Stress Analysis of the Above-Knee Prosthesis during Gait Cycle

Bakr Noori Khudher
Mechanical Department / College of Engineering
University of Mosul

Abstract

In this paper the finite element analysis was achieved on the above-knee prosthesis to investigate a picture of stress distribution in the socket. Previous works on the prostheses used the symmetry approximation in shape modeling and most of them are all about static loading. The analysis and shape modeling in this work were achieved in high accuracy with the aid of ANSYS 12.1 package software capabilities. Of this study, stress analysis was achieved under dynamic loading at the three main gait cycle; soon after heel strike, foot flat and just before tow off as traditional stages used in researches. This work lies on the dynamic loading calculated with the ground reaction forces, dynamic forces, and moments as well as the angular and linear acceleration of foot up to the thigh during the three main gait cycle.

The stress distribution was achieved and it is imported to note that the maximum stress induced in the socket are at the upper brim whereas most parts of the socket are considered as a low stress region.

Key Words: stress, dynamic loading, socket , prosthesis, above knee, finite element.

تحليل الأجهادات لوقب الطرف الصناعي أعلى الركبة خلال الخطوة الواحدة

بكر نوري خضر
مدرس مساعد
جامعة الموصل-كلية الهندسة-قسم الهندسة الميكانيكية

الخلاصة

في هذا البحث تم أجراء عملية تحليل العناصر المحددة لوقب الطرف الصناعي أعلى الركبة لمعرفة خارطة توزيع الأجهادات المتولدة خلال الطرف. أجريت الأعمال السابقة على هذا النوع من الطرف باستخدام الشكل المتماثل كما كان التركيز كثيرا على حساب الأجهادات بتأثير الأحمال الساكنة. في هذه الدراسة كانت عملية التحليل ونمذجة شكل الوقب قريبة جدا من الشكل الحقيقي بالاستفادة من ألإمكانيات الكبيرة لبرنامج (ANSYS 12.1) . تضمنت الدراسة عملية تحليل للأجهادات بتأثير الأحمال الحركية عند المراحل الرئيسية الثلاثة للخطوة وهي مرحلة ما تلي مباشرة ضرب الكعب الأرض ومرحلة تسطح القدم والمرحلة التي تسبق بقليل ابتعاد أصابع القدم عن الأرض وهي مراحل تقليدية دأب عليها الباحثون. واعتمدت الدراسة على حساب الحمل الحركي بحساب قوى رد الفعل الأرضي والقوى والعزوم الحركية المصاحبة للتعجيل الخطي والدوراني من القدم صعودا الى عظم الفخذ عند المراحل الرئيسية الثلاثة للخطوة. تم الحصول على صورة توزيع الأجهادات على المناطق المختلفة للوقب ولوحظ أن قيمها العظمى تركزت في منطقة الحافة العليا فيما تميزت معظم المناطق الأخرى بأنها ذات مستويات أجهاد متدنية.

Received: 23 – 10 - 2011 **Accepted: 26 – 2 - 2012**

1. Introduction

The long term performance of the above-knee socket prosthesis depends on the kinematics, pressure and stresses generated within the socket. Retrieval studies have shown that the pressure between the residual limb and the socket as well as the stress distribution are the most dominant factors in socket design. Van et al.[1] used a mathematical model to investigate the dynamic behavior of an above-knee prosthesis in the swing phase and analyzed the influence of mass and mass distribution on the maximal stump load and the required energy. Barbara et al.[2] stated the influence of prosthetic design parameters and alignment variations on the interface stress distribution. VSP etal.[3] designed and built a system for measuring the stump socket interface pressure using a strain gauged type load cell. They used a quadrilateral ischial containment socket and found that higher pressures were recorded at the proximal brim of the socket. Ross [4] determined the load paths of the prosthetic socket using finite element analysis and calculated the linear and angular acceleration of foot, shank and thigh during gait cycle. Tae Soo Bae etal.[5] studied the amputated limb dynamically from the musculoskeletal view.

In any finite element analysis, the work can be divided into three phases; first is pre-processing which defines the finite element model and environmental factors to be applied to it, then analysis solver implying toward the solution of finite element model and finally post-processing of results using visualization tools. The following sections describe the dynamic analysis performed over AK prosthesis using the latest version ANSYS 12.1, a commercial FE software program. The motivation of this study is to investigate the behavior of newly designed socket prosthesis under body weight during gait cycle. Due to irregular geometry, the modeling shape of the prosthetic socket is achieved by measuring the coordination of points located at the boundary stripes in small measures. With the aid of ANSYS modeling abilities, the shape modeling was created and manipulated. With this model, three different stages of the gait cycle (soon after heel strike, foot flat, and just before toe off) were simulated (Fig. 1). The loading on the thigh are calculated starting from dynamic analysis of foot up to thigh including all loads as shown in the FB and kinetics diagrams in the Appendix A.

