps to keep the skin of the residual limb healthy and keep the limb in position even during unloaded conditions. Excess of such movements may increase user discomfort with the prosthesis and ultimately hampers the efficiency (Ali et al., 2012; Brunelli, Delussu, Paradisi, Pellegrini, & Traballesi, 2013). Commonly seen socket residuum movements are rotation, and vertical movement (pistoning).

Pistoning also known as vertical movement or vertical displacement is a type of socket and residuum movement and is defined as the up-and-down movement of the residual limb inside the socket during ambulation. It occurs when tibia moves vertically during alternate weight bearing and non-weight bearing periods during gait. The process is cyclic where the tibia comes to the starting position again and ascends vertically during weight bearing. This phenomenon is most seen when the socket is too large, or the suspension is inadequate. It is in fact one of the major indications defining successful or unsuccessful suspension in lower limb prosthesis and is reported as the main challenge for prosthetic users and found to be investigated frequently in the last decades (Al-Fakih, Abu Osman, & Mahmad Adikan, 2016; Eshraghi et al., 2014; Mak, Zhang, & Boone, 2001; Paterno, Ibrahimi, Gruppioni, Menciassi, & Ricotti, 2018; Safari, 2020). The suspension system which is the method of connecting the residual limb to the prosthesis plays a vital role to secure the prosthesis on the residual limb and to decrease pistoning. Thus, measuring the pistoning would be helpful in determining the optimal prosthetic fit and suspension. Several prosthetic suspension systems are available for lower limb amputees. Suction, self-suspending (supracondylar) suspension, elevated vacuum, locking pin, sealing liners, belt and straps suspension systems are some examples of suspension systems. Liner, which is a barrier made up of either polyurethane, silicone or thermoplastic elastomer and a lock system, which connects to the rest of the prosthetic components are most used types. Other component of prosthesis is shown in fig 1.

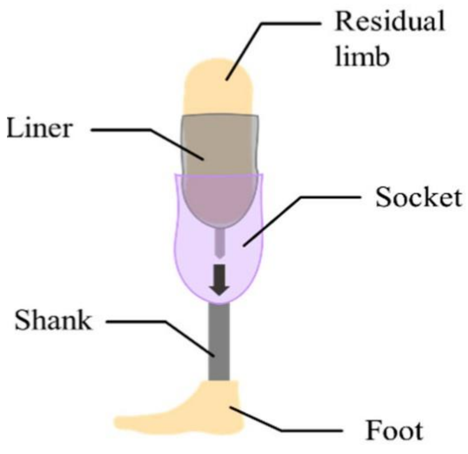


Figure 1: Components of lower limb prosthesis.

Source: https//www.mdpi.com/994428

Several studies exist that have studied the vertical displacement or pistoning in the socket residual interface. These studies have typically been assessed under static loading conditions selected to mimic the loads acting during gait. For example, in a study by (Gholizadeh, Osman, et al., 2012) the vertical displacement (pistoning) was measured between the liner and socket in single limb support on the prosthetic limb (full-weight bearing), double limb support (semi-weight bearing), and non-weight bearing on the prosthetic limb, and also under three static vertical loading conditions (30 N, 60 N, and 90 N) in six transtibial amputees, using two different types of suspension system, i.e., Iceross Seal-In® X5 and the Iceross Dermo®. Similarly, there are only a couple of studies that focused on the occurrence of pistoning during gait (Sanders, Karchin, Fergason, & Sorenson, 2006). Moreover, these pistoning measurement for both static and dynamic conditions were found to use complicated devices and settings like roentgenology, cineradiography, transducer or X-rays (Convery & Murray, 2000; Erikson & Lemperg, 1969; Lilja, Johansson, & Öberg, 1993; Narita, Yokogushi, Shii, Kakizawa, & Nosaka, 1997; Söderberg, Ryd, & Persson, 2003) and found to mostly be limited to laboratory. Almost no studies can be found where there is studied vertical movements between socket and residuum during more challenging and demanding activities like fast walking, jumping or sudden turning. These types of activities are very common during highly demanding sporting activities like skiing, running, etc.

Sport and physical activity participation by amputee have increased during the last decade. The popularity of paralympic sports have also raised expectations for ordinary prosthetic users to participate in sports and do better in daily activities. A survey done in 2016 revealed that nearly 8 in 10 people (78%) surveyed have taken part in some form of exercise, physical activity, or sport in the last 12 months and over 8 in 10 people (83%) surveyed would like to take part in more sport and physical activity in the future. However, prosthetic limitations and socket fit, and comfort were the most common barriers to taking part in those sports and physical activities. (LimbPower Amputee sport and Physiocal Activity Survey 2016). These activities in addition may sometime also require participants to perform activities with very high velocity. This can again create fear of falling or injury to self. Therefore, there remains huge importance in finding out the most suitable prosthesis with suitable suspension system and greater comfort so that people with prosthesis can also benefit physically, socially, and mentally from a physically active lifestyle.

Studies suggests that most suitable suspension system with lower pistoning can eventually contribute to the best performance by the users (Deans, Burns, McGarry, Murray, & Mutrie, 2012; Matthews, Sukeik, & Haddad, 2014). However, other parameters like volume fluctuations, temperature, axial loads, rotation, velocity are also very important when it comes to performance. A study by (Modalsli et al., 2021) has studied rotation resistance with axial loads in 6 different suspension types on a mock limb and found that rotation resistance increases with increasing in the axial loads. These axial loads are said to be analogue with prosthetic limb loading during gait. In the study, active vacuum had higher resistance against rotation compared to passive suction with "sleeve" suspension, but lower rotation resistance than passive suction with the "elastomeric coated liner" suspension. "Non-vacuum" had the lowest rotation resistance. The study has also mentioned the need of evaluation of different types of suspension systems with respect to movements seen in the residuum and socket and its relationship with comfort and stability.

This is a pilot study, where the purpose is to study socket residuum movement through different approaches, i.e., proximal, and distal approaches in 3 different suspension systems namely Pinlock, Active vacuum and Passive vacuum systems during activities like walking, fast walking, turning (towards both amputated and healthy side), and jumping. No study has so far given the exact value for vertical displacement. The value is found to be varying greatly with respect to method of assessment and mainly the marker placement for the measurement technique. In accordance with similar study we hypothesize that (1) Vacuum suspension has the lowest pistoning compared to non-vacuum pinlock system (2) there will be an increase in pistoning irrespective of the type of suspension system used when the velocity of activity performed increases, and (3) the comfort, stability, and overall user satisfaction are related to the pistoning, i.e lesser the pistoning during activity better will be the comfort, stability, and overall satisfaction. Study by (Modalsli et al., 2021) using the similar system has previously shown that differences in rotation resistance using different suspension systems and axial loads.

Methods

This study used a single subject for the test settings. The participant was a male with a unilateral transtibial amputation secondary to trauma (89 kg, 181.5 m, 45-65 years, 1-year post-amputation). He was an active adult prosthetic user who was using Seal in X liner with hypobaric sealing ring and pinlock system in his daily activities. Ethical approval was taken from regional ethical committee (REK 218767) before the study. Written consent was taken before beginning the tests. The participant was made aware of the test procedures before the consent was taken. The inclusion criteria were an active trans- tibial amputee, pinlock system user and age group between 35-60 years old. Exclusion criteria was any cardiopulmonary, neurologic, or orthopedic disorders other than the amputation.

