Al-Khwarizmi Engineering Journal
ISSN (printed): 1818 – 1171, ISSN (online): 2312 – 0789
Vol. 21, No. 1, March (2025), pp. 28-34

Al-Khwarizmi Engineering Journal

Impact Loading Rate Measuring with Different Heel Shoe Design for Transtibial Amputation

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(Received 29 October 2023; Revised 6 August 2024; Accepted 1September 2024; Published 1 March 2025)
https://doi.org/10.22153/kej.2025.09.001

Abstract

Humans experience impact peaks due to the repetitive pressures placed beneath the heel during walking, and these peaks are marked by high rates and magnitudes of loading. Momentum is transferred from the ground to create impact peaks at the effective mass to the part of the body that stops moving at that point. The stiffness of the heel affects impacts generated by that momentum. This study aims to improve our understanding of how the body produces impact peaks and how the stiffness and features of the shoe heel affect parameters such as peak magnitude (F_{max}) and impact loading rate (F'). A shoe heel model is presented, and walkers wearing less stiff foot heels are expected to have less effective mass and vertical impulse. A human amputee adult male participated in evaluating the model by walking in 15 different heel designs. Minitab software, which applies response surface approach, was used to acquire the shoe's design properties. The subject walked on a force plate while 3D kinematic data were collected. Design of Experiment was carried out using Minitab software to determine the optimal shoe heel design (depending on material and shape) that reduces the impacting effect. Statistical results show that heel height has a more significant effect (p=0.053) on impact loading rate than elastic modulus and cross-sectional area. According to the optimisation results based on the response surface design, wearing a heel with a modulus of elasticity of 0.5864 mPa, an area of 60.0 cm^2 and a height of 0.50 cm may help improve the amputee's gait.

Keywords: *ANOVA; DOE; Impact loading rate; Minitab; RSM*

1. Introduction

Every time a person walks or runs and their heel becomes in contact to the ground, their foot experiences a tremendous amount of force known as ‘peaks’. These ‘peaks’ occur when a specific area of the body has a brief (often between 10 and 50 ms) temporary shift in energy. Much controversy exists with regard to whether or not these sorts of forces might result in repetitive stress injuries; nevertheless, many studies were conducted on mechanisms underlying the production of these forces and the extent to which they are impacted by the surrounding environment [1–8]. Several studies examined how an individual’s footwear influences the forces of impact that their body experiences. Many people believe that by wearing shoes with varying degrees of stiffness, they might lessen the possibility of experiencing discomfort and injury from potential impact peaks while they move. [3,9]. A number of experimental and theoretical research on the subject indicates that softer shoe heels result in a decline in F' that is mostly due to an increase in the time interval (t) between impacts rather than an alteration in F_{max} [10–14]. Researchers also examined the connection between a factor called F_{max} and the stiffness of shoe heels, but the findings are not obvious and unambiguous [15]. Some studies found that the stiffness of the heel raised F_{max}, while other studies reported opposite results. Moreover, the stiffness of the heel was found to have no correlation at all with F_{max} [4,16–18]. Modelling studies are academic enquiries that model an environment or process using mathematical equations. According to a report, these simulations suggest that the stiffness of a shoe's heel should minimise the force needed to execute any task ($F_{\max}$) and that muscular activity in the lower body may also have an effect.

After observing that the loading rate during walking in one transtibial amputee was higher in the intact limb than in the prosthetic limb, researchers hypothesised that the loading variables in the intact limb would be greater than in the prosthetic limb [19–21].

A statistical methodology known as Design of Experiments (DOE) was employed to systematically plan and execute tests to gather data and investigate the effects of different components on a process or system. This tool creates a plan for the experiment that includes several treatments or conditions and a system for randomly assigning those treatments to the experimental units [25,26]. DOE seeks to identify the components that have the most impact on a process or system and determine the ideal amount of such factors to achieve the desired results [22–24]. Data were gathered and analysed using statistical techniques to gauge the effect of each therapy on the desired goal. Overall, DOE is an effective technique used to comprehend and improve intricate systems and procedures. Instead of relying on instinct or guesswork, it enables academics and practitioners to make knowledgeable decisions based on factual evidence [27–30]. This study aims to improve our understanding of how the body produces impact peaks and how the stiffness and features of the shoe heel affect three parameters: peak magnitude ($F_{\max}$), impact loading rate (F') and vertical impulse. These parameters have been associated with the start of several musculoskeletal disorders. Gait analysis was conducted by evaluating videos and selecting the optimal material for the shoe heel on Minitab to determine the optimum shoe heel-wearing design for transtibial amputation.