2. Above-knee prosthesis Description

The artificial limb consists of a foot-ankle unit which needs to be attached to the remainder of the amputee's natural leg or stump. The foot ankle unit is attached directly to the socket frame. The artificial shank can be attached to the foot ankle unit and then attached to the knee unit which in turn, is attached to the socket frame for an above-knee amputation. Today the sockets are roughly quadrilateral in shape. They attempt to have total contact between the stump and the socket.

3. Socket Material Properties

The material of the socket, adopted by Mosul Factory for Prosthetics and Orthotics, is polypropylene. The mechanical properties are: Young modulus is 11.72 GPa, the Poisson's ratio is 0.3, yield strength is 35 MPa and the density is 0.92 gm/cm3 [6] .The measured thickness of the socket is 4 mm.

4. Socket Loading

In order to find the socket loading, the leg segment geometry and the ground reaction force are required at the required phases of gait. The segment lengths, masses and inertias were calculated.

By taking the physical subject geometry and weight, the ground reaction forces during walking can be calculated. Using these values, all the leg joint forces can be found. The hip forces are then applied to the socket model. To achieve this goal, each segment should be drawn with its own free body and kinetics diagrams. The lateral components for this study has been neglected as it is insignificant compared to the vertical forces. Traditional theory has the ischium transferring most of the load to the socket during stance. However, during swing phase the ischium moves away from the limb so little contact is made and hence their loadings are neglected.

The subject is 173 cm high and 80 kg weight, the body segment lengths are calculated as a percentage of height following Drillis and Contini [7] .

$$Foot\ length = 0.152\ H = 274\,mm$$
$$Shank\ length = 0.246\ H = 443\,mm$$
$$Thigh\ length = 0.2\ H = 360\ mm$$
$$Heel\ length = 0.039\,H = 70\ mm$$

Where H = height of the subject.

The only way to find the segment mass is as a percentage of total body mass as measured on a live subject is inaccurate. Although old, one of the best studies done on segment masses and their inertia was by Braune and Fisher [8]. They had access to large numbers of cadavers allowing for an accurate study. With the application of Braune approximation on the subject of this study, the followings are calculated.

Foot:

$$Mass = 0.022 \times Body\ mass = 1.68\ kg$$
$$Center\ of\ mass = 0.35 \times Segment\ length = 0.35 \times 274 = 96\ mm$$
$$I = (0.3 \times 0.274)^2 \times 1.68 = 0.01135\ kg.m^2$$
$$Heel\ length = 0.039\,H = 70\ mm$$

Shank:

$$Mass = 0.045 \times Body\ mass = 3.6\ kg$$
$$Center\ of\ mass = 0.433 \times Segment\ length = 0.433 \times 433 = 192\ mm$$
$$I = (0.3 \times 0.433)^2 \times 3.6 = 0.064\ kg.m^2$$

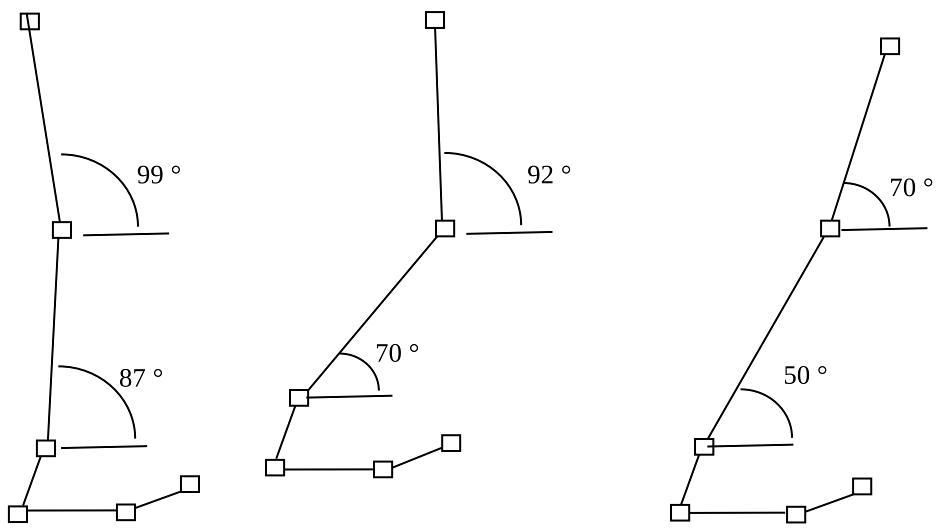
Thigh:

$$Mass = 0.11 \times Body\ mass = 8.8\ kg$$
$$Center\ of\ mass = 0.435 \times Segment\ length = 0.435 \times 360 = 157\ mm$$
$$I = (0.3 \times 0.36)^2 \times 8.8 = 0.1026\ kg.m^2$$

Table (1) Ground reaction force as a percentage of body weight[4] .

