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Keywords

fatigue, evaluate, approach, numerical, life, monolimb

Disciplines

Engineering | Science and Technology Studies

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A numerical approach to evaluate the fatigue life of monolimb

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Abstract

Monolimb refers to a transtibial prosthesis with the prosthetic socket and the shank being molded into one piece of thermoplastic material. Shank flexibility of a monolimb can improve gait and comfort. However, fatigue failure of monolimbs under cyclic walking load is an important concern. This study is to evaluate the fatigue life of a monolimb designed for a transtibial amputee, based on finite element analysis, the statistical Miner's rule and reliability analysis. Stress uncertainty due to modeling error and the scatter in fatigue test data were considered. Results indicated that the accuracy of fatigue life evaluation of monolimb depends significantly on the precision of stress estimation. In addition, relationship between fatigue failure probability and the number of walking steps was suggested providing a reference for clinicians to determine the interval of the inspection for the monolimb.

Keywords: monolimb, fatigue life, finite element analysis, the statistical Miner's rule, reliability analysis

Introduction

Thermoplastics have been growing in use in the field of lower limb prosthetics. One kind of transtibial prosthesis are fabricated with the prosthetic socket and the shank being molded into one piece of thermoplastic material [1-6]. Different names are assigned to the prosthesis such as monolimb [1, 2], endoflex [3], total thermoplastic prosthesis [4] and ultra-light prosthesis [5, 6]. The term “monolimb” will be used throughout this paper. Monolimb has a characteristic that the shank can deflect more than the modular prostheses during walking. By proper use of material and structural design, the shank can deform leading to simulated dorsiflexion and plantarflexion of the prosthetic foot, which might improve gait and comfort [7]. Light weight and low cost are the other advantages of the uses of monolimb.

In spite of the potential benefits, monolimb is still not commonly used. One major reason is the concern of the structural integrity of monolimb. Failures of thermoplastic prosthetic components are not uncommon [6, 8], and the majority of the failures are fatigue related under cyclic walking loads. In clinical practice, clinicians inspect the structural integrity of the monolimb during follow-up visits. Th prosthesis can fail, which usually lead to serious consequences such as fall and injury, before the clinical visit. It is highly desired that the fatigue life of a newly prescribed monolimb can be predicted so that the monolimb can be replaced well before it fails. To test the fatigue failure, monolimbs can be subjected to mechanical testing under cyclic loadings of walking. Performing such test experimentally [9-11], however, is expensive and time demanding. A numerical method predicting the fatigue life of the monolimb can help ease the problem.

Fatigue life can be simply predicted by studying the stress along the monolimb and the material stress-fatigue life curve. However, it is not an accurate method since it does not consider the uncertainty such as modeling error and the scatter of fatigue test data. To address the uncertainties in design, traditionally, safety factors are often used to provide confidence. However, the safety factor approach is questionable because it usually does not take into account the underlying probability distributions. As a result, the evaluation of the fatigue life of monolimb reasonably should be based on reliability analysis.

Much work on fatigue reliability of engineering structures has been done, which is usually based on various accumulative damage rules, such as the Miner’s rule[12], the statistical Miner’s rule[13], the double linear Miner’s rule[14], the iso-damage curve method[15] and the consecutive Wöhler curve approach[16] etc. Among those various accumulative damage rules, the statistical Miner’s rule is most widely used in fatigue reliability analysis because of its compact expression and precision, and has been proved to be more effective in engineering fields by fatigue experiments [17].

In this paper, the statistical Miner’s rule and reliability analysis are applied to implement the fatigue life evaluation for monolimb. The monolimb of a 55 year old transtibial amputee is taken as a subject. Stress along the monolimb is estimated using finite element analysis. Based on the stress obtained from the finite element model, fatigue life of a monolimb is evaluated using the statistical Miner’s rule and reliability analysis considering stress uncertainty due to modeling error and the scatter of fatigue test data. Also, the effects of variations of random variables on fatigue failure probability of monolimb are discussed.

Methods

Finite element analysis

Finite element (FE) analysis is performed to predict the stress distribution at the monolimb designed for the transtibial amputee, 55 year-old and 81kg in body mass. Fig. 1 shows the geometries of the FE model. The geometry of bones and their relative positions to the skin surface were obtained from magnetic resonance imaging processed by Mimics 7.1 and those of the soft tissue and monolimb were obtained from BioSculptor^{TM} digitizing system processed by ShapeMaker^{TM} 4.3. A prosthetic foot, partitioned into keel and surrounding rubber foam, was created in SolidWorks^{TM} 2001 and was connected to the distal end of the shank. The socket together with the shank was given a 4mm thickness. The monolimb has a uniform cross sectional elliptical shank with anteroposterio dimension 25mm and medialateral dimension 40mm (Fig.1). Details of the geometry preparation were described in [2].

