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Effect of Different Prosthetic Feet on the Kinematics Using Advanced Gait Analysis: Trans-Tibial Amputee Gait Perspective

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Author`s Contribution

[1] Conception and design, Collection and assembly of data, [2]Analysis and interpretation of the data, [4-6]Critical revision of the article for important intellectual content, Statistical expertise [1-6] Final approval and guarantor of the article.

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A B S T R A C T

Objectives: To evaluate the effect of different prosthetic feet on the kinematics of trans-tibial user using advance gait analysis.

Methodology: This Single blinded randomized crossover study recruited a sample of N=25 unilateral trans-tibial amputees who were 18-45 years old, using convenience sampling. Study was conducted at PIPOS, from August 2019 to January, 2020. Dynamic plus foot, Flex foot, Carbon Copy II, Seattle, & IC130 feet, Simi Motion Analysis Camera System & Simi Aktisys software were used for data collection. SPSS Version 22 was utilized for data analysis & general linear model statistics calculated. P<0.05 was considered significant.

Results: Dynamic plus foot revealed significantly bigger stride length on amputated (p=0.038) and intact (p=0.041) side compared to other feet and greater Cadence and higher velocity was seen for dynamic plus foot. Though not significant, hip flexion at terminal swing was maximum for dynamic plus foot, knee flexion at terminal swing on amputated side was maximum with pre-data, knee flexion at mid swing was highest for amputated side using carbon copy foot II foot. Similarly, no significant difference was seen for Stance phase, Swing phase, Lateral trunk flexion at mid stance, forward lean of the trunk at mid stance and pelvic tilt of amputee while using all type of prosthetic feet.

Conclusion: Dynamic plus feet give a significantly higher stride length compared to trias, carbon copy, flex, and seattle foot and give a insignificant but higher cadence, and velocity. However, the kinematics of gait were not significantly different among different types of feet.

Key Words: Amputation, Gait parameters, Kinematics, Prosthetic feet, Trans-Tibial.

Introduction

Trans-tibial amputation (TTA) also known as below knee amputation (BKA) involves removal of distal tibia, fibula and corresponding soft tissues including ankle and foot [1]. Prevalence of Lower limb amputation has revealed an increase from 12.89 to 18.12 / 10000 from 2008 to 2018 in American Veterans[2] with majority (57%) of Lower Limb Amputations (LLA) are BKAs.[3]

Etiology varies in different regions with diabetes mellitus (DM), vascular disease, trauma and tumors being common etiological factors of which peripheral vascular diseases is quite common in developed countries.[4] On the other hand DM has been reported to be commonest etiology in adults and trauma in younger population in an Indian study.[5] A local study revealed that the most common cause (38.38%) was Road Traffic Accidents and this was followed by DM (15.42%), infection (14.26%), other traumatic causes (12.37%)[6], while traumatic injury was reported to be common the commonest cause in local military study with mine blast related trauma being incriminated in 59.3% cases with most having received modular prosthesis.[7] Following TTA, a transtibial prosthesis, consisting of socket, interface, suspension and a prosthetic foot, replace the amputated limb [8]. The prosthetic feet design influence the kinematics and limbs loading.[9] There is lack of literature and knowledge gap in connection with impact of different components and their mechanical features of the lower limb prosthesis.[9] Similarly, a variety of Prosthetic feet are available to choose from by a professional to meet patients' needs, however the right prescription should focus on patient needs and knowledge of foot biomechanics during gait cycle since numerous advances have been made in the last few years as regards development of prosthetic feet.[10]

New prosthetic feet designs are said to store and release energy as body moves forward helping to passively propel the limb.[11] With only few options of prosthetic feet in the past, the type of foot was not a concern, however with a number of new feet having been developed and described in recent literature and the difference in the structure and make of these may affect amputee gait with characteristics like damping of flexibility and stiffness, roll over, toe clearance during swing and dynamic push off in the phase of late stance.[12] It is essential to know how the prosthetic foot behaves during gait including effect on kinematics so that the prosthetist can easily prescribe the suitable device. Knowledge of characteristics of prosthetic feet including characteristics like energy release at terminal stance [13], smooth rollover from heel to forefoot, balance at mid-stance, effect on gait kinematics, energy storing ability [14], light weight, flexibility of keel and dynamic response[15] can be helpful in prescription of proper prosthetic feet.