Stage	Vertical	Anterior-posterior
Heel strike	120%	-20%
Foot flat	70%	- 4%
Toe-off	110%	15%

Fig. (1) shows the geometry of the artificial limb under three conditions; soon after heel strike, foot flat, and just before toe off.



Soon after heel strike Foot flat Just before toe off

Figure (1) Geometry of the segments at the three main gait cycles [4]

Table (2) The accelerations of the body segments [4]

	Foot			Shank			Thigh		
	a_y	a_z	α	a_y	a_z	α	a_y	a_z	α
Heel strike	-2.17	2.42	19.03	-6.86	-0.28	15.53	-6.24	-0.18	-15.71
Foot flat	0.22	0.11	-2.23	0.59	0.15	-0.66	0.01	-1.16	3.44
Tow off	2.37	1.16	-23.41	6.75	0.11	11.05	5.19	-0.96	13.96

The complete calculations of the socket loading are in the Appendix A

Fig. (2) shows the socket Loadings at the three main stages of the gait.

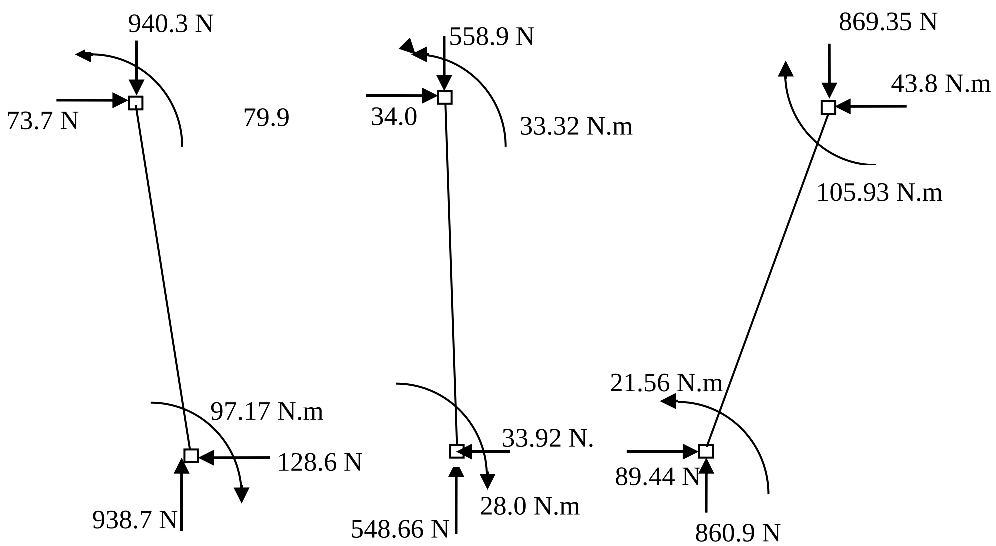


Figure (2) Socket loadings at the three main stages of the gait.

5. Solution Teqnique

In above-knee socket, the ischial bone supports all loads, the loads are applied on the control nods at the ischial plane of the socket proximal end. These loads include normal loads such as that in y and z direction as well as that of torque (Fig. 2). The boundary condition for the socket concluded from the distal end of the socket attached to a fixed end. Thus all the nodes at the distal end with displacements and rotations set to zero. The element is shell 63. The shape of the socket is modeled by dividing the socket into large numbers of stripes and measuring the coordinates of each stripes with respect to a fixed convenient origin. With ANSYS package software these points are created as well as the lines and areas (Fig. 3). Having all steps of the preprocessing are achieved including the mesh operation, the boundary conditions and loads are applied to obtain the solution (Fig. 4). The postprocessing includes the ploting of contours where the stress distribution are found in different directions at the main stages of gait cycle.

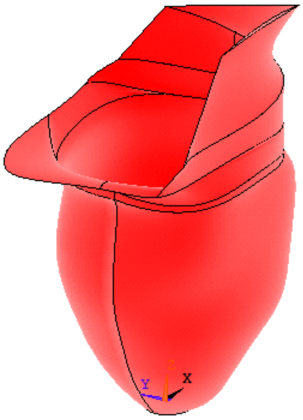


Figure 3 Above knee prosthesis socket with ischial containment

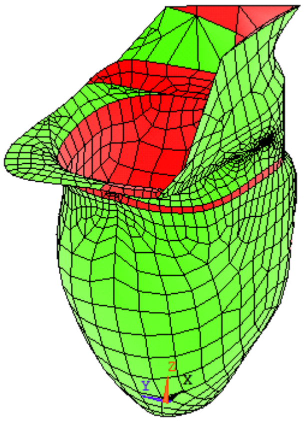


Figure 4 Finite element model

6. Results

Through finite element models of the socket, stress distributions were obtained for different conditions of gait cycle. Table (3) shows the maximum stresses developed at the three main gait cycle. The maximum stresses, including Von Mises stresses obtained in the socket at tow off were higher than those obtained at heel strike and much greater than those at foot flat. At heel strike, the maximum stresses were 0.081 MPa, 0.0083 MPa, 0.204 MPa and 0.19 MPa in x, y ,z ,and Von Mises respectively; the values obtained at foot flat were 56%, 43%, 56% and 59% lower respectively and that obtained at tow off were 17%, 31%, 17% and 17% higher respectively.