Young's modulus and Poisson's ratios are assigned to the model according to the literature resembling the material property of soft tissue, polypropylene homopolymer, prosthetic keel and surrounding rubber foam (Table 1). Bones were given fixed boundary conditions, and eighteen load cases were applied separately at the centers of pressure on the plantar surface of the prosthetic foot to simulate the stance phase (Table 2). The center of pressure was obtained by projecting the positions of center of pressure calculated on the force platform onto the plantar surface of the foot. Kinematic data of the limb and monolimb and ground reaction forces were obtained from the Vicon Motion Analysis System and a force platform respectively. Contact between the limb and the socket was simulated considering friction/slip using automated contact technique described in [18].

Fatigue accumulative damage of Monolimb

Based on the finite element analysis simulating the amputee subject walking for a gait cycle (Table 2), it was found that maximum principle stress was peaked over the postero-distal end of the shank (Fig.2) at terminal stance (45.1% of gait cycle). This suggests that it is the region where fatigue failure would most likely happen.

During normal walking, the monolimb is subjected to the cycle load and the periodical stress is applied to the monolimb. The statistical Miner's rule [13] which is suitable to evaluate the fatigue life of a structure subjected to cyclic load [17] is used to evaluate the fatigue accumulative damage of monolimb according to the maximum principal stress of shank at the postero-distal end of the shank. The statistical Miner's rule is defined as

$$\sum \frac{n_i}{N_i} = \alpha \tag{1}$$

where n_i is the number of cycles of the ith specified stress S_i acting on structure; N_i the median of fatigue life of material under S_i; α fatigue damage of at failure. The α is often regarded as a lognormal random variable reflecting the uncertainties of Miner's rule [12] with mean value 1.0 [19].

Usually, stress uncertainty exists inevitably in the finite element analysis of monolimb due to modeling error. The actual stress of somewhere of Monolimb is defined as

$$S^a = BS^e \tag{2}$$

where S^e stands for the estimate stress obtained from finite element analysis; B the stress uncertainty which is usually assumed to be a lognormal random variable [19].

After finite element analysis for the monolimb of the amputee subject, the maximum principal stress at the postero-distal end of the shank of the monolimb during stance phase of the gait cycle is shown as Fig.3. It is found from Fig.3 that there are two peaks of maximum principal stress at the stance phase of the gait cycle, the one is S_1^e =11.9 MPa at 16.9% of gait cycle and another is S_2^e = 21.8 MPa at 45.1% of gait cycle. The superscripts '*e*' suggests that S_1^e and S_2^e are estimate values. So the statistical Miner's rule for monolimb is expressed as

$$\frac{n}{N_1} + \frac{n}{N_2} = \alpha \tag{3}$$

where n is the number of walking steps; N_1 and N_2 the median of fatigue life of material at the postero-distal end of the shank of monolimb under the actual maximum principal stresses $S_1^a (= BS_1^e)$ and $S_2^a (= BS_2^e)$, respectively. It is assumed that the stress uncertainty is B at the postero-distal end of the shank during finite element analysis.

In order to compute the N_1 and N_2 in Eq.(3), Wirsching *S-N* curve model [20,21] which is suitable to most materials such as thermoplastic materials is adopted here

$$NS^m = K \tag{4}$$

where m is fatigue strength exponent; K is fatigue strength coefficient; N the fatigue life of material under stress S. To account for scatter in fatigue test data, K is treated as a lognormal random variable. After regression analysis of the fatigue test data of the material (Table 3 [22]) , m=8.59

and $K = 1.23\times10^{18}$. The *S-N* curve of material is thus expressed as

$$NS^{8.59} = 1.23\times10^{18} \tag{5}$$

The graph of the *S-N* curve is shown in Fig.4. It is seen from the graph that Wirsching model matches the test data well. So the $N_1$and N_2 are easily obtained from the Eq.(5) according to S_1^a and S_2^a.

With the substitution of Eq.(2) and (4) into Eq.(3), Eq.(3) is reformulated as

$$\frac{B^m[(S_1^e)^m + (S_2^e)^m]\,n}{K} = \alpha \tag{6}$$

Fatigue reliability analysis of Monolimb

Generally, reliability analysis considers ultimate limit state to define a failure event. For an ultimate limit state, the resistance or capability is represented by some measure of a structural strength, representing a maximum value of the structural resistance. Failure is said to occur when the predicted load or demand exceeds the predicted strength.

In the paper, the limit state equation of fatigue failure of Monolimb is defined as

$$f(\mathbf{X}) = \alpha - \frac{B^m[(S_1^e)^m + (S_2^e)^m]n}{K} = 0 \tag{7}$$

where $\mathbf{X}$ stand for a vector of variables in limit state equation.

Make a transformation, the limit state equation Eq.(7) is reformulated as

$$g(\mathbf{X}) = \ln\alpha + \ln K - m\ln B - \ln[(S_1^e)^m + (S_2^e)^m] - \ln n = 0 \tag{8}$$

According to probability theory, the probability of fatigue failure P_f of Monolimb is defined as

$$P_f = P[g(\mathbf{X}) \le 0] \tag{9}$$

where $P(E)$ stands for probability of an event E occurs.