Equipment

One duplicate transparent total surface bearing prosthetic socket was designed by a certified prosthetist. The transparent socket was also built with a combined pinlock and vacuum valve suspension (Ice lock 562 hybrid®) compatible to a ratchet pin. A part of Dermo® liner was used as sleeve for sealing the passive and active vacuum in the sleeve locking textile liner. 3 different suspension types were used. The first suspension system was without vacuum which is normally called a pin-lock suspension where the liner has a pin (smooth or ratchet) which the prosthetic user puts into a lock mechanism distally inside the socket. The second system used was sleeve locking textile liner (LTL) with passive suction where the air in the socket is pushed out from the socket by a one-way valve while the RL enters the socket. A knee sleeve seals the suction that occurs in the socket-RL area. The third was sleeve LTL with active vacuum where the air in the socket is pushed out from the socket by a one-way valve while the RL enters the socket, and a knee cuff (sleeve) seals the vacuum. Air is extracted from the RL-socket interface with a pump through a valve to create negative pressure. All three suspension systems basically had same liner, i.e., with pinlock.

A GOPRO® camera was mounted on a chamber anteriorly on the distal part of transparent socket in the prosthesis (Fig 3). A transparent socket enabled the camera to record video between the socket and the liner. Small led light was fitted along with the camera to track the start and end of the recording. Furthermore, several points were marked for reference with a 0.2 mm pen on the dorsal part of the two liners in the middle of the camera frame for detection in the video tracking analysis. The video from the GOPRO camera was stored on a secure digital card with a sampling frequency of 120 frames per second and used for tracking the socket-RL displacement. In addition, 3D motions capture system (Vicon Nexus 2.12; Los Angeles, California) using 12 motion capture cameras was also utilized to assess the trials, detect events, and find velocity of the activity in the trials. We fixed 16 reflective markers to the participant's lower limbs in accordance with the Vicon Lower Body Plug-In Gait model. The Vicon Lower Body Plug-In Gait model was modified to include two additional markers to track the movement of the residual limb segments (Fig 2). Additional markers were applied on the proximal prosthesis and proximal stump on the same axis and were also defined as proximal prosthesis and proximal stump markers respectively. The transparent socket could create some reflection that could be mistakenly considered as markers; therefore, we used paper tape (except for the areas where additional markers were located) to mask the socket wall. We also used Kistler force plates to identify the proper heel strike hits during a gait cycle. A gait cycle was defined as the heel strike of one foot to the heel strike of the same foot. We adopted a sampling frequency of 200 Hz and 1000 Hz for the 3D motion capture system and Kistler plates respectively.

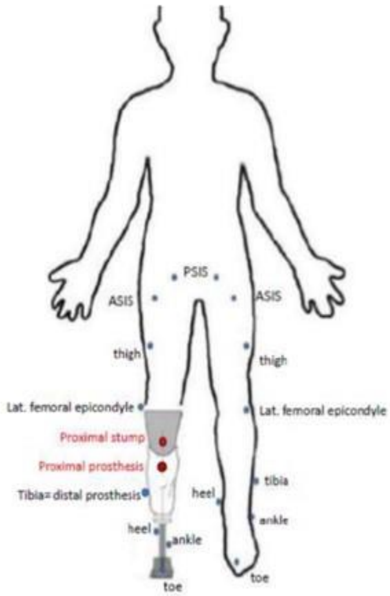


Figure 2: Marker placement layout

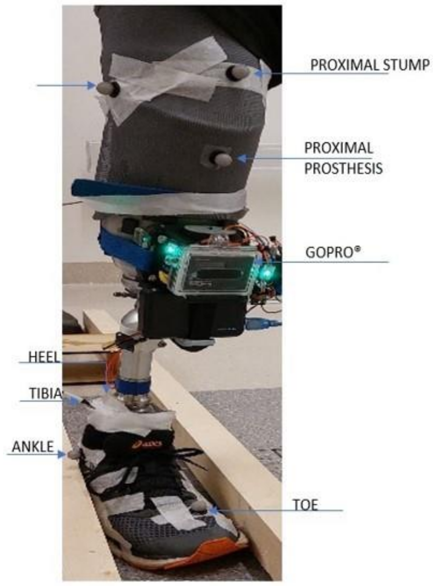


Figure 3: Marker placement in prosthesis

Protocol

A registered prosthetist fitted and aligned the prosthetic limb. The prosthetist made sure that there was no misalignment and that the fit of the prosthetic sockets was satisfactory. The alignment was assessed by standing in an upright position for static and walking for dynamic. The participant was not allowed to sit in a low-height chair after the assessment to avoid pressure changes until the new suspension system was put in again. For obtaining vacuum inside the interface the sleeve was used where the air in the socket was pushed out from the socket while RL was entering the socket through a one-way expulsion valve. In addition, for the active vacuum system air was extracted from the RL-socket interface with a pump through a valve to create negative pressure at 60 kPa. The participant had already attended one test session before the trial in the Next Move Laboratory, Trondheim, Norway.

The participant was asked to complete 6 dynamic trials each for 3 different dynamic conditions, i.e., normal walking, fast walking, and turning (TA, TH) with 3 different types of suspension systems. In addition, he was also asked to perform 3 trials each of 10 seconds with one specific task, i.e., jumping with the same suspension system types. Prior to the test, we asked the participant to walk around the motion analysis laboratory to accustom himself to the suspension system. Afterward, he walked at a self-selected speed on an 8 m walkway. We recorded 6 successful trials per task with each type of suspension system. There was a 1 min rest interval between the trials. Pinlock, Active vacuum (Sleeve LTL with active vacuum), and Passive vacuum (Sleeve LTL with passive suction) suspension systems were used. The first suspension used was pinlock without vacuum followed by passive vacuum and at last active vacuum. During each suspension system used participant was asked to perform normal walking task at first followed by fast walking and turning (TH) and turning (TA). Jumping was performed after the end of all other tasks in every suspension system in the same order. The schematic presentation of the protocol is shown in figure 4.