The locations of maximum stress, at the three main gait cycle, are occurred at the brim of the socket and this seems reasonable since this area receives most of the loads. However, the stress distribution decreases down the socket.

Comparing the tow off stage with the other two stages of gait cycle, the tow off stage demonstrated great influence on Von Mises stress. The maximum Von Mises stress during the three stages are occurred at the tow off stage. However, it is much less than the yield stress of the socket material, 35 MPa.

Fig. 5 to Fig. 8 display contour plots of stress distribution in x, y and z direction as well as that of Von Mises stress during the three main gait cycle; soon after heel strike, foot flat and just before tow off respectively.

Table (3) The maximum stresses at the three main gait cycle.

Stress	Heel strike, MPa	Foot flat, MPa	Tow off, MPa
σ_x	-0.081	-0.045	-0.095
σ_y	-0.0083	-0.0036	-0.0109
σ_z	-0.204	-0.115	-0.239
$\sigma_{VonMises}$	0.19	0.108	0.223

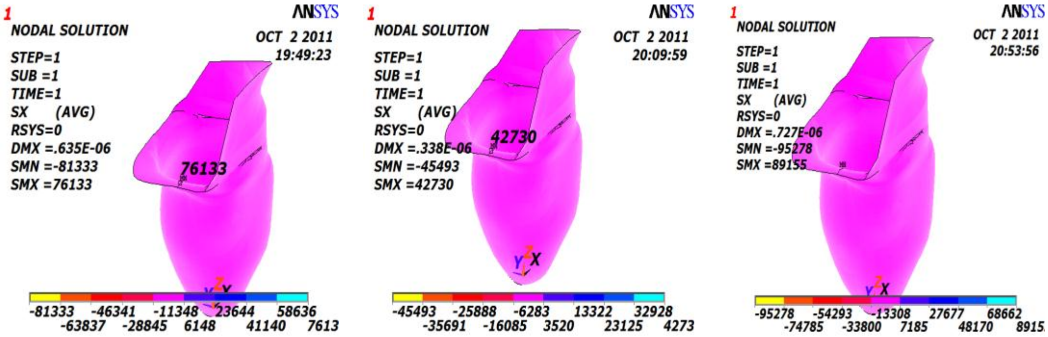


Figure (5) Stress distribution in anterior-posterior (x-direction) developed during three main gait cycle.

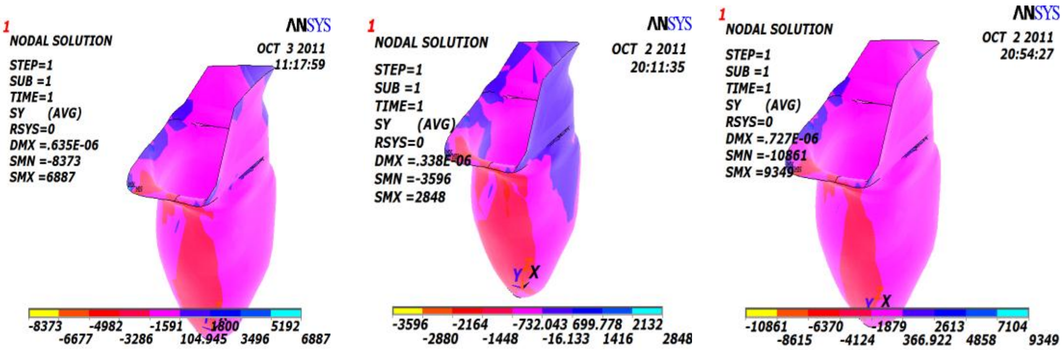


Figure (6) Stress distribution in lateral medial (y-direction) developed during three main gait cycle.

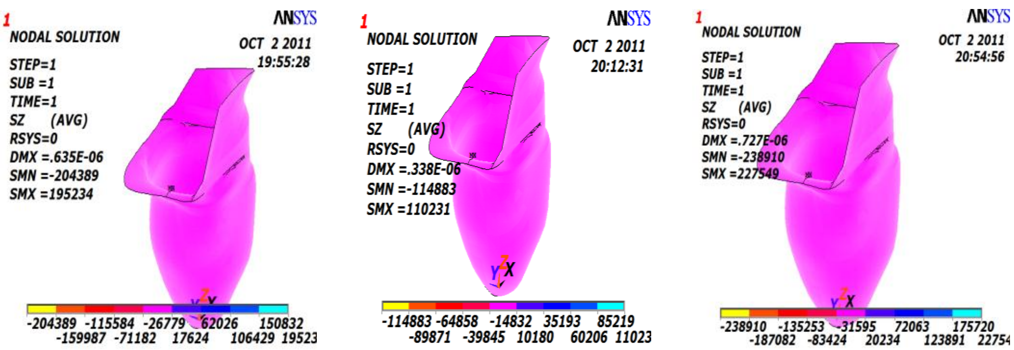


Figure (7) Stress distribution in transverse (z-direction) developed during three main gait cy-cle.

