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Roll-over analysis of a new design carbon fiber prosthetic foot

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Abstract

Many researchers adopted the quasi static roll over testing in the calculation of a prototype prosthetic feet roll over shape**.** In this work, the prototype of a new carbon fiber prosthetic foot was tested for roll over characteristic. An inverted pendulum like apparatus has been built to achieve the required test, and the prosthesis roll over shape calculated. Roll over characteristics were estimated as: effective radius of curvature about 202mm, center of curvature of 26.55mm, and the forward travel against shank angle was plotted.

Keywords:prosthetic foot, Roll over shape.
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1- Introduction

The foot roll-over shape represents the center of pressure locations, on the foot with respect to a fixed point on the ankle during the period of the stance phase of the human gait. Human sound foot has curves and multi-degrees of freedom that it provides a smooth transition from heel to toe. The more successful prosthesis the one has a continuous and easy-going roll over shape, to be appears similar to the physiological foot roll over shape. The roll over test also can provide a close enlightening about how the prosthesis keel and heel complying under load.

Lots of research works involves with roll over shape and characteristics, for sound feet and prosthetic feet. Research that worked on the sound foot of the human provided many of the conclusions that represented the basics of foot performance during walking gait. The human foot rolls over the ground similar to a rolling wheel [1] since the leg functioned as an inverted pendulum [2],[3], with a center of mass located almost at the pelvis level. The human natural foot has a curvature of about 30% of human leg length during rolling over the ground [4], and it will not significantly change due to the walking speed, the carried loads, or the wearied shoe heel height [5]. This percentage was reported as the optimal metallic costs during walking [6].

2- Experimental work

Quasi-Static Roll-Over Testing

A testing rig was designed and built to investigate the new prosthetic foot roll over characteristics, which was like an inverted pendulum apparatus. The roll over shape of the prosthesis was simulated to a default subject with a body mass of 70 kg and a body height of 1.80 m.

The apparatus consisted of a frame, test angles panel, vertical and horizontal scales, loading shaft with the prosthetic foot attached to the lower end and a mass (m) of 70kg mounted to the upper end of the shaft (figure 1). The center of the added mass was mounted on the loading shaft at a distance of 0.98m from the foot sole. This distance is identical to the ideal leg length of a person with body height of 180 meters, which is adopted by most of the researches that worked on the test of prosthetic feet roll over shape by means of the inverted pendulum-like apparatus [7], [8], [9]. The apparatus was provided with a lateral guide and tow stoppers bars, to guide the testing path and restrict anterior and posterior to predefined limits. The prosthetic foot sole base was supplied with rough surface and heel height compensation block of 15mm in thick, in order to test the prosthesis without costume. The prosthetic foot was mounted and the loading shaft aligned to the right angle line then the rig loaded. A marker line traced on the loading shaft presenting the shank vertical axis. The loading shaft and the prosthetic foot were tracked with a high resolution camera, then the required photos picked and data was taken with loading shaft angles of -15°, -10°, -5°, 0°, 5°, 10°, 15°, and 20°.

Figure (1) the designed roll over rig.

Roll over shape calculation

The two-dimensional roll-over shape of the new ankle-foot prosthetic was calculated from the trajectory of the markers line placed on the axis of the loading shaft and the center of pressure in the direction of forward progression. The marker line coordinate represent the vertical direction (Z) and the direction of forward progression was the X-axis. Since it was a two-dimensional analysis, the lateral coordinates (Y-axis) was not used. Figure (2) represent aschematic diagramof the leg during the gait stance phase, illustrating the analysis coordinates and angles.

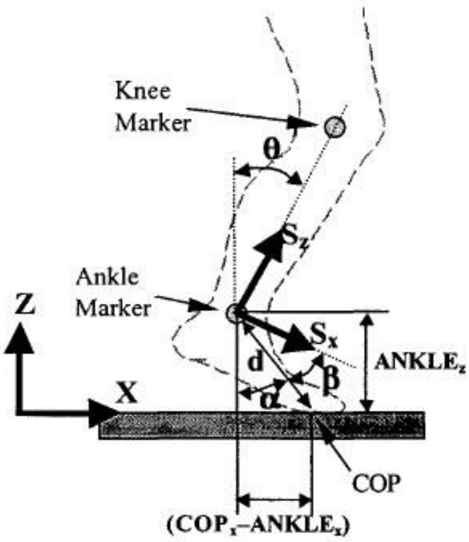


Figure (2) the roll over analysis coordinates and angles [10].