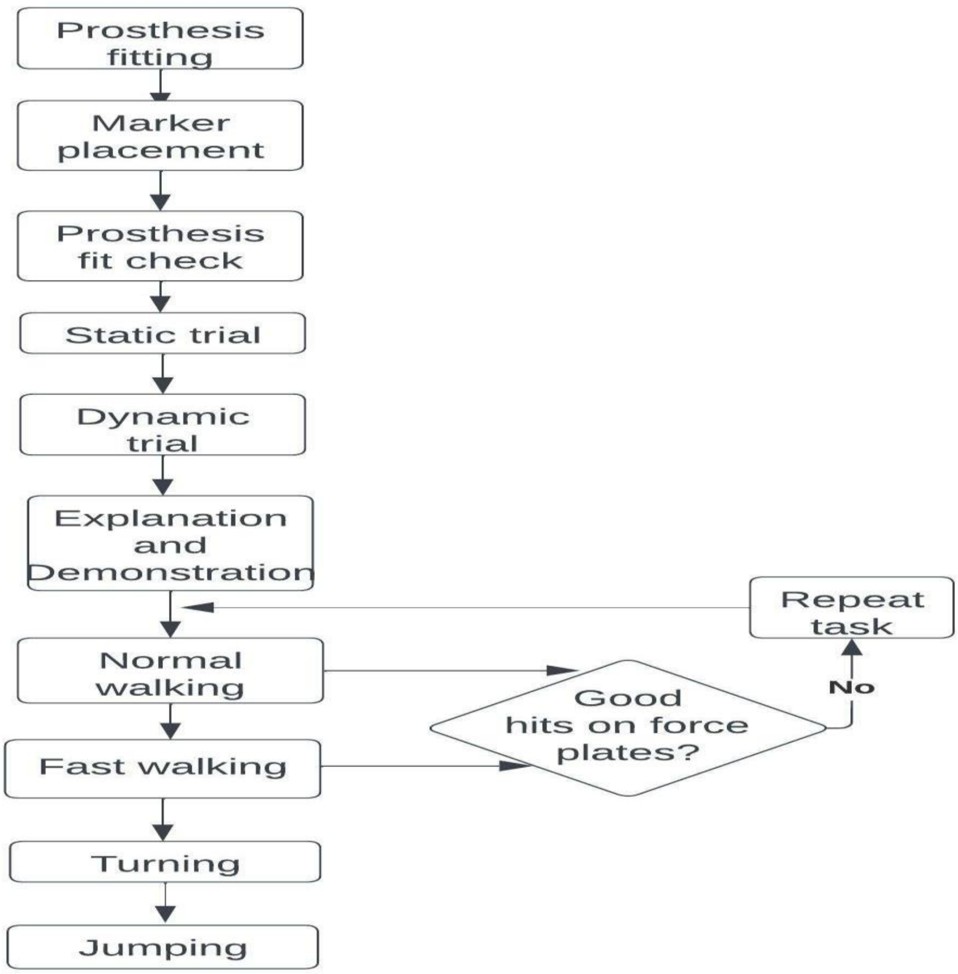


Figure 4: schematic presentation of the protocol for each suspension system

Normal Walking

On each end of the walking path, lines were drawn to mark the starting point and end point. The participant was asked to follow the path and walk normally from the starting point to the end point at a self-selected pace. Reaching the points would indicate the completion of the trial, and from that very point, the participant was asked to make a turn, take a 2-second pause, and walk back to the other point which would indicate the completion of another trial in a row. This way total of six trials was taken, and all the trials were carefully watched on the computer and physically to make sure that the foot has at least hit the force plates well enough. A good force plate here signifies a clean heel strike by prosthetic feet on any plate without hitting any other plate together. In case, there were fewer than 3 good hits, the participant was asked to re-do the task.

Fast Walking

Fast walking in this test is described as an increased pace than normal walking but keeping comfort. The participant was asked to walk as fast as possible but within his comfort zone. He was instructed not to walk beyond pain. The trials were taken the same way as normal walking where the participant was asked to perform the task for six consecutive trials.

Turning

Turning activity is described as walking fast as possible from point A (starting point) and taking a sudden 180-degree turn at point B which is basically at force plate 3 keeping the feet in contact with the floor. The first 3 trials were turning tasks toward the healthy side (TH), while the rest 3 were turning tasks toward the amputated side (TA).

Jumping

With the two-foot each on force plates 1 and 2, the participant was asked to jump continuously for 10 seconds. The activity was not exaggerated too much as there remains the chance of breaking the camera chamber.

Comfort and stability Questionnaire

Following the trial, we asked the participant to complete visual analogue scale (VAS) for comfort and stability for each activity. We rated the responses on a VAS scale from 0 to 10, where 0 indicated “very comfortable” with the system and 10 indicated “completely uncomfortable” for the comfort rating. In the same way, for the stability rating, 0 indicated “very stable” and 10 indicated “very unstable” with the system. In addition, feedback was also asked about the suspension system and comments were noted.

Data Analysis

Following the trial period, we initially checked every single trial in the motion capture system. The force plate hits were also checked. The trials with proper hits were then further saved for analysis. The processing of data started with registering the events first. The events during the trials were registered as heel strike during the beginning of the trial and heel strike at the end of the trial. The time frames for these two events were also noted. The velocity for normal walking and fast walking was calculated by distance traveled by amputated side heel marker by time taken from heel strike during the beginning of gait cycle to heel strike at the end of gait cycle in a trial.

$$velocity = distance\ traveled / time\ taken$$

We did this for all the trials for normal walking and fast walking. Time taken to turn was also calculated from heel strike during the beginning to heel strike at the end of turn by the same foot. The vertical displacement evaluation using camera system and motion capture system is discussed below. We considered a trial to be successful if the cameras could capture all the markers and have a proper hit on Kistler force plates.

Vertical displacements from camera system mounted on the prosthesis

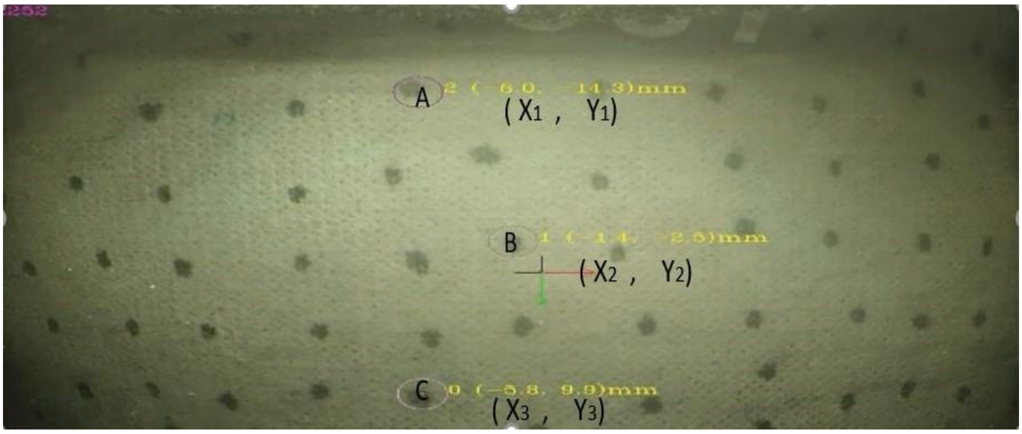


Figure 5: picture of liner with GOPRO coordinates value in a specific frame, (represented in color yellow) only y-coordinates were taken into consideration (red arrow indicates rotation while green arrow vertical movement

To identify the pistoning movement inside the prosthetic socket we used the video tracking analysis procedure. Initially from the video, 3 different reference points on the liner were taken. The reference point values were shown in the form of coordinates represented as A (x_1, y_1), B (x_2, y_2) and C (x_3, y_3) (figure 5). We confirmed the initiation of any trial with the help of the blink of a LED light on the video camera and video from the motion capture system. The force plate hits on Kistler plates and video from 3D system was used to identify the heel strike in any gait cycle. The co-ordinates on light on period was taken as the reference points for the subsequent coordinates to calculate the difference in the displacement. The coordinates basically represented the horizontal and vertical components of the values. Only y-axis values

(y_1, y_2 and y_3) were taken for the study as it gives the values for vertical displacement. To obtain the change in position, we then subtracted the subsequent coordinates value with the origin value for any gait cycle. This provided the distance between the origin and subsequent coordinates, and we did it for all three trials for any activity. Following that, we computed the average that occurred across three successful gait trials. The highest distance was obtained from subtracting the minimum to the maximum distance from the average. Also, to analyze the vertical movement pattern between the suspension system, an average was taken from those 3 trials, and the graph was plotted against one complete gait cycle. One gait cycle for walking and fast walking is defined by an initial heel strike from the prosthetic foot to a consecutive heel strike from the same foot.