Most previous research has focused on functional outcome and or evaluation of the prosthetic feet with research gap in literature focusing on foot kinematics. In addition a high local prevalence and no local study on the subject instigated us to conduct this study with a comparatively novel area of research with the objective to evaluate the effect of different prosthetic feet on the kinematic of trans-tibial user using advance gait analysis. The current study will be of significant help for clinicians in managing their cases with TTA, so that they can be fitted with the correct foot according to the need of the patient. It will also act as a research base initiating further research.

Methodology

This Single blinded randomized crossover study design was conducted at Biomechanical Gait Lab of Pakistan Institute of Prosthetics and Orthotic Sciences (PIPOS), over a period of six months from 1st August 2019 to 31st January, 2020. Utilizing non-probability convenience sample, study recruited a sample of N=25, 18-45 years old participants with unilateral trans-tibial amputation due to trauma, having no other deformity, currently using prosthesis for at least 1 year and were able to walk without assistive device. A sample size of N=24 was calculated using G*Power 3.1.9.4 application for which type I error (α) probability was set to be 0.05, Power (1-β err Prob) was fixed at 0.80 and effect size f taken as 0.85, and a sample of N=25 taken to cater to any case which may have been lost to follow up.

Sample participants had a functional level 3 or 4 with medium or long stump and muscle power in grade 5. To avoid data variation prosthesis protocol including PTB socket with self-suspension, modular prosthesis with pyramid system and tape-foam soft-liner was followed. Participants with bilateral amputation, those having persistent stump pain, stability was at risk, those with poor socket fit with scores less than 4 and those with bilateral amputation were excluded from the study.

A number of prosthetic feet are available with different characteristics including the IC30 Trias, dynamic plus, Seattle, flex, and carbon copy 2 foot. The dynamic plus device is made from carbon fiber laminate and soft material and it releases quite a high energy after the terminal stance [13] and is quite suitable for patients who need both higher stability and mobility. It bears load at initial contact and has smooth rollover starting at heel to forefoot. It also gives higher balance during mid-stance and effects of the kinematic of gait. Carbon copy 2 is energy storing foot and hence useful for active amputees.[14] On the one hand its carbon keel gives stability, while on the other hand its double spring design is responsible for smooth rollover starting from initial contact to terminal stance. Trias 1C30 foot is lightweight and its double spring provide smooth rollover with energy return. Flex foot is has flexible keel with shank suitable for even terrain. Seattle foot also has flexible keel and gives dynamic response and can be fitted with ankle unit. [15]

Five different types of prosthetic feet were used for comparison in current study including Dynamic Plus foot, Flex foot, Carbon Copy II, Seattle, and IC130. Each subject tried all the shoes. Each foot was fitted to each participant for gait assessment and participants scored the level of comfort with it on a 10 point linear scale with 1 for most uncomfortable to 10 for being most comfortable. Active color markers placed on anatomical landmarks i.e. hip, knee and ankle of the participant were used to collect data of 2D gait analysis. Patients walked with comfy cadence at their self-selected velocity, while high speed "Simi Motion Analysis Camera System" measured the parameters of gait related to temporal-spatial gait parameters as well as kinematics. Simi Aktisys software calculated the data and provided the parameters data and angles data of different joints as portable document format. The stride parameters were recorded on a pathway 10 meters long and a measuring tape was used to measure the stride length. The impressions for the measurements were obtained by putting magnesium oxide below the shoes. The distance between two heel strides (stride length-SL) and time taken for in completing one stride (stride time –ST) was noted and cadence and velocity calculated as per following formula:

Velocity = Stride Length / Stride time & Cadence = Velocity / Step Length

To make the patient comfortable with the testing with active markers and camera system, before the instrumental gait analysis, each participant was allowed to first practice walking and to eliminate image distortion, the area for specific camera was defined and segment angles for each subject were rectified while standing in a standard anatomical position. Subjects were advised to walk several times over gait pathway at the self-selected comfortable speed for 10 meters.