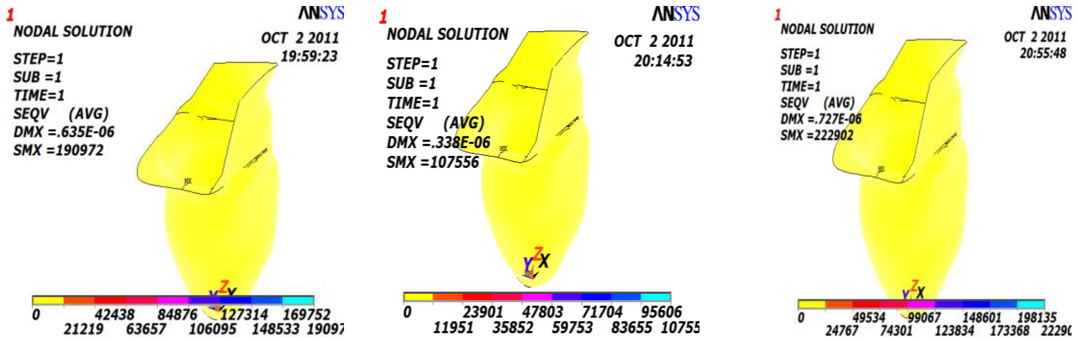


Figure (8) Von Mises stress distribution developed during three main gait cycle.

7. Discussion

Direct comparison of the results of this study with others is difficult, due to the individual differences. The stages of gait at which the load cases are calculated referred to Ross [4] .The change in the load distribution due to the different stage of gait increases stresses in some regions and reduces them in others. It has been reported that the stress concentrates at the upper brim of the socket [4] . However, the results of this study mimics that of Ross. At the three main stages of gait, most of the socket are characterized as low stress region of σ_x and σ_z and developed uniformly through all over the socket except for the concentration of stress at the upper brim. The posterior side of the socket is subjected to high stresses σ_y in addition to the maximums at the upper brim. Even the Von Mises stress are developed in low values.

8. Conclusions

From the above analysis, we can notice clearly that:

1. The stresses developed at tow off are much greater than that of other stages of gait. This stage can be considered as a design stage.
2. The maximum stress developed in this model was below the yield stress of the socket material altogether. hence, it can be concluded that the socket withstands loading efficiently and there is no probability of failure.
3. As the maximum Von Mises stress developed at tow off is about 0.75% of the yield stress, the material of the socket can be optimized by reducing the thickness of the socket without affecting the strength of the socket and hence the cost will be decreased.

Glossary

Anterior: In front of the body.
Brim: Top lip of the socket.
Distal: Furthermost part from the center of the body.
Gait: Manner of walking.
Heel strike: When the foot touches the ground at heel strike.
Ischium: Bone on the inside posterior of the hip.
Lateral: Outside of the body.
Medial: Inside of the body on a lateral plane.
Phase: Particular instance of gait.
Posterior: rear section of the body.
Prosthetic: Artificial limb.
Socket: Interface component between the prosthesis and the stump.
Stance: Phase of gait when part of the foot is in contact with the ground.
Swing: Phase of gait when the foot is off the ground.

Tow off: When the foot leaves the ground, to start the swing phase of gait.

References

1. Braune W. and Fischer, " Bestimmung der Traggetitsmomente des Menschlichen korpers und Seiner Glieder" published by S. Hirzel Leipsig 1892, " Determination of Body Moments of Inertia of the Human Body and its limbs" Translators P Maguit and R. Fulong, Springer Ferlag, 1988.
2. Drillis, R. and R. Contini, "Body Segment Parameters", Report No. 1363-03, Office of Vocational Rehabilitations, Department health, Education and welfare, New York.
3. Van P.G., and etal. " Bondgraph Modeling and Simulation of the Dynamic Behavior of above-Knee Prostheses" , Journal of Prosthetics and Orthotics International, Vol. 11,1987,pp. 65-70.
4. Barbara M., and etal. "A Review of Prosthetic Interface Stress Investigation", Journal of Rehabilitation Research and Development, Vol. 33, No. 3, July 1996, pp.253-266.
5. VSP and etal., " Stump-Socket Interface pressure as an aid to Socket Design in Prostheses for Transfemoral Amputees", Journal of Engineering in Medicine" Part 2, Feb. 1, 1997, pp. 167-180.
6. Ross Steward " Prosthetic Development", REHAB Tech.- Monash Rehabilitation Technology Research Unit, C/-C.G.M.C., Australia 1998.
7. Meriam J.L. and L.G. Kraige, " Engineering Mechanics' Dynamics", John Wiley & Sons, Inc. 6th ed. 2007.
8. Jweeg, J. and Bakr N. Al-Hasan ,Optimum Shape and Location of Opening in Syme Prosthesis Under General Loading, Al-Rafidain Engineering Journal, Vol. 16, No. 1, 2008, pp. 59.
9. Bae, T. S. et al. " Dynamic Analysis of Above Knee Amputee Gait", Jounal of Clinical Biomechanics, Vol. 22, 2007, 557-566.