Because α, K and B are lognormal random variables, $g(\mathbf{X})$ is subjected to normal distribution. Then, the P_f will be [23]

$$\begin{aligned} P_f &= \int_{-\infty}^{0} \frac{1}{\sqrt{2\pi}\sigma_g} \exp\left[-\frac{(g-\mu_g)^2}{2\sigma_g^2}\right] dg \\ &= \int_{-\infty}^{-\frac{\mu_g}{\sigma_g}} \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{t^2}{2}\right] dt = \Phi(-\beta) \end{aligned} \tag{10}$$

where μ stands for the mean of random variables; σ the standard deviation of random variables; $t = \frac{g-\mu_g}{\sigma_g}$; $\Phi(.)$ the standard normal cumulative distribution function; $\beta = \frac{\mu_g}{\sigma_g}$ the safety index in reliability analysis. The higher safety index, the more robust will be the structure.

Results and discussion

In the fatigue life evaluation of the monolimb, the mean of α, *B* and *K* are 1.0, 1.0 and 1.23×10^{18}, and the coefficient of deviation (COV) of α is chosen to be 0.2 according to the suggestion of [19]. The COV of *B* is assumed to be 0.3 by experience and the COV of *K* is taken as 0.5 since the scatter of fatigue test data is often serious. The relationships between safety index / fatigue failure probability of the monolimb and the number of walking steps are shown as Fig.5. In addition, in order to identify the influence of uncertainties of α, *B* and *K* on fatigue failure probability of monolimb, the relationships between fatigue failure probability of the monolimb and the number of walking steps at different COV of α , *B* and *K* are studied and the results are shown in Fig. 6, 7 and 8, respectively.

Fig.5 (a) shows that the safety index of monolimb and the absolute value of curve slope decrease with the number of walking steps. Fig.5 (b) shows that the fatigue failure probability of monolimb increases with the number of walking steps whereas the curve slope decreases with it. The results suggest that the probability of occurrence of fatigue failure of monolimb increases with the number of walking steps but the rate of progression of fatigue failure probability of monolimb decreases with walking steps.

Fig.5 (b) also shows that the fatigue failure probability of monolimb more than 0.1 when the number of walking steps exceeds 200,000. This indicates that the amputee subject should be back to the clinic to inspect the structural integrity of the monolimb and make any necessary replacement after walking for 200,000 steps to prevent any occurrence of fatigue failure. The figure showing the relationship between the failure probability and the number of the walking steps may provide a reference for clinicians to determine the interval of inspection for the structural integrity of monolimbs of amputees.

Fig.6 and Fig.8 shows that the fatigue failure probability of the monolimb is insensitive to the change of the COV of α and *K*, which suggest that the influence of the uncertainties of α and *K* on the fatigue life evaluation of monolimb is not significant and α and *K* may be taken as constants if necessary.

Fig.7 shows that the fatigue failure probability of monolimb of the amputee subject is more sensitive to the change of the COV of the stress uncertainty *B*, which indicates that the accuracy of fatigue life evaluation of monolimb depends significantly on the estimate of stress uncertainty. In addition, Fig.7 shows that fatigue failure probability of monolimb of the amputee subject increase evidently with the increase of the COV of *B*, which indicate that decreasing modeling error of finite element analysis of monolimb will decrease significantly the fatigue failure probability of monolimb. As a result, improving the precision of finite element model of monolimb to estimate accurately the stress of monolimb under walking condition is of paramount importance in fatigue life evaluation of monolimb.

It was suggested that some flexibility provided by the monolimb can improve the comfort and gait of the amputees [4, 5]. Attempt was therefore made in previous studies to increase the flexibility of the monolimb [2] by reducing the thickness of the material and the cross sectional area of the shank, or choosing a more flexible thermoplastic material. However, it compromises with the structural strength of the monolimb. Failure of the monolimb should be prevented as it can lead to fall and injury of the amputee. While trying to increase the flexibility of monolimbs in the design optimization stage, it has to be ensured that they are structurally strong enough to withstand forces experienced in normal walking. Failures of thermoplastic structures are usually fatigue-related and doing a fatigue test on the prosthesis is time-consuming and expensive, this study introduces a numerical approach to evaluate the fatigue life of the monolimb based on reliability analysis.

It is important to note the limitation of the approach of the fatigue life evaluation of monolimb. The fatigue failure of monolimb is said to occur when the fatigue failure at the postero-distal end of the shank occur and the fatigue failure at other parts of monolimb are not considered. Fatigue failure is a system failure may consist of different failure modes. The validation of the approach by experiment has not been done in the paper and will be done in future study.

Conclusion

In the paper, the statistical Miner’s rule and reliability analysis were applied to fatigue life evaluation for a monolimb designed for a transtibial amputee subject with consideration of modeling error of finite element analysis and the scatter of fatigue test data based on finite element analysis. The preliminary results provide the relationship between fatigue failure probability and the number of walking steps giving a reference for clinicians to determine the interval of the inspection for the monolimb. In addition, study results still show that the accuracy of the evaluation of fatigue life of monolimb depends significantly on the precision of stress estimate.