To calculate the roll-over shape, a transformation ofcenter of pressure data from laboratory based coordinates to shank-based coordinates must be achieved. As seen in figure (2), (X, Z) are the laboratory based coordinates, while (S_X, S_Z) represent the shank-based coordinates, with the origin at the ankle. The roll over shape can be calculated using the transformation matrices [9]:

$$Translation\ matrix = \begin{bmatrix} 1 & 0 & X \\ 0 & 1 & Z \\ 0 & 0 & 1 \end{bmatrix} \text{----------------- } \mathbf{(1)}$$

$$Rotation\ matrix = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \text{--------------- } \mathbf{(2)}$$

Calculation can also doing using the following equations [11]:

$$d = \sqrt{(COP_X - ANKLE_X)^2 + (ANKLE_Z)^2} \text{--------- } \mathbf{(3)}$$

$$\theta = tan^{-1}\left(\frac{KNEE_X - ANKLE_X}{KNEE_Z - ANKLE_Z}\right) \text{--------------------- } \mathbf{(4)}$$

where: (d) The distance from the ankle to the center of pressure.

(θ) is the angl ($\propto$) is the angle between the laboratory Z-axis and the line connected the ankle to the center of pressure, while (β) is angle between this line and the shank X-axis. ($\propto$) and (β) can be calculated from the equations:
e that the shaft made with the Z-axis. In this work's apparatus, the angle (θ) can be read directly from the apparatus.

$$\propto = tan^{-1}\left(\frac{COP_X - ANKLE_X}{ANKLE_Z}\right) \quad \text{---------------------(5)}$$

$$\beta = \frac{\pi}{2} - \theta - \propto \quad \text{--------------------- (6)}$$

The coordinates of the center of pressure with respect to the shank-based coordinate system can be calculated from the equations:

$$COP_{S_X} = d\cos(\beta) \quad \text{--------------------- (7)}$$

$$COP_{S_Z} = d\sin(\beta) \quad \text{--------------------- (8)}$$

All calculation must be repeated for every coincide sample of marker and center of pressure data cause the parameters change throughout the entire test. As a result, the center of pressure points with respect to the shank-base coordinates, the COP_{S_X}, andCOP_{S_Z}, will mark out a hypothetical rocker shape of the foot during gait stance phase, which represent the roll over shape of the prosthetic foot.

Effective radius of curvature (ρ)

Over a part of the gait stance phase, human foot-ankle system functions as a smoothly curved stiff body. Like a rolling wheel with a specific radius, the foot center of pressure proceeds forward from heel to toe. A method suggested by Hansen et al. [1] to calculate the effective ankle-foot roll over shape, from the center of pressure data of the specific ankle-foot system. There method was universally applicable, since it can be used in analyzing a simple rolling wheel, deformable objects, and any multi-joint system. The method based on transforming the center of pressure data from the laboratory-based coordinate system to the shank-based coordinate system, outcome the effective curvature shape. In case of foot-ankle system the resulting roll over shape is a semi-circular shape, reflects the system overall movement. After fitting the transformed data by the best fit circle, the radius of curvature will represents the circle radius.

Center of curvature (X_o)

The center of curvature (X_o) is the horizontal position with respect to the shank. It determines the orientation of the foot curvature. Feet with anterior center of curvature to the shank, pointed as feet with an extended orientation while if it is posterior, the feet will diagnoses with a flexed orientation.The "flexed" alignment moves the center of pressure backwards, encouraging the body to roll forward, while "extended" effective rocker prompt the body to stop moving forward. The able-bodied ankle-foot system roll-over shapes exhibit an overall "flexed" orientation during the first step of gait initiation as it realigned an "extended" orientation during the last step of gait termination.

Forward travel (S)

The center of pressure moves along the foot curvature, as the foot rolled over. A very large radius of curvature foot resulting in fast forward travel (S) as a function of shank angle (θ), while a small radius of curvature resulting little forward travel as a function of shank angle. In addition, the largest the radius of curvature the more stable.
The ankle-foot radius of the curvature can be calculated using equation (9) assuming it has constant curvature.

$$S = \theta\rho + X_0 \quad \text{------------------------ (9)}$$

3- Roll over results and discussion

The roll over test was accomplished using the designed rig described in chapter four. After tracking the test process by a movie camera, the required screenshots were taken for assumed shank angles of -15°, -10°, -5°, 0°, 5°, 10°, 15°, and 20° as seen in figure (3).

(a) **(b)**

(c)

Figure (3) the test processscreenshots at angles (a) -15°, (b) 0°, and (c) 20°.

The data estimated from the taken screenshots are: COP_{S_X},$ANKLE_X$, and,$ANKLE_Z$, for each individual angle were as seen in table (1).

Table (1) roll over test parameters.