Appendix A
The Complete Calculations of Socket Loading

Soon After Heel Strike

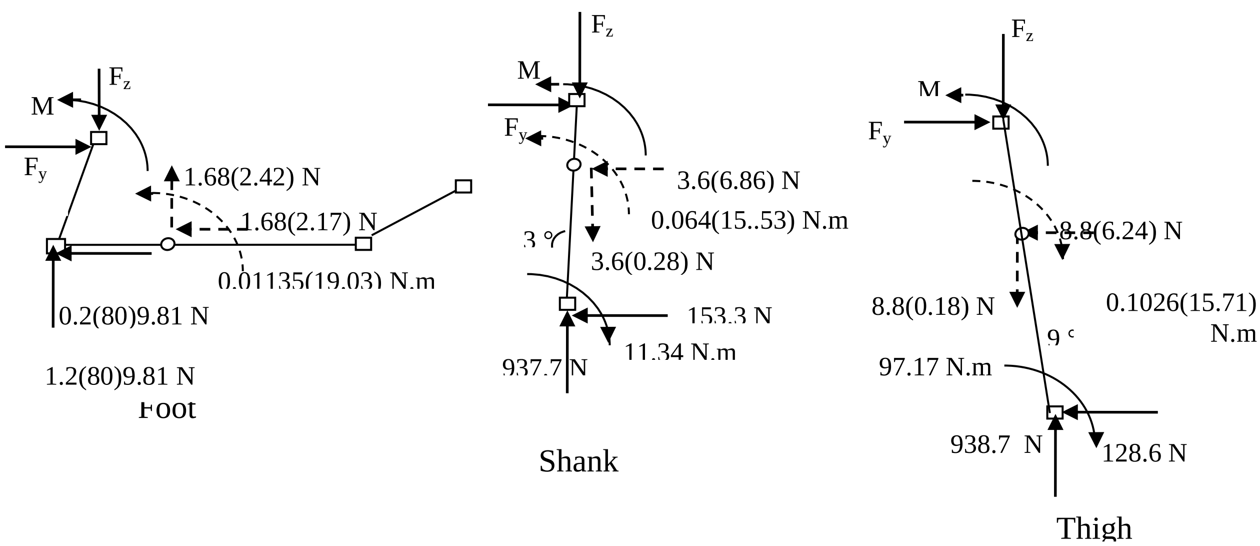


Figure (A.1) Free body and kinetic diagrams of foot, shank, and thigh respectively soon after heel strike.

Foot

$\sum M = \bar{I}\alpha + \sum m\bar{a}d$ [7]

$M - 0.2(80)9.81 \times 0.07 = 0.01135 \times 19.03 + 1.68 \times 2.42 \times 0.096 - 1.68(2.17) \times 0.07$

$M = 11.34\ N.m$

$\sum F_y = m\bar{a}_y$ [7]

$-F_y + 0.2(80)9.81 = 1.68(2.17)$

$F_y = 153.3 \quad \rightarrow$

$\sum F_z = m\bar{a}_z$ [7]

$-F_z + 1.2(80)9.81 = 1.68 \times 2.42$

$F_z = 937.7\ N \quad \downarrow$

Shank

$\sum M = \bar{I}\alpha + \sum m\bar{a}d$

$M - 153.3 \times 0.443\cos 3^\circ - 937.7 \times 0.443\sin 3^\circ - 11.34 = 0.064(15.53) + 3.6(0.28) \times 0.192\sin 3^\circ$

$-3.6(6.86) \times 0.192\cos 3^\circ$

$M = 97.17\ N.m$

$\sum F_y = m\bar{a}_y$

$-F_y + 153.3 = 3.6(6.86)$

$F_y = 128.6\ N \quad \rightarrow$

$\sum F_z = m\bar{a}_z$

$F_z - 937.7 = 3.6(0.28)$

$F_z = 938.7\ N \quad \downarrow$

Thigh

$\sum M = \bar{I}\alpha + \sum m\bar{a}d$

$-M + 128.6 \times 0.36\cos 9^\circ - 938.7 \times 0.36\sin 9^\circ + 97.17 = 0.1026(15.71) + 8.8(6.24) \times 0.157\cos 9^\circ$