Acknowledgement

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Table 1. Material properties assigned in the finite element model

	Young's modulus	Poisson's ratio
Soft tissue	200 kPa	0.45
Bones	Fixed boundary condition	
Keel	700 MPa	0.3
Rubber foam of prosthetic foot	5 MPa	0.3
Socket	2500 MPa	0.3

Table 2 Loadings applied in the finite element model

Percentage of gait cycle	Ground reaction forces (N)			Position at the shank where the maximum principal stress peaks	Maximum principal stress value (MPa)
	Anteroposterior	Medialateral	Vertical		
0	0.0	0.0	0.0		0.0
4.2	46.2	-13.7	132.9	Postero-proximal	1.6
5.6	60.6	-11.2	192.8	Postero-proximal	2.1
7.0	81.6	-19.11	329.3	Postero-proximal	3.1
8.5	98.8	-9.7	474.4	Postero-proximal	4.8
12.7	65.8	61.4	747.1	Postero-proximal	7.7
15.5	13	64	936.7	Postero-proximal	8.7
16.9	-23.5	63.6	979.7	Postero-proximal	12.5
19.7	-69.5	71.2	897.7	Postero-distal	11.3
25.4	-52.9	51.7	599.5	Postero-distal	8.4
29.6	-40.2	43.7	515.5	Postero-distal	8.6
32.4	-38.4	45.2	569.4	Postero-distal	11.5
35.2	-72.6	58.5	646.3	Postero-distal	15.8
42.3	-74.2	65	802.2	Postero-distal	21.4
45.1	-75.8	68.7	772.5	Postero-distal	21.8
49.3	-76.8	61.1	595.1	Postero-distal	17.3
52.1	-58.1	35.8	397.3	Postero-distal	14.0
62	0.0	0.0	0.0		0.0

Table 3 The data of material fatigue test of Polypropylene adopted from [22]

Point	Stress (MPa)	Fatigue Life Median (cycles×10^6)
1	19.6	10
2	19.7	9.6
3	19.8	9.1
4	20.0	8.6
5	20.2	8.0
6	20.4	7.3
7	20.9	6.4
8	21.3	4.5
9	22	3.7
10	25.1	0.80
11	25.8	0.73
12	26.4	0.65
13	27.6	0.53
14	29.6	0.37
15	34.0	0.10

Captions of Figures:

Figure 1 The geometries of the finite element model of monolimb

Figure 2 Maximum principal stress distribution of monolimb at terminal stance (45.1% of gait cycle)

Figure 3 Maximum principal stress at the postero-distal end of the shank of monolimb during stance phase of the gait cycle

Figure 4 The *S*-*N* curve of Polypropylene

Figure 5 Relationships between (a) safety index β / (b) fatigue failure probability P_f of monolimb and the number of walking steps at normal walking condition(where the coefficients of deviation (COV) of α , *B* and *K* are 0.2, 0.3 and 0.5, respectively)

Figure 6 Relationship between the fatigue failure probability of monolimb and the number of walking steps at different coefficient of deviation (COV) of fatigue damage at failure α (where the COV of *B* and *K* are 0.3 and 0.5)

Figure 7 Relationship between the fatigue failure probability of monolimb and the number of walking steps at different coefficient of deviation (COV) of stress uncertainty *B* (where the COV of α and *K* are 0.2 and 0.5)

Figure 8 Relationship between the fatigue failure probability of monolimb and the number of walking steps at different coefficient of deviation (COV) of fatigue strength coefficient *K* (where the COV of α and *B* are 0.2 and 0.3)