Shank calculated Angle	COP_X **(mm)**	$ANKLE_X$ **(mm)**	$ANKLE_Z$ **(mm)**	$KNEE_X$ **(mm)**	$KNEE_Z$ **(mm)**
-15.1°	247	205	100	233	201
-9.9°	244	198	96.2	216	199
-5.2°	241	190	95.3	200	199
0° $\begin{cases} at\ heel \\ at\ keel \end{cases}$	230 76	185	95	185	200
5.8°	70	173	103	162	204
9.5°	72	174	104.7	157	2207
14.8°	66	162	111	136	211
19.84°	61	154	119	120	217

Equations (3) to (8) were used to achieve the require analysis calculations, table (2) to approach the roll over shape figure (4).

Table (2) roll over calculations results.

(θ)	($\propto$)	(β)	(d)	COP_{S_X}	COP_{S_Z}
-15.1	22.54	52.36	108.27	66.12	85.73
-9.9	25.66	54.44	106.75	62.08	86.84
-5.2	28.13	56.67	108	59.34	90.2
0 $\begin{cases} at\ heel \\ at\ keel \end{cases}$	29.5 48.79	60.5 41.57	105.45 144.2	51.92 107.88	91.78 95.68
5.8	43.93	40.27	142.7	106.82	92.29
9.5	44.22	36.28	146.1	117.77	86.45
14.8	40.84	34.36	147.14	121.46	83.04
19.84	37.77	32.39	151.8	128.2	81.33

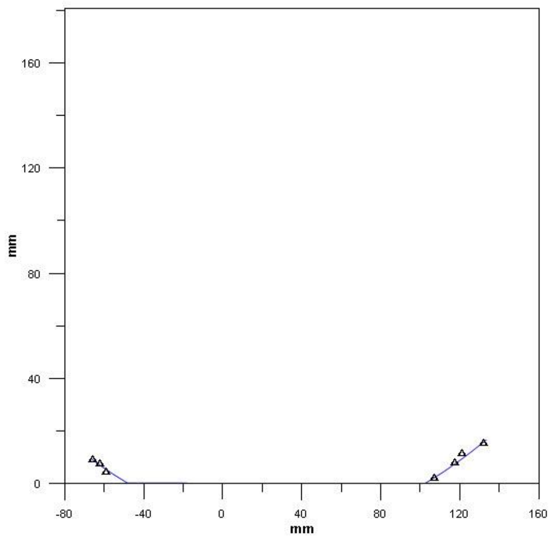


Figure (4) the estimated roll over shape of the new ankle-foot prosthetic.

Effective radius and center of curvature (ρ) and (x_o)

The least square method was used to estimate the best circle fitting roll over points, figure (5).

The radius of curvature was measured as the radius of the fitted circle, which was about 202mm. Since the effective radius of curvature is used as an indicator for the feet overall stability, the estimated radius can gave a sign of moderate overall stability of the new prosthesis. The estimated effective radius of curvature can evaluated comparing to figure (6). Again, the testing procedure under non costumed ankle-foot system can explain the relatively small value comparing with values of figure (6).

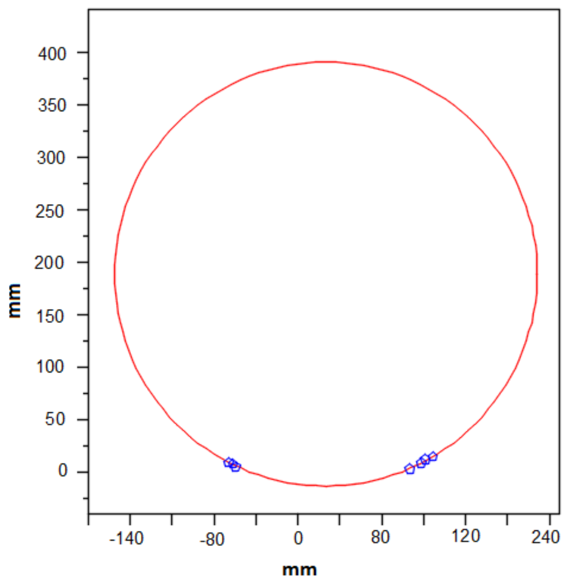


Figure (5) least square circle best fit for the roll over points.

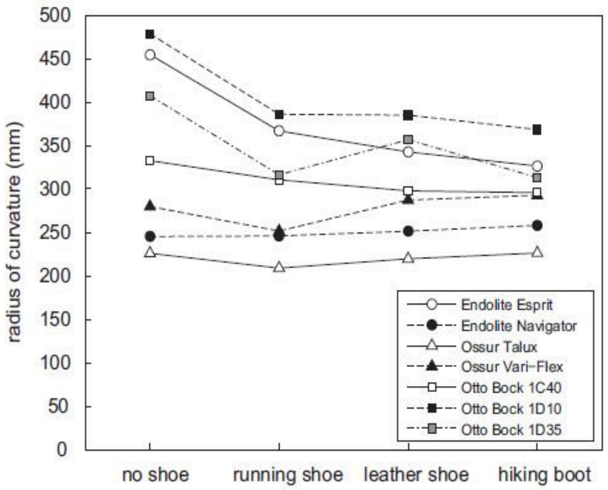


Figure (6) the effective radius of curvature for different feet types [7].