Each participant was tested for all the 5 prosthetic feet with 5 participants tested each week and each participant fitted with a different prosthetic feet each day, hence each participant was tested for 5 different prosthetic feet in that week. On first day data of 5 subjects was collected with pre-data taken at the start and after 10 minutes break dynamic foot was fitted and data taken. Following this Trias foot data was taken on 2nd day, seattle foot data on 3rd day, carbon copy foot data on 4th day and flex-foot data collected on 5th day and in the second, third, fourth and fifth week procedure was repeated for the remaining participants.

The study was conducted after obtaining ethical approval of the research from Institutional Research Board of Isra University vide registration number 1609-MPhil (P&O)-041 and permission from Managing Director of PIPOS and informed consent of the sample population.

Gait parameters recorded include stride length, cadence, velocity, stance time, duration of swing, knee flexion (terminal stance, mid-swing) hip flexion (terminal swing), Hip rotation at forward lean, rotation of pelvis and lateral trunk bending.

SPSS version 22 was used for data analysis. Descriptive statistics was utilized. For normality testing Shapiro-Wilk test was used. Pair wise comparison between mean scores obtained by using different prosthetic feet was done using General Linear Model and $p<0.05$ was considered significant.

Results

In Current study (table I), 22(88%) male and 3(12%) female, unilateral trans-tibial amputees participated who had a mean age of 32.68±8.86 years with around half of the population 13(52%) being overweight with a BMI of 25 to 29.9. Trauma was the major 23(92%) cause of amputation with most 17(68%) participants being right sided amputees with majority 23(92% at K3 activity level.

Table I: Participant Characteristics (N=25)

Variable	Group	Frequency	%
Gender	Male	22	88
	Female	3	12
BMICat	Healthy weight (18.5-24.9)	12	48
	Overweight (25-29.9)	13	52
Cause of Amputation	Trauma	23	92
	Disease	2	8
Side	Right	17	68
	Left	8	32
Activity Level	2	2	8
	3	23	92

Results (table II) for Stride Length revealed a significant difference with p=0.038 & p=0.05 respectively on amputated side using dynamic plus and Trias foot. Similarly on the intact side, significant difference (p=0.041) was observed for dynamic plus foot revealed significant greater stride length (1.37+.09) than other feet. Stance phase did not reveal any significant difference in means of amputated and intact side for all five type of feet.

Greater Cadence was seen using dynamic plus foot (103.8+5.4 steps / min) and lowest with trias foot (98.9+8.6) however difference was not significant. While intact side revealed significant difference in mean cadence between pre-data and dynamic foot (p=0.048).

Highest velocity was seen on both amputated and intact side for dynamic plus foot and lowest with Trias foot, however the difference between the different feet was not significant. Swing phase also did not reveal significant difference among different feet on amputated and intact side.

Gait Kinematics (table III) revealed as regards Hip flexion at terminal swing, all feet on amputated side had normal degree of hip flexion with maximum for dynamic plus and lowest for carbon copy and difference was not significant. Similarly intact side also did not reveal any significant difference.

As regards knee flexion at terminal swing on amputated side was maximum with pre-data and lowest with carbon copy with no significant difference, similarly no significant difference was observed on intact side.

The highest knee flexion at mid swing of amputated side was achieved by carbon copy foot II while the lowest was observed with Trias foot however no significant difference was present between different feet. Similarly, no significant difference was seen on intact side with maximum flexion seen with trias and lowest with pre data.