Distance measurement from 3D motion capture system

To calculate distance between the markers from this method, we used proximal stump and proximal prosthesis trajectory values and put them in the 3D displacement formula. Trajectory values were defined as the locations of the marker in a 3D space. The formula $d\ (PS, PP) = \sqrt{(x_2 - x_{1)}{}^2 + (y_2 - y_{1)}{}^2 + (z_2 - z_{1)}{}^2}$ provided the distance between two points (PS, PP) where PS means Proximal Stump and PP means Proximal Prosthesis respectively, and x_2, y_2 and z_2 represented x, y and z co-ordinate respectively from the proximal prosthesis and x_1, y_1 and z_1 represented x, y and z coordinates respectively from the proximal stump. Obtained distance between these two markers after the formula was pistoning between residuum and socket in the gait cycle.

Gait cycle used for analysis of data was similar for both methods. The gait cycle in similar time periods was obtained by subtracting time during light on period to the time during heel strike for the gait cycle. The light on and heel strike time frames was obtained from 3D motion capture system.

For the walking and fast walking task, only 3 out of 6 trials for every suspension used were used for the analysis. One gait cycle per trial was used, and the complete gait cycle was determined by looking at the proper heel strike on the Kistler force plates. A proper heel strike was defined as the strike at any one force plate without hitting another plate by the same foot together. However, for turning, all 6 trials were used, i.e., 3 trials (3 gait cycles) representing turning towards the amputated side and 3 trials (3 gait cycles) representing turning towards the healthy side.

The trial for jumping was recorded for continuous 10 seconds for every suspension system, therefore it is the only trial from each suspension system used for the analysis of the jumping task. The jumping height range was calculated by highest height observed subtracted by lowest height observed for a one marker, i.e., marker named as PSIS (on the right posterior superior iliac spine) The movement change was determined by subtracting the highest distance calculated to the lowest distance calculated between the markers.

Results

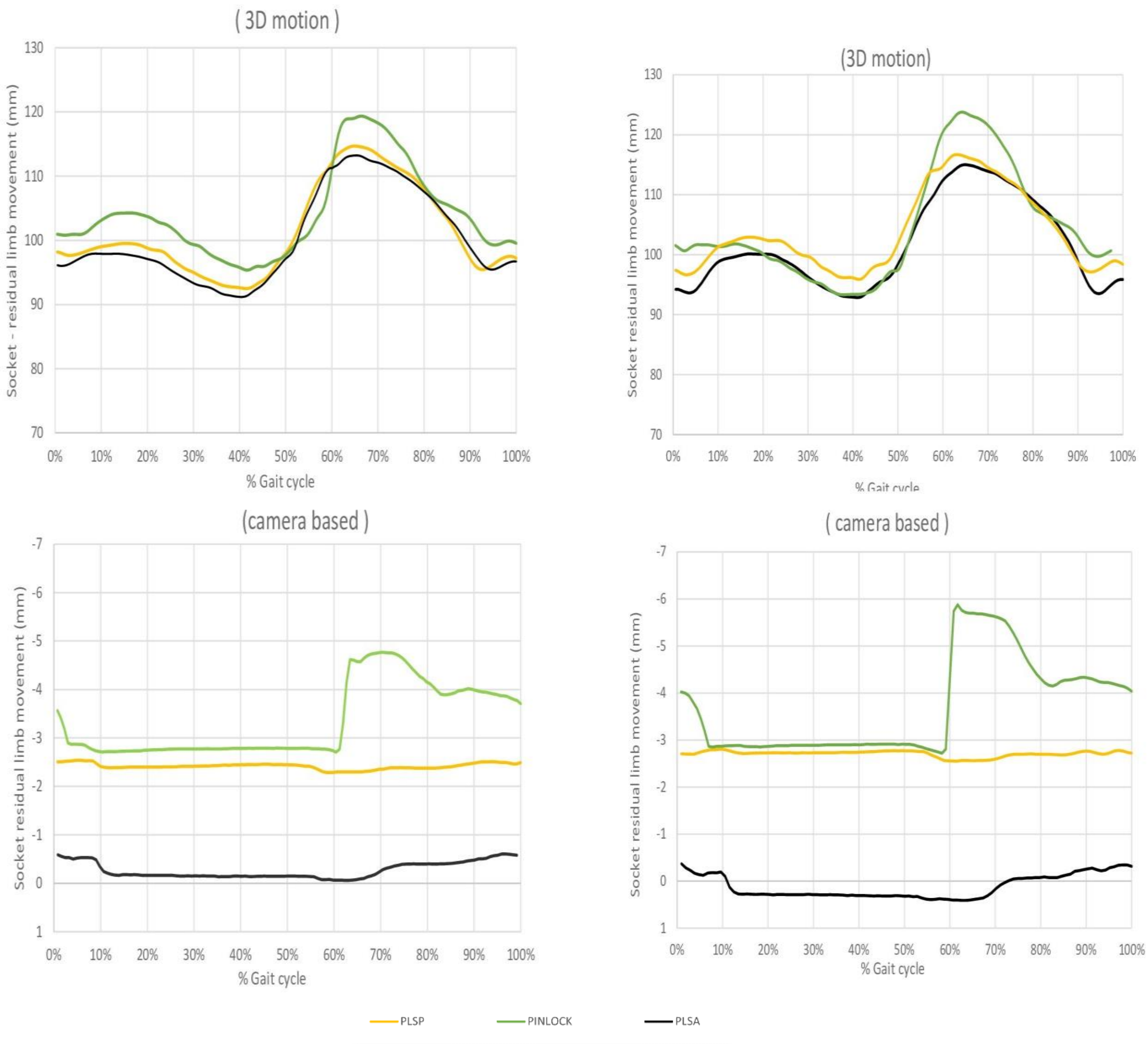
All the trials were successfully completed without any damage to the prosthetic socket. However, during the jumping task, due to the high impact on the prosthetic socket, the camera could not store data.