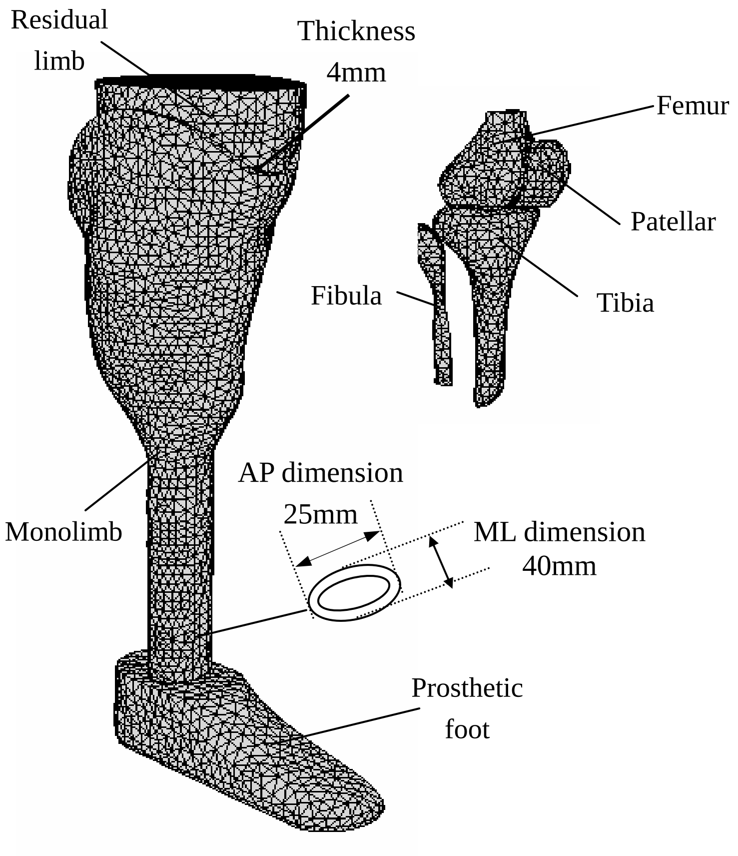

Residual
limb
Thickness
4mm
Femur
Patellar
Fibula
Tibia
AP dimension
25mm
Monolimb
ML dimension
40mm
Prosthetic
foot

Figure 1

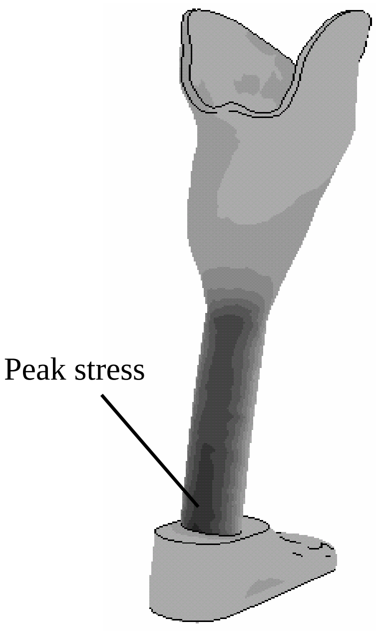


Figure 2

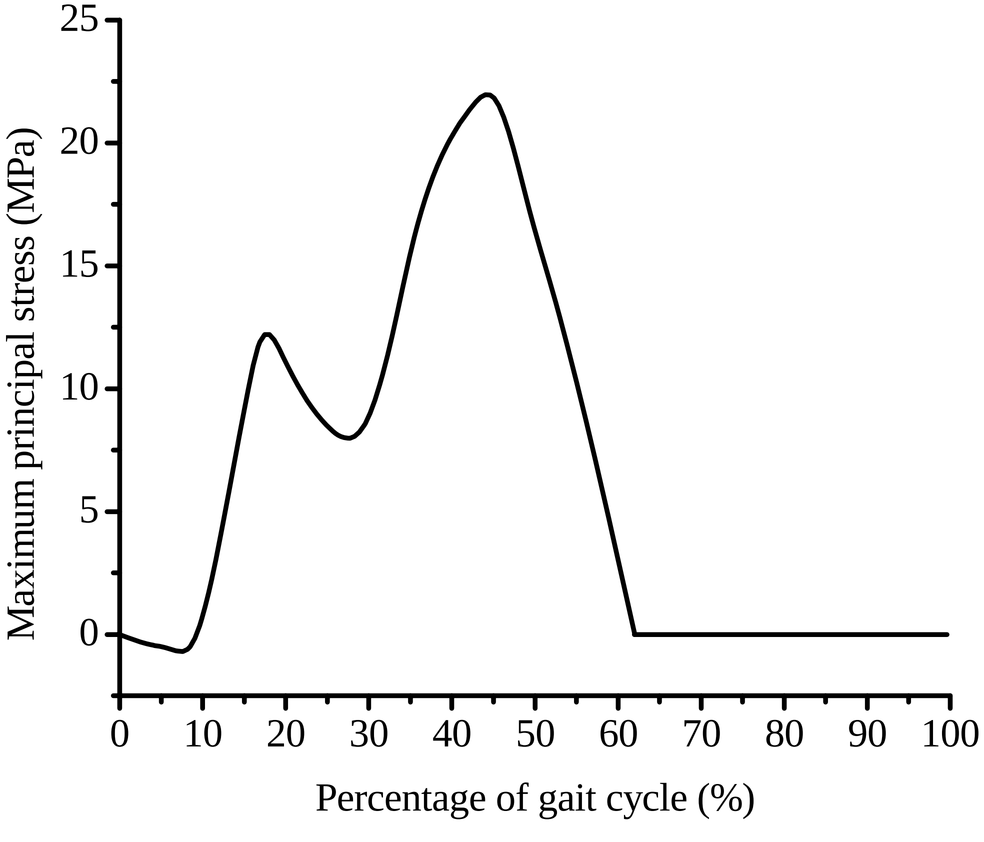

25
20
15
10
5
0
Maximum principal stress (MPa)
0
10
20
30
40
50
60
70
80
90
100
Percentage of gait cycle (%)