Table II: Gait parameters: Pairwise comparison using general linear model (n=25)							
Foot type		Amputated side (df=14)			Intact side		
		Estimated Marginal Means	Mean Difference (I-J)	p-value	Estimated Marginal Means	Mean Difference (I-J)	p-value
Pre data	Stride length (m).	1.21±.10	.009	1	1.36±.10	-.066	1
Dynamic plus foot		1.20±.10	.067	0.038	1.37±.09	.074	0.041
Trias-Foot		1.14±.05	-.048	0.544	1.29±.06	-.028	1
Carbon Copy		1.18±.09	.018	1	1.32±.09	.028	1
Flex foot		1.17±.11	.017	1	1.33±.09	.008	1
Seattle Foot		1.15±.09	-.062	0.16	1.29±.09	-.066	0.065
Pre data	Stance phase %	61.82±5.51	.600	1	61.86±5.17	.298	1
Dynamic plus foot		61.22±5.34	.341	1	61.57±4.86	-.575	1
Trias-Foot		60.88±4.98	-1.558	1	62.14±5.29	1.487	1
Carbon Copy		62.44±5.00	.214	1	60.65±4.96	-1.78	1
Flex foot		62.22±6.68	2.757	0.867	62.43±7.28	-.270	1
Seattle Foot		59.46±5.12	-2.355	1	62.7052	.840	1
Pre data	Cadence steps/min)	101.4±6.7	-2.360	1	108.7±6.6	-4.68	0.048
Dynamic plus foot		103.8±5.4	4.920	0.256	113.4±4.8	4.640	0.159
Trias-Foot		98.9±8.6	-2.800	1	108.8±6.1	-2.20	1
Carbon Copy		101.7±7.6	-.760	1	111.0±4.6	.560	1
Flex foot		102.4±7.3	.120	1	110.4±5.8	-.440	1
Seattle Foot		102.6±5.4	1.120	1	110.8±5.1	2.120	1
Pre data	Velocity (m/sec)	.99±.09	-.012	1	1.24±.19	-.029	1
Dynamic plus foot		1.00±.07	.080	0.079	1.27± .17	.099	0.462
Trias-Foot		.92±.11	-.054	0.951	1.17±.11	-.054	1
Carbon Copy		.97±.11	-.006	1	1.23±.13	.006	1
Flex foot		.98±.10	-.003	1	1.22±.10	.008	1
Seattle Foot		.98±.08	-.005	1	1.23±.17	-.014	1
Pre data	Swing phase %	38.29±5.58	-.517	1	39.05±5.19	.621	1
Dynamic plus foot		38.82±5.29	-.403	1	38.43±4.86	.897	1
Trias-Foot		39.22±4.96	1.537	1	37.53±5.25	-1.92	1
Carbon Copy		37.68±4.96	-.328	1	39.46±4.87	1.775	1
Flex foot		38.01±6.69	-2.642	0.995	37.69±7.23	.235	1
Seattle Foot		40.655.05	2.354	1	37.45±4.92	-1.60	1

Lateral trunk flexion at mid stance did not reveal significant difference among different feet for amputated and intact side. Forward lean of the trunk at mid stance on the amputated side was near normal using all type of prosthetic feet with no significant difference and for intact side. No significance mean difference was observed in pelvic tilt of amputee while using all type of prosthetic feet.

Discussion

In anticipation of differences in the parameters of gait and kinematics of different prosthetic feet [16, 17], we conducted this study. However, it was noted that the Dynamic Plus foot stood out from the other feet as regards some parameters. This is not surprising because the geometric shape and fabrication of Dynamic Plus feet is different from other feet evaluated in the current study. The Dynamic feet have "S" shaped carbon composite keel attached to a rigid pylon at level of the ankle which is different from other feet. Literature suggests that Dynamic Energy Return (DER) prosthetic feet's alignment is differently dictated by manufacturer as each have their own unique physical design.[18]

Current study revealed that the Stride length using Dynamic foot was significant for amputated (1.20 m ± .10, p = 0.03) and intact side (1.37 m + .09, p = 0.04). Wagner J et al. [19] in their study involving 6 participants compared SACH with Flex-Foot, however they found no significant difference in the stride data between the two.[19]

In the present study, cadence of comfortable walking velocity was greater with the Dynamic Plus (103 steps/min) as compared to the Trias, Flex, and Settle feet (around 102.4 steps/min). However, this difference is just routine variability in

Table III: Gait Kinematics: Pairwise comparison using general linear model (n=25)