Table 1 : Performance of activities during different tasks (the values are average taken from 3 different trials for each suspension type, except for jumping task where only one trial value is taken)

Task and variables		**Type of suspension system**		
		Pinlock	**Passive Vacuum**	**Active Vacuum**
Normal walking (velocity m/s)		1.29 ± 0.2	1.42± 0.1	1.59± 0.3
Fast walking (velocity m/s)		1.82 ± 0.4	1.91 ± 0.4	1.94 ± 0.2
Turning (Time seconds)	**Non-Amputated side**	0.93	0.92	0.94
	Amputated side	0.94	1.28	1.02
Jump height (cm)		27.79	32.77	29.88

In the table 1, it can be seen that, the average velocity at which normal walking and fast walking activities were performed was lowest during pinlock suspension system than other two suspension systems. The result also showed that for turning activity, turning towards amputated side had higher turning time than time taken to turn towards healthy side for every suspension system. The highest and lowest average turning time was seen in passive vacuum system while turning towards amputated side with 1.28 seconds and the turning towards non amputated side with 0.92 seconds respectievely. Passive vacuum also showed highest jumping distance with 32.77 cm while pinlock had the lowest jumping distance of 27.79 cm. All the values for variables (velocity, time, and distance is shown in table 1.

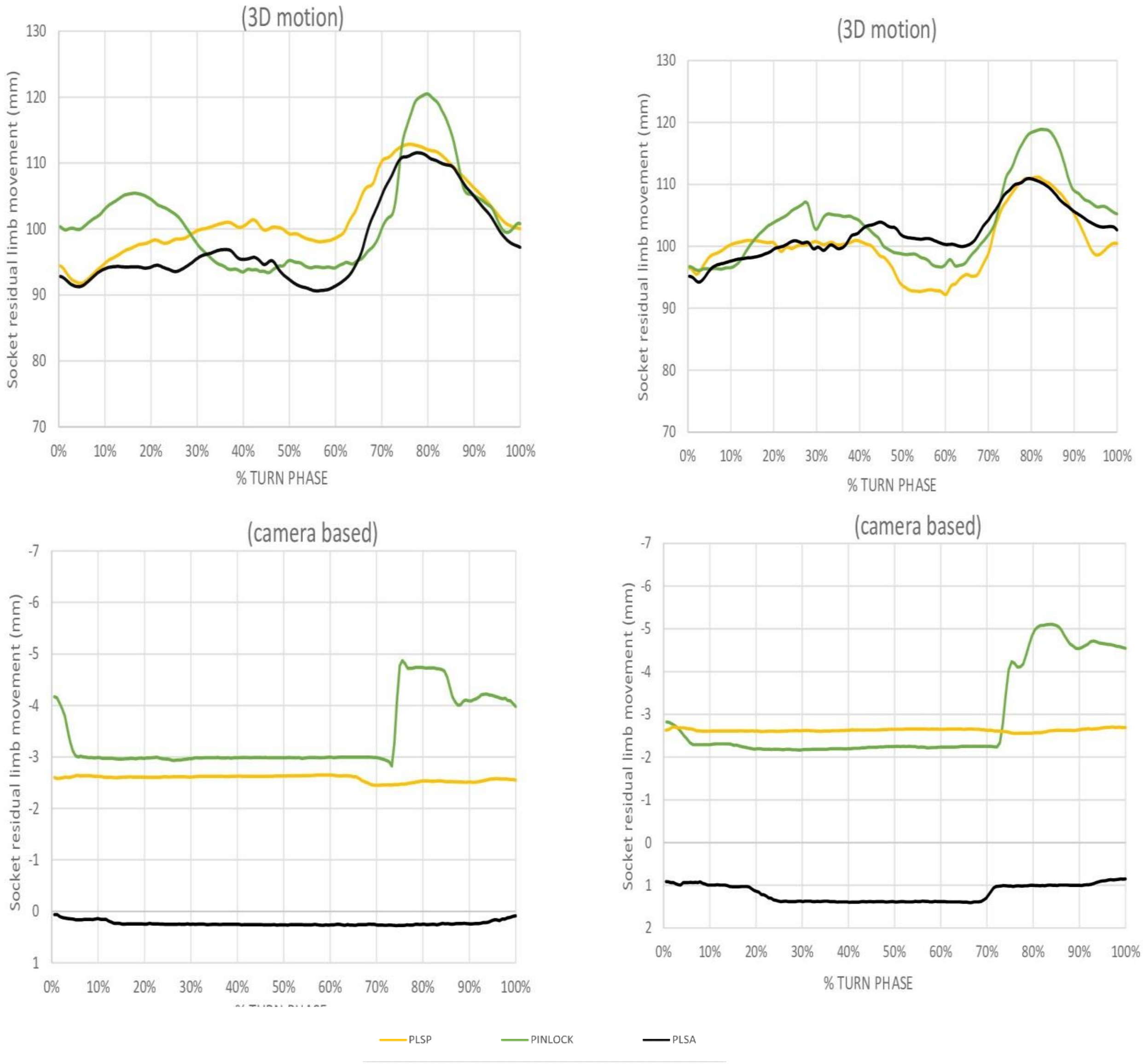
From the graphical study of the result (fig 6) it is seen that over the 100% gait cycle the vertical movement between the socket and residuum is seen very less for every suspension system during stance phase (0%-60%). The proximal marker placement approach using 3D motion capture system shows that there is slight displacement of socket and residuum during initial phases, 5% - 25% (fig 6, both 3D motion graphs), before starting for the maximum displacement during swing phase. The results from the graphs for camera-based approach (fig 6, camera based) where the markers were more distal shows that there was almost no change during until the 60%, before sudden change in displacement. (The origin points in the graphs are just arbitrary which play no roles, but it is only pattern that is to follow here).



(a) Normal walking **(b)** Fast walking

Figure 6: Socket residual limb movement pattern from average of 3 trials for every suspension system during (a) Normal Walking, and (b) Fast Walking using camera based and 3D motion technique

All in all, the result for normal walking and fast walking showed the displacement is seen maximum during 60% to 80% of a gait cycle, i.e., during the initial swing to mid-swing phase, and it tends to reach at the initial stage at the end of the gait cycle. The pattern is cyclic. Figure 6 (a and b) is an example from one of the trials showing the displacement pattern in normal walking and fast walking in different suspension systems. Similar pattern tends to follow in the next gait cycle also.



(a) Turning towards healthy side **(b)** Turning towards amputated side

Figure 7: Socket residual limb movement pattern from average of 3 trials for every suspension system during (a) Turning towards healthy side, and (b) turning towards amputated side using camera based and 3D motion technique

For turning, the graphical presentation for displacement during both turning towards amputated side turning towards non amputated side showed that the displacement was more after 70% turn phase. The graphical presentation of movement pattern shown by 3D motion also shows that for both turning there were also presence of some irregular displacement patterns during 0% to 70% (Fig 7, a, b).