2. Materials and Methods

2.1 Subject

An adult male with body mass of 83 kg, height of 185 cm and age of 36 years who suffered from transtibial amputation participated in the experiment.

The experiment was conducted in the Department of Biomedical Engineering laboratory. The methodology was approved by the ethical committee of Al-Nahrain University.

The subject has to be able to heel strike while walking for the whole 30-second trial period on all foot heel pads and meet other requirements (walk straight with own speed and without assistive devices).

Three materials with different moduli of elasticity (Table 1) were used in the design of shoe heels. They had two polymer bases but with different physical characteristics according to the data sheets provided by the manufacturer (Soudal International).

Table 1,
Materials used and their modulus of elasticity

Material names	**Bases**	**Elasticity modulus**
GASKETSEAL	Polysiloxane	0.35 mPa
Soudaflex 40FC	Polyurethane	0.80 mPa
Silirub NO5-HE	Polysiloxane	0.50 mPa

The experiment was carried out with the following steps:

Step 1 - preparation of shoes:

The heels were created in accordance with the measurements generated by Minitab software (Table 2). Fifteen shoes were designed with different dimensions of the heel area, and the proper heel height was determined. Three heel cuts were created with heights of 0.5, 0.87 and 1.25 cm. A mould was created to cast the desired material. Figure 1 shows the preparation steps from measurement up to cutting and casting for the suggested design. The steps were repeated for all 15 designs suggested by Minitab software.

Fig. 1. Preparation of shoes. Starting from cutting the entire heel area and re-casting it with the used materials, according to the dimensions and areas given by the program.

Table 2,
Design characteristics of shoe heels suggested by Minitab.

Design name	E (MPa)	A (cm^2)	L (cm)
a1	0.35	53.7	1.25
a2	0.35	53.7	0.5
a3	0.35	60	0.875
a347	0.35	47.4	0.875
b1	0.575	60	0.5
b147	0.575	47.4	0.5
b2	0.575	53.7	0.875
b2	0.575	53.7	0.875
b2	0.575	53.7	0.875
b3	0.575	60	1.25
b347	0.575	47.4	1.25
c1	0.8	53.7	0.5
c2	0.8	60	0.875
c247	0.8	47.4	0.875
c3	0.8	53.7	1.25

Step 2- A force plate test was conducted, with three trials for each model. The patient was told to walk correctly and with planned steps to obtain the best results and prevent any possible errors. The lower limb ground response forces during the impact peak were measured and identified as the initial vertical force peak. The AMTI force plate contains six transducers to measure the displacement of the upper surface in 1 minute on all three axes when force is applied vertically to the surface of the device.

2.2. Impact loading rate (F`) calculations

Impact peak magnitude ($F_{\max}$) can be obtained from the data collected from the force plate and represents the first peak on the gait cycle diagram (Figure 2). Impact loading rate (F`) can be calculated by dividing the value of $F_{\max}$ on the time from the beginning of the curve (heel strike) to the first peak ($F_{\max}$) [18].

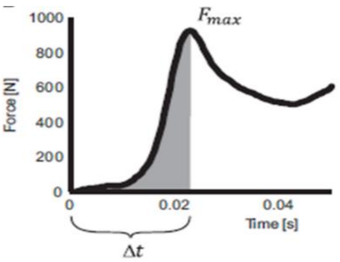

Fig. 2. Vertical ground reaction force estimated impact peak magnitude. [18]

2.3. Data analysis

Statistical software MINITAB (Minitab 18) was utilised to perform regression and ANOVA. The chosen dominating parameters were subjected to ANOVA to evaluate the performance of the second-order model for each response of the machining process. The null hypothesis stated that the observed values were random and was tested using ANOVA with a 95% confidence level. Fisher's statistical test (F-test) was used to determine the parameter's significance, and a high result denotes high relevance. If the p-value is less than 0.05, then the factor's influence is considered statistically significant [32].

3. Results and Discussion

Numerous studies were performed to investigate the impacts of input variable parameters on responses to determine the degree to which these factors influence the walking pattern and identify the most significant of the components. The characteristic values for $F_{\max}$ and F' are tabulated in Table 3. Regression analysis was conducted to analyse the connection between the input variable parameters and the responses. A general second-order model was developed using RSM based on mathematical formulations developed using the experimental data.