$+8.8(0.18) \times 0.157\sin 9^\circ$

$M = 79.9\ N.m$

$\sum F_y = m\bar{a}_y$

$-F_y + 128.6 = 8.8(6.24)$

$F_y = 73.7\ N \quad \rightarrow$

$\sum F_z = m\bar{a}_z$

$F_z - 938.7 = 8.8(0.18)$

$F_z = 940.3\ N \quad \downarrow$

At Foot Flat

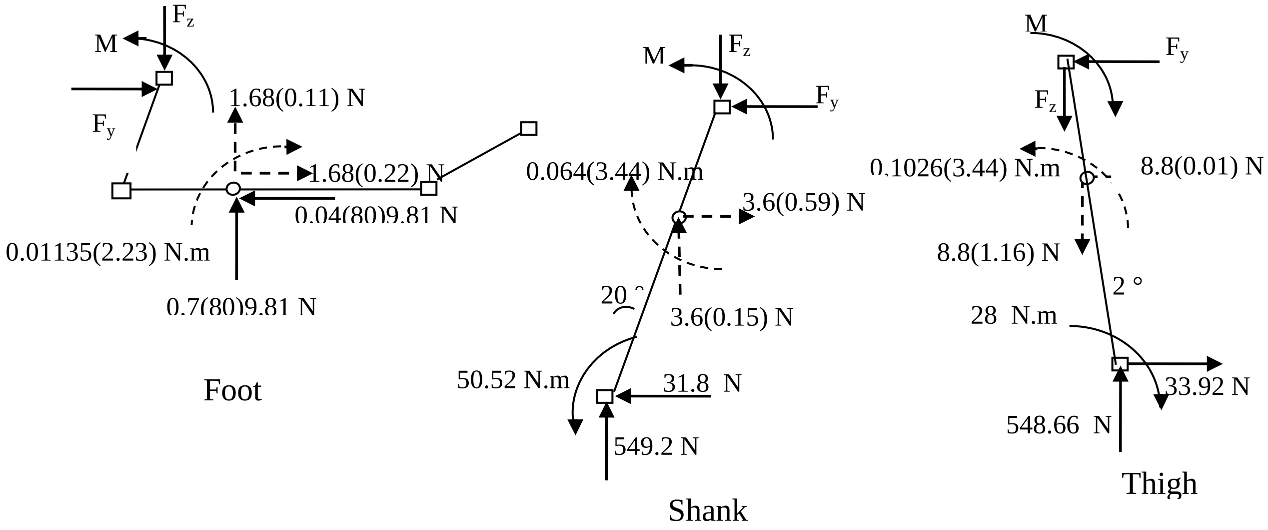


Figure (A.2) Free body and kinetic diagrams of foot, shank, and thigh respectively at foot flat.

Foot

$\sum M = \bar{I}\alpha + \sum m\,\bar{a}\,d$

$-M - 0.7\times 80\times 9.81\times 0.096 + 0.04\times 80\times 9.81\times 0.07 = 0.01135(2.23) - 1.68(0.22)(0.07)$

$-1.68(0.11)\times 0.096$

$M = 50.52 \ \ N.m$

$\sum F_y = m\bar{a}_y$

$F_y - 0.04\times 80\times 9.81 = 1.68(0.22)$

$F_y = 31.8\ N \quad \rightarrow$

$\sum F_z = m\,\bar{a}_z$

$-F_z + 0.7\times 80\times 9.81 = 1.68(0.11)$

$F_z = 549.2\ N \quad \downarrow$

Shank

$\sum M = \bar{I}\alpha + \sum m\,\bar{a}\,d$

$-M + 31.8\times 0.36\ \cos 20^{\circ} + 549.2\times 0.36\ \sin 20^{\circ} - 50.2 = 0.064(3.44) + -3..6(0.59)\times 0.192\ \cos\ 20^{\circ}$

$+3.6(0.15)\times 0.192\ \sin 20^{\circ}$

$M = 28 \ \ N.m$

$\sum F_y = m\,\bar{a}_y$

$-F_y - 31.8 = 3.6(0.59)$

$F_y = 33.92\ N \quad \rightarrow$

$\sum F_z = m\,\bar{a}_z$

$-F_z + 549.2 = 3.6(0.15)$

$F_z = 548.66\ N \quad \downarrow$

Thigh

$$\sum M = \bar{I}\alpha + \sum m\bar{a}d$$

$$-M - 28 - 33.92 \times 0.36 \cos 2^{\circ} + 548.66 \times 0.36 \sin 2^{\circ} = 0.1026(3.44) + 8.8(0.01) \times 0.157 \cos 2^{\circ}$$