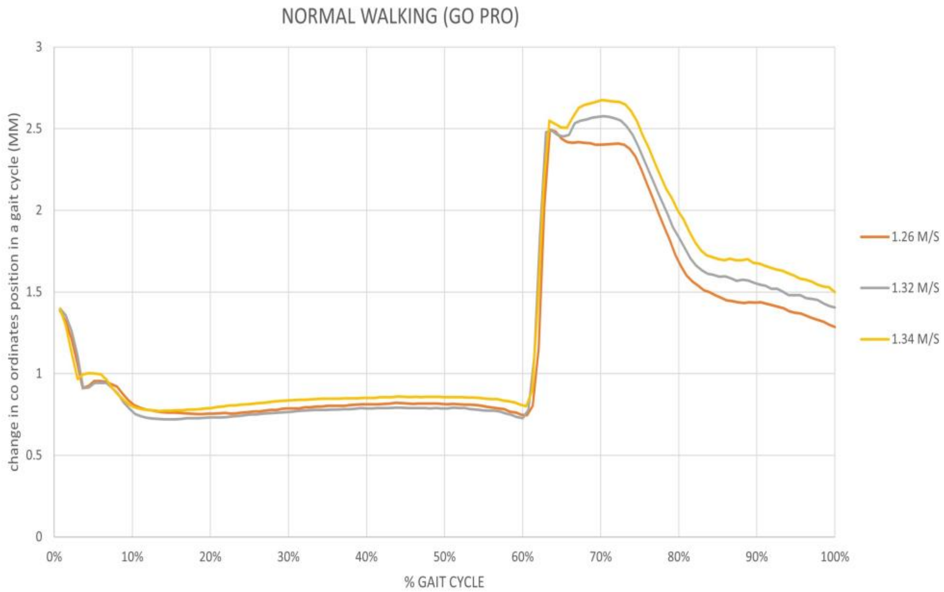
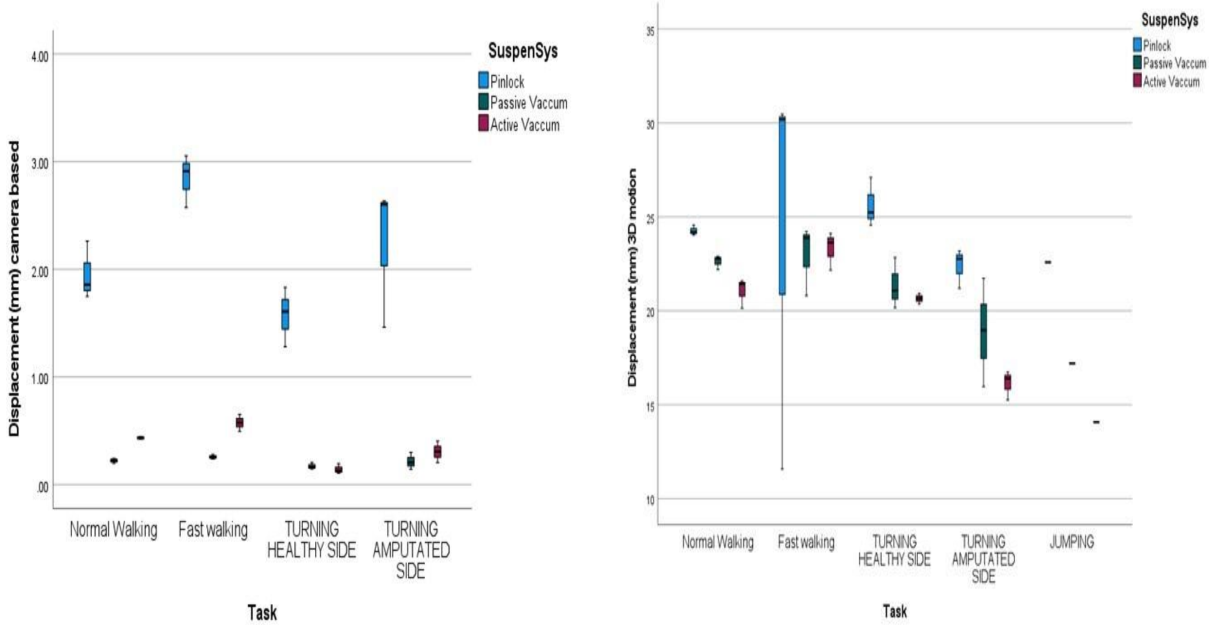


Figure 8: Sample displacement pattern during walking using pinlock suspension in different velocities

The result from the graphical presentation of displacement pattern during walking with different velocities (fig 8) shows that , with the increase in velocity of the activity, there is increase in vertical displacement between residuum and socket. Example of change in vertical displacement with velocity is shown in figure 8.



(a) Camera system

(**b)** 3D motion system

Figure 9: Average displacements seen during different activities using camera and 3D motion techniques

The average displacements values using 3 trials for all the suspension systems for every task except jumping task using both methods are shown in table 2. Fig 9 (a and b) also shows the same in the box plot presentation. The results showed pinlock suspension system to be having highest displacement while using both camera and 3D motion method.

Table 2 Average displacement during the different activities for all suspension systems using camera system named as GOPRO and 3D motion capture system named as VICON.

Task	**Method**	**Type of suspension system**		
		Pinlock	**Active Vacuum**	**Passive Vacuum**
Normal Walking	GOPRO	1.9 mm	0.4 mm	0.2 mm
	VICON	24.2 mm	21 mm	22.6 mm
Fast Walking	GOPRO	2.8 mm	0.5 mm	0.2 mm
	VICON	30.3 mm	23.3 mm	22.9 mm
Turning (Healthy side)	GOPRO	1.5 mm	0.14 mm	0.17 mm
	VICON	25.6 mm	20.6 mm	21.3 mm
Turning (Amputated side)	GOPRO	2.2 mm	0.3 mm	0.2 mm
	VICON	22.3 mm	16.1 mm	18.8 mm
Jumping	GOPRO	**	**	**
	VICON	22.5 mm	14 mm	17.1 mm

Satisfaction

The VAS scores for stability were lowest for passive vacuum in an average from all the activities. Passive vacuum system had score of 2 only during jumping task while the rest tasks were scored 0. Active vacuum was scored highest overall in the stability. The VAS scores for stability are shown in table 3.

Table 3 VAS scores for satisfaction with stability using different suspension system during different activities. The score ranges form 0-10, where 0 indicates very stable and 10 indicates very unstable.

Task	**Type of suspension system**		
	Pinlock	**Passive Vacuum**	**Active Vacuum**
Normal Walking	0	0	1
Fast Walking	0	0	2.5
Turning	2	0	2
Jumping	2	2	1

VAS scores for comfort in the other hand showed highest scores in passive vacuum than rest two. All the activities during pinlock suspension were scored 0. The highest score of 3 was scored in turning activity using passive vacuum system. The VAS scores for comfort are shown in table 4.

Table 4 VAS scores for satisfaction with comfort using different suspension system during different activities. The score ranges form 0-10, where 0 indicates very comforting and 10 indicates very uncomforting.