The estimated radius was highly sensitive to the small variance in the roll-over shape due to the fitting process sensitivity.

The center of curvature (x_o) was 26.55mm as seen in the figure (5). This indicated that the new ankle-foot prosthetic was with flexed orientation as most ankle-foot prosthetic devices. That was important to encouraging the prosthesis user body to roll forward.

Forward travel (s)

The new ankle-foot prosthetic shows a good forward travel as a function of shank angleas indicated in figure (7), when it compared with another commercial types of prostheses figure (8) [7].

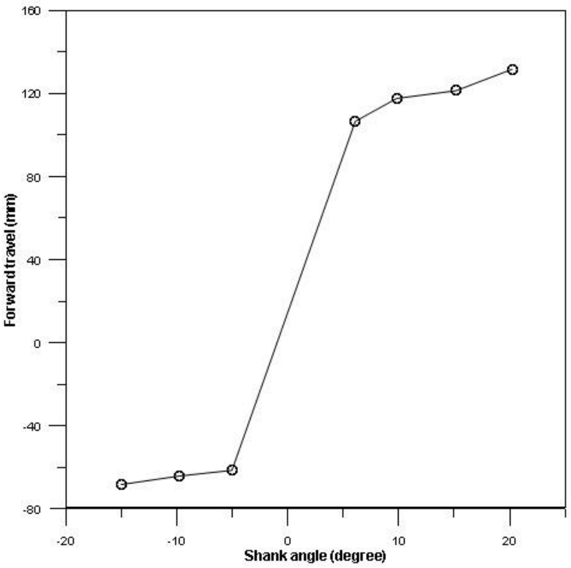
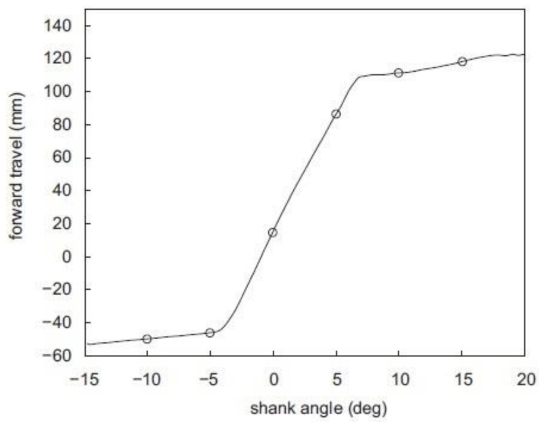
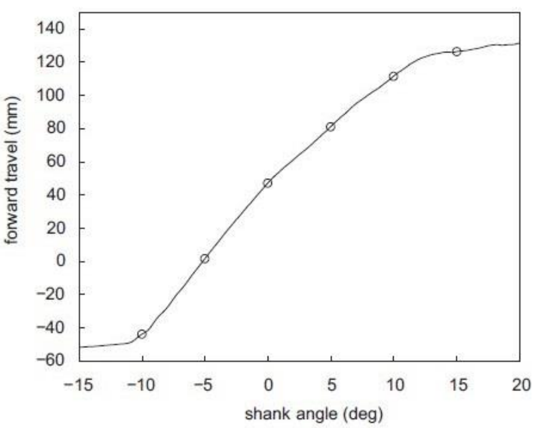


Figure (7) the forward travel with respect to shank angle during roll over.



(a)



(b)

Figure (8) the forward travel as a function of shank angle at the no-shoe condition of the Endolite Esprit foot (a) and theOssurVari-Flex foot (b).

4- Conclusions and Future work

1- The ankle-foot roll over shape and its characterization, gives overall judgment about the ankle-foot system performance during the gait stance phase, therefore a high consideration must be taken for it in the design of the ankle-foot prosthetic.

2- While this method allows the body weight to be simulated for the person who moves wearing a prosthetic foot, it cannot mimicking the complex dynamics of the foot components, occur during an amputated gait.

3- In this study, the prosthetic leg simulated by the inverted pendulum, which moved robustly in the sagittal plain with the prosthetic foot pointing straight forward. While in clinical practice, it is sometimes necessary todeviate the prosthetic foot orientation. The different foot orientation can significantly effect on the produced roll-over characteristics.

In the future the following work, recommended to be achieve:

1- Modifying the new prosthesis heel and keel components in order to enhance the ankle-foot prosthetic roll over characteristics.

2- Repeat this work procedures using a force plate and more precise motion tracking equipment’s.

3- Study the effect of the foot costume and the various wearing types of shoes on the new prosthesis roll over characteristics.

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