Figure 3

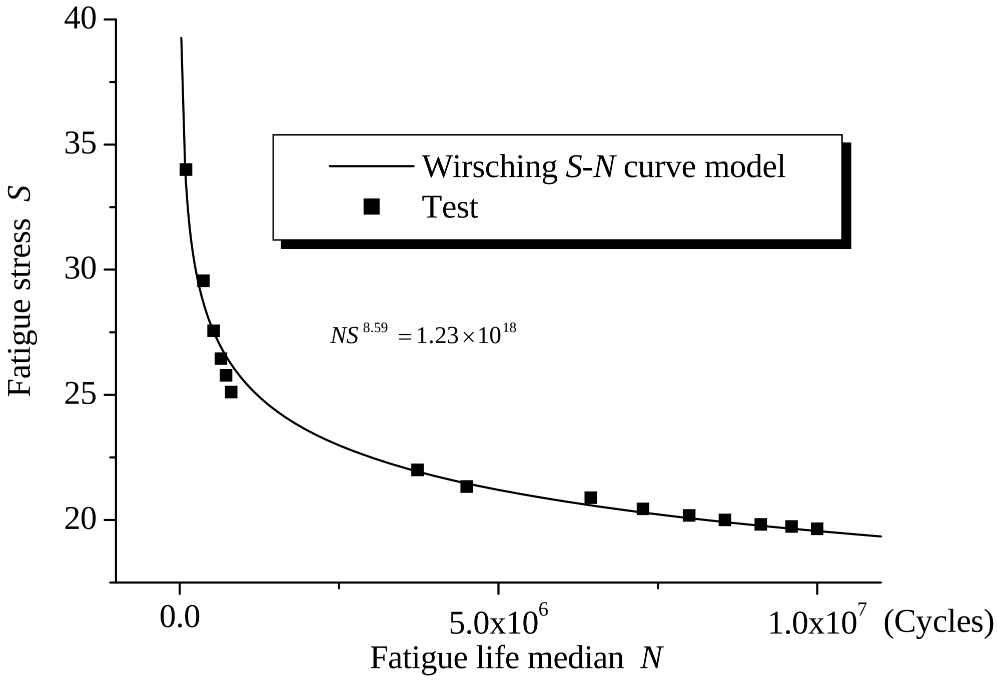
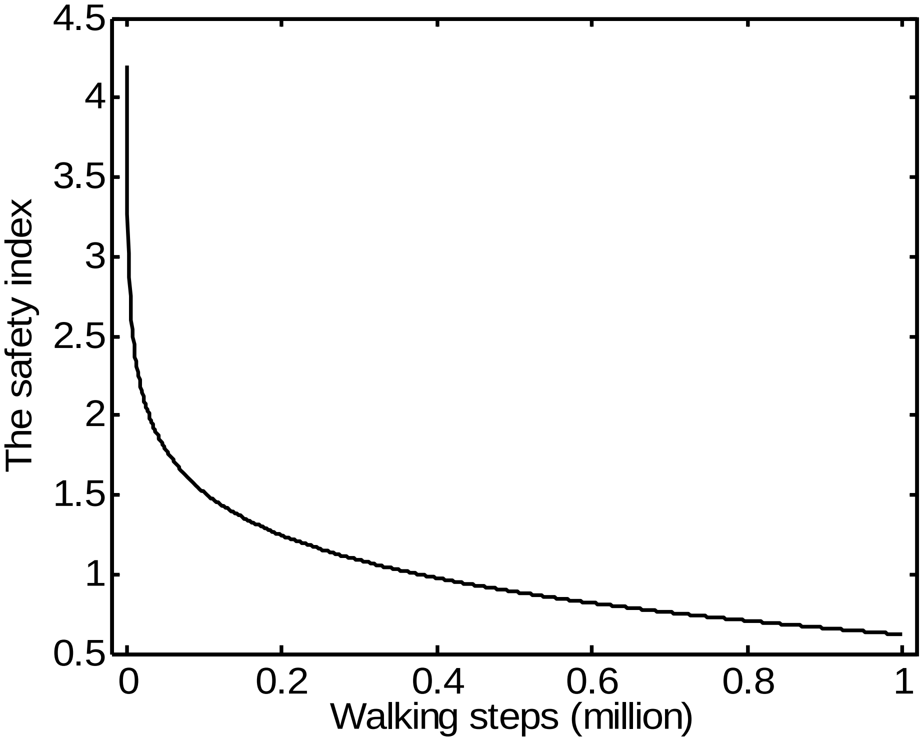

40
35
30
25
20
Fatigue stress S
0.0
5.0×10^6
1.0×10^7 (Cycles)
Fatigue life median N
Wirsching S-N curve model
Test
$NS^{8.59} = 1.23\times10^{18}$

Figure 4


4.5
4
3.5
3
2.5
2
1.5
1
0.5
The safety index
0
0.2
0.4
0.6
0.8
1
Walking steps (million)

(a)

(b)