$$-8.8(1.16) \sin 2^{\circ}$$

$$M = 33.32 \ \ N.m$$

$$\sum F_y = m\bar{a}_y$$

$$-F_y - 33.92 = 8.8(0.01)$$

$$F_y = 34 \ N \quad \rightarrow$$

$$\sum F_z = m\bar{a}_z$$

$$F_z - 548.66 = 8.8(1.16)$$

$$F_z = 558.9 \ N \quad \downarrow$$

Just Before Two off

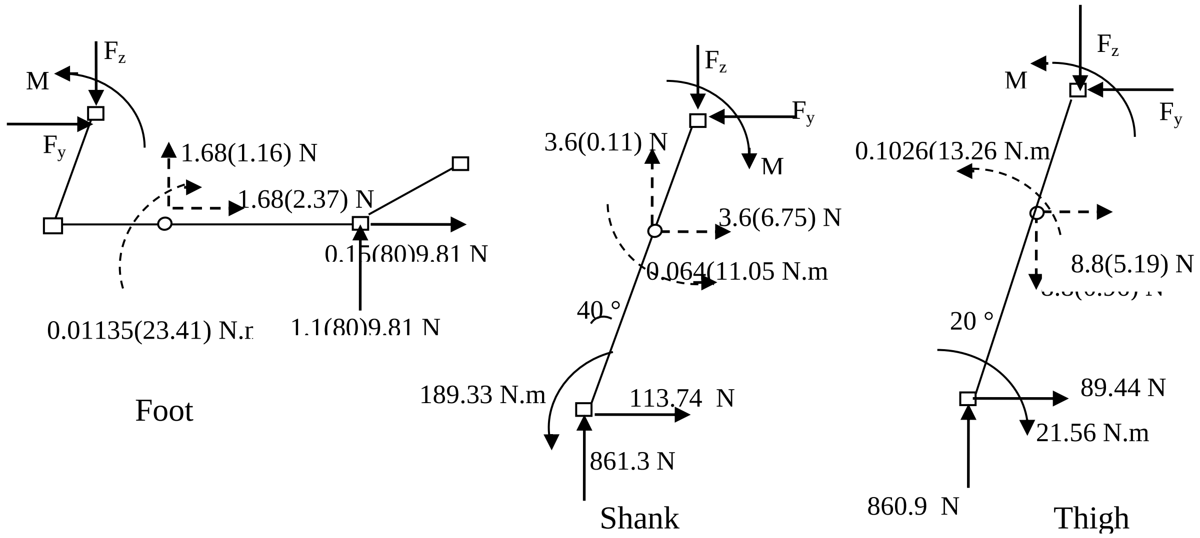


Figure (A.3) Free body and kinetic diagrams of foot, shank, and thigh respectively just before two off.

Foot

$$\sum M = \bar{I}\alpha + \sum m\bar{a}d$$

$$-M - 0.15(80)9.81 \times 0.07 - 1.1(80)9.81 \times 0.210 = 0.01135(23.41) - 1.68(2.37)0.07$$

$$-1.68(1.16)0.096$$

$$M = 189.33 \ \ N.m$$

$$\sum F_y = m\bar{a}_y$$

$$-F_y + 0.15(80)9.81 = 1.68(2.37)$$

$$F_y = 113.74 \ N \quad \leftarrow$$

$$\sum F_z = m\bar{a}_z$$

$$-F_z + 1.1(80)9.81 = 1.68(1.16)$$

$$F_z = 861.3 \ N \quad \downarrow$$

Shank

$\sum M = \bar{I}\alpha + \sum m\bar{a}d$

$-M + 189.33 + 113.74 \times 0.433\cos 40^\circ - 861.3 \times 0.443\sin 40^\circ = 0.064(11.05) + 3..6(6.75) \times 0.192\cos 40^\circ$

$-3.6(0.11) \times 0.192\sin 40^\circ$

$M = 21.56 \quad N.m$

$\sum F_y = m\bar{a}_y$

$-F_y + 113.74 = 3.6(6.75)$

$F_y = 89.44\ N \quad \leftarrow$

$\sum F_z = m\bar{a}_z$

$-F_z + 861.3 = 3.6(0.11)$

$F_z = 860.9\ N \quad \downarrow$

Thigh

$\sum M = \bar{I}\alpha + \sum m\bar{a}d$

$M - 21.56 + 89.44 \times 0.36\cos 20^\circ - 860.9 \times 0.36\sin 20^\circ = 0.1026(13.96) + 8.8(5.19) \times 0.157\cos 20^\circ$

$+8.8(0.96) \times 0.157\sin 20^\circ$

$M = 105.93 \quad N.m$

$\sum F_y = m\bar{a}_y$

$-F_y + 89.44 = 8.8(5.19)$

$F_y = 43.8\ N \quad \leftarrow$

$\sum F_z = m\bar{a}_z$

$F_z - 860.9 = 8.8(0.96)$

$F_z = 869.35\ N \quad \downarrow$

The work was carried out at the college of Engineering. University of Mosul