Task	Type of suspension system		
	Pinlock	Passive Vacuum	Active Vacuum
Normal walking	0	0	1
Fast walking	0	0	1
Turning	0	3	0
Jumping	0	1	0

Discussion

The main findings of this study were first, that the highest pistoning was seen in pinlock suspension without vacuum system not only during normal walking but also during other physically demanding activities. This finding supports the previous studies which also showed pinlock suspension to be having highest pistoning when compared with vacuum types (Darter, Sinitski, & Wilken, 2016; Klute et al., 2011). Therefore, pinlock only suspension may not be a good alternative when it comes to sports as there may exist a risk of prosthesis falls due to excessive vertical movement between socket and residuum during activity. However, for day-to-day use, which includes normal walking, doing household chores it still can be a good suspension choice due to its easiness in wearing on and off (Gholizadeh, Abu Osman, et al., 2012). Secondly, for the vacuum system, there was no huge difference between the systems in vertical displacements during any activities. So, any vacuum system can be an option for highly demanding activities. Having said that, no claims can be made just from this study due to very low sample size. However, a study by (Darter et al., 2016) has shown that bone-socket displacement was significantly reduced in participants wearing a vacuum-assisted suspension system compared to a passive suction system in the non-randomized study. Vacuum-assisted, elevated vacuum, or active vacuum which all are basically the same systems, therefore, be better in terms of vertical displacement (pistoning). Our study also showed lesser pistoning during active vacuum during fast walking, turning towards healthy side and while jumping, however the subjective response from the participant in other hand showed that he least preferred active vacuum in terms of stability. Therefore, to be specific about which vacuum suspension system to use, further studies using a larger sample are required. It also questions if pistoning is the main factor that determines overall satisfaction of the users. Large sample studies done in a real sport setting like skiing, running using vacuum types of suspension systems would help greatly in finding out proper suspension for sports and other factors which may possibly compromising the overall satisfaction of vacuum types.

Additionally, the velocity also showed to play a very important role in the amount of pistoning occurring inside the socket and residuum. Activities with higher velocities showed higher pistoning when compared to a similar task using the same suspension systems, which means in a real world setting when the participant using any suspension system during sporting activities increases his/her activity speed, the change in the vertical displacement is thus predictable. It may arise the question how much is then the threshold for the vacuum system before the prosthesis falls off. In such cases, maybe these types of vacuum suspension systems are also totally useless for sports and only specific designed prosthesis for example curved blade design advanced prosthetic devices for running made from carbon fiber can be used. We had instructed the participant to perform every activity just within the range of comfort, however, it is seen that he had performed normal waking and fast walking tasks with higher velocity during using an active vacuum. In other words, the suspension type altered the walking and fast walking speed. However, it couldn't possibly explain the result of VAS for stability where the active vacuum was perceived as least stable among other systems. The participant had performed faster on active vacuum even though he felt it least stable. The hypothesis that pistoning or vertical displacement is associated with stability is then not certain because for active vacuum had shown lowest pistoning in many activities but simultaneously perceived the least stable system from our study. The participant was new to the vacuum system as he was used to use just pinlock system in his daily life, so maybe therefore he might have felt more comfortable in pinlock system even though vertical displacement is seen more on this system.

Selecting a suitable suspension system for physically active individuals who have undergone transtibial amputation can be very critical. In this study, we studied 3 different prosthetic suspension systems in a single subject with transtibial amputation during 4 different dynamic activities. The camera system of vertical displacement measurement was introduced for the purpose of evaluating pistoning for the first time during these dynamic activities which were priorly used in a mock test to asses rotation resistance (Modalsli et al., 2021). Unlike radiological methods using X-ray, spiral helical CT our method was quite convenient, easy, and fast. Moreover, this method doesn't harm the participant with radiological exposure like in the earlier established methods. From this study, using the camera method our minimal average pistoning finding was 0.1mm and maximum was 2.8mm which were considerably lower than the findings from the earlier studies (Gholizadeh, 2011). In a recent study pistoning was assessed in trans-tibial prosthetic sockets during gait, using different suspension systems where they reported a range of pistoning between 0 and 5.1 mm, across all the suspension systems. All the activities using vacuum types in this study has very less pistoning value and very less difference between them, and it is interesting to note such small differences in vertical displacement between different systems and how such small differences can also actually affect the performance of the users. The method was used for the first time to assess pistoning, therefore the values couldn't be compared with the values from a similar method. In addition, pistoning during activities like fast walking, jumping, and sudden turning has also not been studied before. Several factors can influence the accurate measurement of pistoning between the residual limb and socket. The location of the measurement site, implementation of measurement techniques, subject 's residual limb parameters, socket fit, and measurement tool accuracy may attribute to the findings. In this study, the study of vertical displacement using camera method was relatively distal compared to 3D motion capture system where the placement of the markers used for data analysis was more proximal and that could be the reason for the difference in pistoning values for these two methods. The vertical displacement pattern seen is also different during initial 0% to 60% between the methods and could possibly be the reason for overall displacement changes. Using the 3D motion system method, the minimal average pistoning was found to be 14 mm, and the maximum of 30.3mm. The movement can be between the hard socket and the liner, between the liner and the skin and between the skin and the bone and it can also be a reason for the difference in the pistoning value among various measurement techniques. Our measurement method using camera measured displacement between hard socket and liner while 3D motion technique showed displacement between hard socket and limb.

Despite having shown better satisfaction with pinlock without vacuum in terms of comfort and stability, it should be noted that the satisfaction may be influenced by several other factors, not just the pistoning. Our hypothesis that comfort, stability, and overall satisfaction are related to the pistoning does not hold true from this study as findings showed lowest pistoning in a pinlock with vacuum systems, but the subjective response showed vacuum system to be the least comfortable and stable, it is worth mentioning that comfort and satisfaction can be influenced by many other factors like pain, blisters, torque and friction between the residuum and socket. Volume fluctuations, temperature can also be responsible for reduced prosthesis fitting thus compromising optimal use and satisfaction. Volume fluctuation can result in uneven distribution of pressure within the system and can impair the fit and provide the feeling of uneasiness. Sweating and irritation with the temperature change inside the interface overtime can also result in poor control of the prosthesis and thus might have resulted in poor satisfaction.

Also, studies have shown that even though the highest pistoning occurs in pinlock suspension, prosthesis users are satisfied with pinlock in terms of easiness in donning and doffing (on and off) of the prosthesis. For non-active amputees pinlock has shown to be the most satisfying prosthesis of choice.

There are various strengths and limitations to this study. This research provides some initial insight into one possible tool for quantifying the movement seen in the prosthetic limb interface. The study describes and implements the unique method of measurement by GoPro™, which was earlier tested in the mock participant. This is an easily repeatable method if further bigger studies should be done either in indoor or outdoor settings. This method of measurement allows to detect very small movement changes inside the interface. Here, we have used the system in an actual participant and looked closer at its implementation technique and probable difficulties.

One limitation of this study was the very small sample size. Bigger sample size could have helped to find if the findings were by chance. In addition to this, further research is needed to compare more results from the same technique.

Conclusions

In summary, vacuum suspension combined with pinlock for any level of activity displayed lesser vertical displacement compared with only pin-lock suspension. Therefore, vacuum can be the choice of suspension for amputees involving in different type of activities or engaging in sports. For all of the activities, an increase in the velocity of the activity increases the amount of vertical displacement. Pistoning increases in the case of vacuum as well when the velocity of the activity is increased, thus users should expect velocity-related changes even while using the best suspension system also. In terms of comfort, only pinlock system can be the best choice as it provides better shock absorption and feels softer. For a more clinically significant result studies with a higher number of subjects are desired. The new measurement technique based on camera is well fit in case of a minimal laboratory setting for pistoning evaluation, however, a few precautions and safety for safe placement of the camera should be upgraded. The presented study demonstrated that not only walking but the vacuum system combined with pinlock is best in terms of pistoning for other demanding activities also.