Foot type	Parameter	Amputated side (df=14) Estimated Marginal Means	Amputated side Mean Difference (I-J)	Amputated side p-value	Intact side Estimated Marginal Means	Intact side Mean Difference (I-J)	Intact side p-value
Pre data	Hip flexion at terminal swing	15.4±4.3	-.418	1	16.2±5.2	.647	1
Dynamic plus foot		15.8±3.8	.237	1	15.6±4.6	-.339	1
Trias-Foot		15.6±5.0	1.055	1	15.9±5.2	-.022	1
Carbon Copy		14.5±3.6	-.848	1	16.0±5.0	.084	1
Flex foot		15.3±4.3	.196	1	15.9±5.2	.423	1
Seattle Foot		15.2±3.5	-.222	1	15.5±4.5	-.793	1
Pre data	Knee flexion at mid swing	45.1±16.5	2.019	1	42.9±14.1	-1.728	1
Dynamic plus foot		43.1±15.8	.202	1	44.6±9.9	-1.943	1
Trias-Foot		42.9±18.1	-3.331	1	46.5±11.2	3.241	1
Carbon Copy		46.2±14.8	.325	1	43.3±11.4	-.684	1
Flex foot		45.9±12.6	1.022	1	44.0±11.8	2.308	1
Seattle Foot		44.9±18.2	-.237	1	41.7±11.37	-1.192	1
Pre data	Forward lean of trunk at mid stance	1.16±2.4	.522	1	-1.86±4.4	-.978	0.269
Dynamic plus foot		0.64±2.7	-.118	1	-0.88±3.6	.656	0.364
Trias-Foot		0.75±2.3	-.260	1	-1.54±4.2	.310	1
Carbon Copy		1.01±2.1	-.467	1	-1.85±4.3	-.354	1
Flex foot		1.48±1.8	.294	1	-1.49±4.1	-.122	1
Seattle Foot		1.19±2.1	.028	1	-1.37±3.8	.448	1
Pre data	Knee flexion at terminal swing	13.4±9.0	.840	1	11.9(8.2)	2.689	1
Dynamic plus foot		12.5±11.3	1.837	1	9.2(5.8)	-1.162	1
Trias-Foot		10.7±8.6	1.176	1	10.3(6.4)	.520	1
Carbon Copy		9.5±7.1	-1.156	1	9.8(6.9)	-1.554	1
Flex foot		10.7±8.3	-.978	1	11.4(8.5)	.942	1
Seattle Foot		11.7±9.1	-1.720	1	10.4(5.9)	-1.435	1
Pre data	Lateral trunk flexion at mid stance	0.63±1.3	.005	1	0.49±1.4	.324	1
Dynamic plus foot		0.62±3.7	-.178	1	0.17±2.6	-1.030	1
Trias-Foot		0.80±1.1	.198	1	1.20±3.0	.598	1
Carbon Copy		0.60±1.7	-.071	1	0.60±1.6	-.823	1
Flex foot		0.67±1.3	.194	1	1.42±3.7	.848	1
Seattle Foot		0.48±1.4	-.148	1	0.49±1.3	.082	1
Pre data	Pelvic Tilt	-4.90±15.8	-2.471	1			
Dynamic plus foot		-2.43±2.8	.322	1			
Trias-Foot		-2.75±2.6	-.163	1			
Carbon Copy		-2.59±3.3	-.279	1			
Flex foot		-2.31±3.1	.170	1			
Seattle Foot		-2.48± 3.1	2.421	1			

gait seen in normal population since cadence of comfortable walking at 21-40 year of age has been reported to be at a threshold of 100 and 130 steps/ min.[20]

In our study dynamic plus foot revealed higher velocity because of its “S” shape with more compliant forefoot design provided increased late stance energy & speed. The results of our investigation are in agreement with the results of Koehler-McNicholas SR et al. [21]

In the current study results of all the feet have indicated nearly identical symmetry of swing & stance phase percentages on both sides indicating that physical asymmetry of the TT amputees, resulting in alterations in normal gait, was seen using most of the differently designed feet. While, Carley K et al. noted slight difference in the stance %GC (62.6 vs 67.9), swing %GC (37.2, vs 32) and gait cycle time in seconds (1.3 vs 1.5) for prosthetic limb compared to sound limb.[22]

The results of kinematics data of the hip and knee joints in current study did not reveal any significant differences on both sides. At terminal swing, dynamic plus feet users demonstrated almost 160 hip flexions compared to 150 by other feet. However, this difference indicates normal variability in gait hence is not clinically significant. Our results are in conformity with the results that have been reported by Wagner J et al. [19] It is likely that this minor increase in range of hip range because of flexibility of Dynamic Plus foot.

Limitations: The study has limitation including the fact that kinematic data was represented in terms of excursions (increase or decrease/ minimum or maximum) rather than values. Excursion may not fully represent gait deviations.

Conclusion

Dynamic plus feet give a significantly higher stride length compared to trias, carbon copy, flex, and seattle foot and give a insignificant but higher cadence, and velocity

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