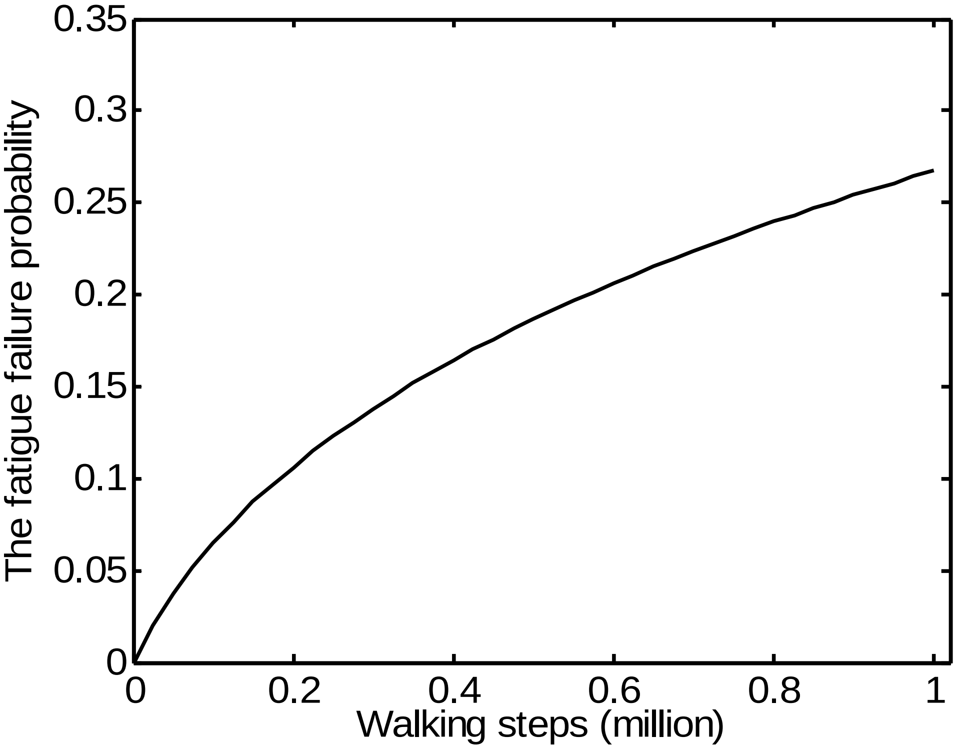

0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
The fatigue failure probability
0
0.2
0.4
0.6
0.8
1
Walking steps (million)

Figure 5

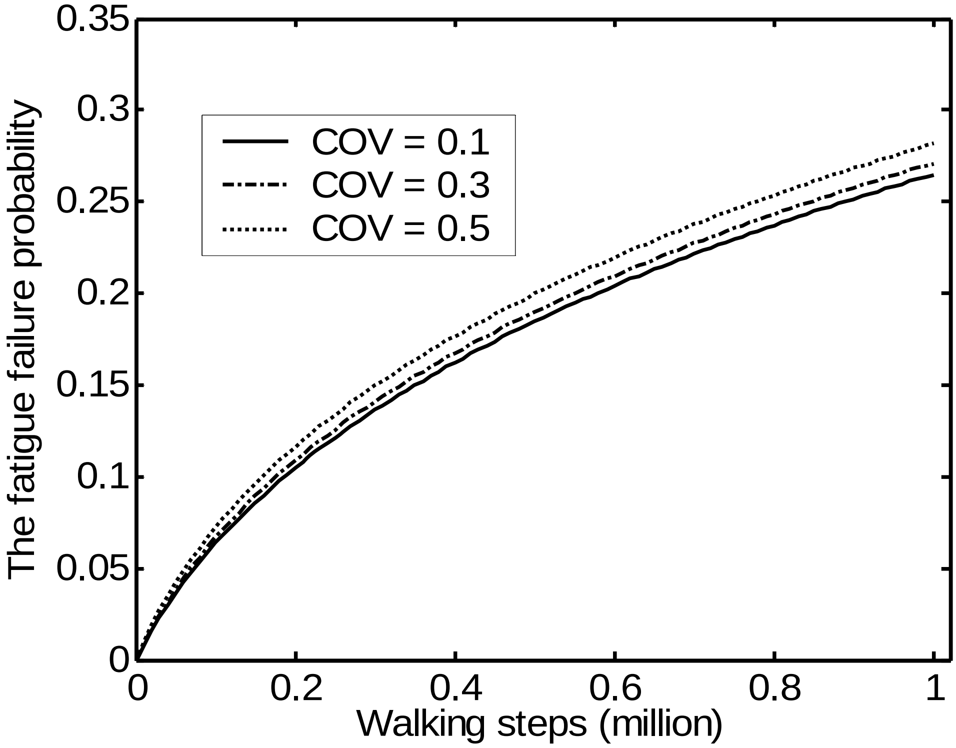

0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
The fatigue failure probability
0
0.2
0.4
0.6
0.8
1
Walking steps (million)
COV = 0.1
COV = 0.3
COV = 0.5