References

Al-Fakih, E. A., Abu Osman, N. A., & Mahmad Adikan, F. R. (2016). Techniques for Interface Stress Measurements within Prosthetic Sockets of Transtibial Amputees: A Review of the Past 50 Years of Research. *Sensors (Basel), 16*(7). doi:10.3390/s16071119

Ali, S., Abu Osman, N. A., Naqshbandi, M. M., Eshraghi, A., Kamyab, M., & Gholizadeh, H. (2012). Qualitative study of prosthetic suspension systems on transtibial amputees' satisfaction and perceived problems with their prosthetic devices. *Arch Phys Med Rehabil, 93*(11), 1919-1923. doi:10.1016/j.apmr.2012.04.024

Brunelli, S., Delussu, A. S., Paradisi, F., Pellegrini, R., & Traballesi, M. (2013). A comparison between the suction suspension system and the hypobaric Iceross Seal-In® X5 in transtibial amputees. *Prosthet Orthot Int, 37*(6), 436-444. doi:10.1177/0309364613476531

Convery, P., & Murray, K. D. (2000). Ultrasound study of the motion of the residual femur within a trans-femoral socket during gait. *Prosthet Orthot Int, 24*(3), 226-232. doi:10.1080/03093640008726552

Crowe, C., Impastato, K., Donaghy, A., Earl, C., Friedly, J., & Keys, K. (2019). Prosthetic and orthotic options for lower extremity amputation and reconstruction. *Plastic and Aesthetic Research, 2019*. doi:10.20517/2347-9264.2018.70

Darter, B. J., Sinitski, K., & Wilken, J. M. (2016). Axial bone-socket displacement for persons with a traumatic transtibial amputation: The effect of elevated vacuum suspension at progressive body-weight loads. *Prosthet Orthot Int, 40*(5), 552-557. doi:10.1177/0309364615605372

Deans, S., Burns, D., McGarry, A., Murray, K., & Mutrie, N. (2012). Motivations and barriers to prosthesis users participation in physical activity, exercise and sport: A review of the literature. *Prosthetics and Orthotics International, 36*, 260-269. doi:10.1177/0309364612437905

Erikson, U., & Lemperg, R. (1969). Roentgenological study of movements of the amputation stump within the prosthesis socket in below-knee amputees fitted with a PTB prosthesis. *Acta Orthop Scand, 40*(4), 520-529. doi:10.3109/17453676909046537

Eshraghi, A., Abu Osman, N. A., Karimi, M., Gholizadeh, H., Soodmand, E., & Wan Abas, W. A. (2014). Gait biomechanics of individuals with transtibial amputation: effect of suspension system. *PLoS One, 9*(5), e96988. doi:10.1371/journal.pone.0096988

Gholizadeh, H., Abu Osman, N. A., Lúvíksdóttir, Á., Eshraghi, A., Kamyab, M., & Wan Abas, W. A. (2011). A new approach for the pistoning measurement in transtibial prosthesis. *Prosthet Orthot Int, 35*(4), 360-364. doi:10.1177/0309364611423130

Gholizadeh, H., Abu Osman, N. A., Eshraghi, A., Ali, S., Sævarsson, S. K., Wan Abas, W. A., & Pirouzi, G. H. (2012). Transtibial prosthetic suspension: less pistoning versus easy donning and doffing. *J Rehabil Res Dev, 49*(9), 1321-1330. doi:10.1682/jrrd.2011.11.0221

Gholizadeh, H., Osman, N. A., Kamyab, M., Eshraghi, A., Abas, W. A., & Azam, M. N. (2012). Transtibial prosthetic socket pistoning: static evaluation of Seal-In(®) X5 and Dermo(®) Liner using motion analysis system. *Clin Biomech (Bristol, Avon), 27*(1), 34-39. doi:10.1016/j.clinbiomech.2011.07.004

Klute, G. K., Berge, J. S., Biggs, W., Pongnumkul, S., Popovic, Z., & Curless, B. (2011). Vacuum-assisted socket suspension compared with pin suspension for lower extremity amputees: effect on fit, activity, and limb volume. *Arch Phys Med Rehabil, 92*(10), 1570-1575. doi:10.1016/j.apmr.2011.05.019

Lilja, M., Johansson, T., & Öberg, T. (1993). Movement of the tibial end in a PTB prosthesis socket: A sagittal X-ray study of the PTB prosthesis. *Prosthetics and Orthotics International, 17*(1), 21-26. doi:10.3109/03093649309164351

(LimbPower Survey 2016) https://www.limbpower.com/resources/publications/amputee-sport-and-physical-activity-survey-201

Mak, A. F., Zhang, M., & Boone, D. A. (2001). State-of-the-art research in lower-limb prosthetic biomechanics-socket interface: a review. *J Rehabil Res Dev, 38*(2), 161-174.

Matthews, D., Sukeik, M., & Haddad, F. (2014). Return to sport following amputation. *J Sports Med Phys Fitness, 54*(4), 481-486.

Modalsli, E., Tan, A., Bakke, M., Eikevåg, S., Kohtala, S., Steinert, M., . . . Roeleveld, K. (2021). Prosthetic socket rotation stability-A mock limb study on different suspension systems. *Gait & Posture, 90*, 154-155.
Narita, H., Yokogushi, K., Shii, S., Kakizawa, M., & Nosaka, T. (1997). Suspension effect and dynamic evaluation of the total surface bearing (TSB) trans-tibial prosthesis: a comparison with the patellar tendon bearing (PTB) trans-tibial prosthesis. *Prosthet Orthot Int, 21*(3), 175-178. doi:10.3109/03093649709164551
Paterno, L., Ibrahimi, M., Gruppioni, E., Menciassi, A., & Ricotti, L. (2018). Sockets for Limb Prostheses: A Review of Existing Technologies and Open Challenges. *IEEE Trans Biomed Eng, 65*(9), 1996-2010. doi:10.1109/tbme.2017.2775100
Safari, R. (2020). Lower limb prosthetic interfaces: Clinical and technological advancement and potential future direction. *Prosthet Orthot Int, 44*(6), 384-401. doi:10.1177/0309364620969226
Sanders, J. E., Karchin, A., Fergason, J. R., & Sorenson, E. A. (2006). A noncontact sensor for measurement of distal residual-limb position during walking. *J Rehabil Res Dev, 43*(4), 509-516. doi:10.1682/jrrd.2004.11.0143
Söderberg, B., Ryd, L., & Persson, B. M. (2003). Roentgen Stereophotogrammetric Analysis of Motion between the Bone and the Socket in a Transtibial Amputation Prosthesis: A Case Study. *JPO: Journal of Prosthetics and Orthotics, 15*(3). Retrieved from https://journals.lww.com/jpojournal/Fulltext/2003/07000/Roentgen_Stereophotogrammetric_Analysis_of_Motion.8.aspx
Taylor, S. M. M. D. F., Kalbaugh, C. A. M. S., Cass, A. L. M. P. H., Buzzell, N. M. B. S., Daly, C. A. B. S., Cull, D. L. M. D. F., & Youkey, J. R. M. D. F. (2008). "Successful Outcome" After Below-Knee Amputation: An Objective Definition and Influence of Clinical Variables/DISCUSSION. In (pp. 607). Philadelphia :.

NTNU
Norwegian University of
Science and Technology