Figure 6

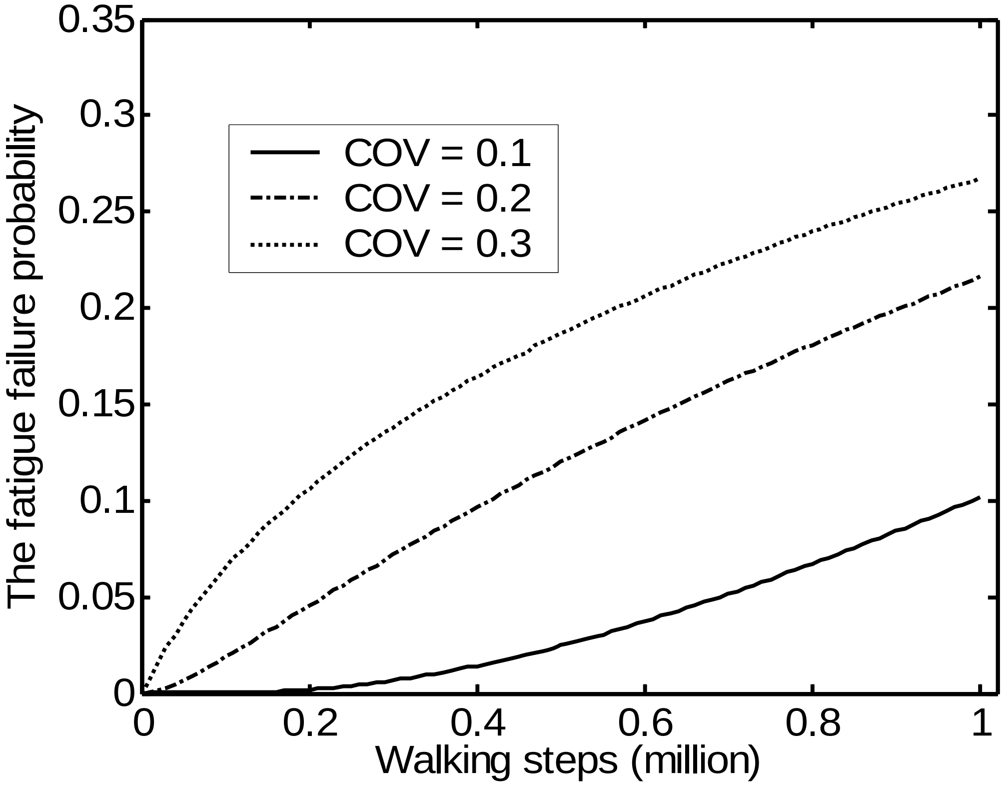

0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
The fatigue failure probability
0
0.2
0.4
0.6
0.8
1
Walking steps (million)
COV = 0.1
COV = 0.2
COV = 0.3

Figure 7

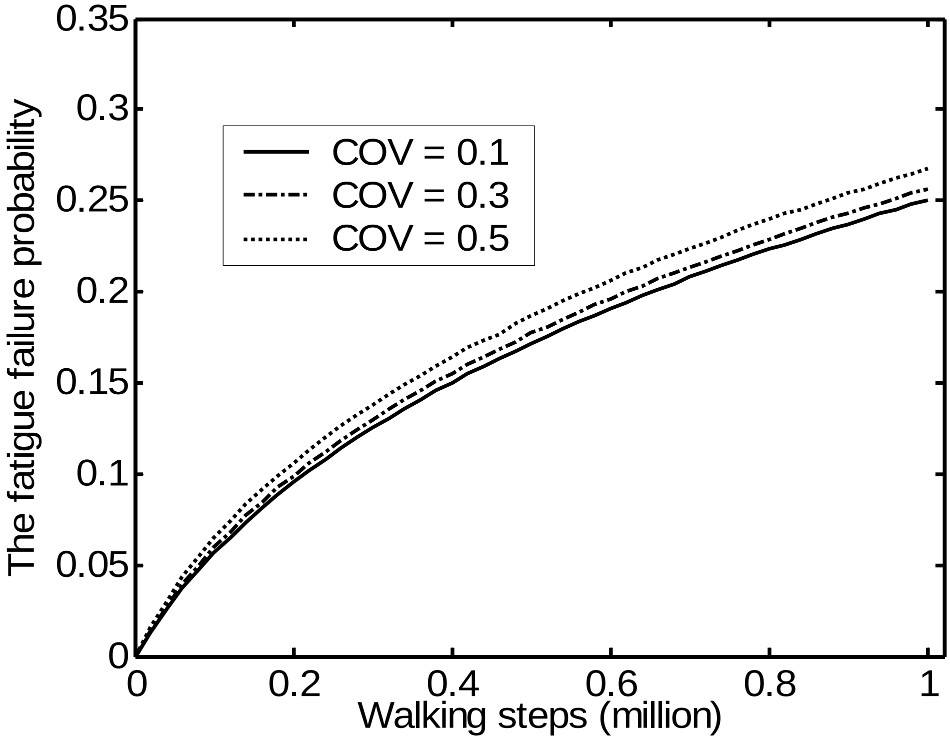

0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
The fatigue failure probability
COV = 0.1
COV = 0.3
COV = 0.5
0
0.2
0.4
0.6
0.8
1
Walking steps (million)

Figure 8