Equations (1) and (2) serve as an example of how the mathematical models for various necessary performance measures were created

$$\boldsymbol{F\text{`} = -10031 + 86\,E + 510\,A - 1208 + 3130\,E*E - 4.63\,A*A + 565\,L*L - 55.1\,E*A - 1110\,E*L}$$

$$\boldsymbol{Fz\,max = 1464 + 298\,E - 25.68\,A - 47.2\,L - 39.8\,E*E + 0.2650\,A*A + 59.5\,L*L - 3.67\,E*A}$$

The goodness of fit of the second-order regression model was evaluated using the coefficient of determination (R^2) function. The values of (R^2) and (R^{2}adj), for all previously constructed mathematical models, are 89.23% and 90.17%, respectively.

Table 3,
Characteristic values for F_{max} and F'

Run Order	**R**	**F_{max} (BW)**	**F` (BW/s)**
1	a1	836.045	3800.20
2	a2	841.962	3238.32
3	a3	852.317	3278.14
4	a347	837.264	3220.25
5	b1	858.234	3065.12
6	b147	859.714	3070.41
7	b2	838.047	3223.26
8	b2	838.047	3223.26
9	b2	838.047	3223.26
10	b3	850.403	3270.78
11	b347	859.366	3069.16
12	c1	860.410	3309.27
13	c2	845.443	3019.44
14	c247	851.186	3273.79
15	c3	839.178	3496.58

Table 4 shows the ANOVA findings for all responses, including SR and WLT. The P-value, mean square (MS), F-test, degree of freedom (DF) and sum of squares (SS) are included.

Table 4,
ANOVA for *F*` Response.

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	9	397049	44117	1.43	0.361
Linear	3	234126	78042	2.54	0.170
E	1	14653	14653	0.48	0.521
A	1	23434	23434	0.76	0.423
L	1	196039	196039	6.37	0.053
Square	3	144385	48128	1.56	0.308
E*E	1	111455	111455	3.62	0.115
A*A	1	856	856	0.03	0.874
L*L	1	37521	37521	1.22	0.320
2-Way Interaction	3	18538	6179	0.20	0.892
E*A	1	565	565	0.02	0.898
E*L	1	4652	4652	0.15	0.713
A*L	1	13321	13321	0.43	0.540
Error	5	153774	30755		
Lack-of-Fit	3	153774	51258	*	*
Pure Error	2	0	0		
Total	14	550822			

Figure 2 demonstrates the primary effect plot for the controllable factors on F'. The height of the heel may be regarded as the most essential parameter among all the variable factors (Table 3). Figure shows that E, A and L have a considerable impact on F'. This graph illustrates the relationship between F' and L. The most important influencing element is the height of the heel, which displays a dramatic increase in the F' mean value (246.02) (BW/s) as the heel height increases from 0.875 cm to 1.25 cm. As illustrated in Figure 2, the F` decreased by 19.29, the area of the heel increased from 47.4 cm^2 to 53.7 cm^2 but decreased by (88.96) (BW/s) when the area increased from 53.7 cm^2 to 60 cm^2. The F decreased by 210.42 (BW/s), the modulus of elasticity increased from 0.35 mPa to 0.57 mPa and slightly increased by 124.83 (BW/s) when E increased from 0.57 mPa to 0.80 mPa).

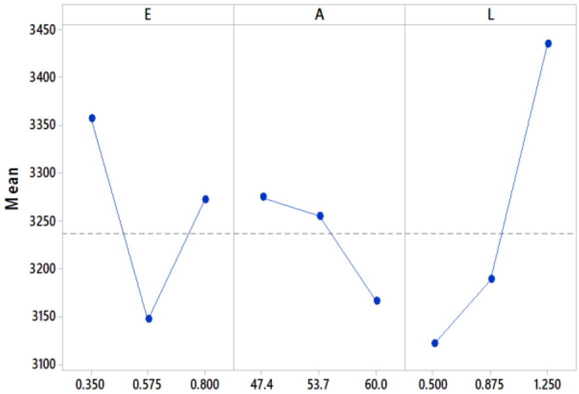

Fig. 2. Main effects plot for impact loading rate. The x-axis shows the effect of height (L, in cm), area (A, in cm^2) and modulus of elasticity (E in MPa) on changing the mean of impact loading rate *F*' (BW/s).

The combined effects of area, height and modulus of elasticity on F' are shown in Figure 3. Optimisation was carried out using Desirability Function Analysis (DFA), which incorporates response surface methodology. In F', the goal of optimisation is often reached at the minimal values of other responses; in the present study, the major purpose is to enhance the amputee's walking pattern and comfort during extended walks. Fig. 4 shows the ideal set of solutions with greater desirability functions under the above restrictions. The optimal solution's parameters for (1)'s highest desirability criterion are modulus of elasticity = 0.5864 MPa, area =60.0 cm^2 and height =0.50 cm.

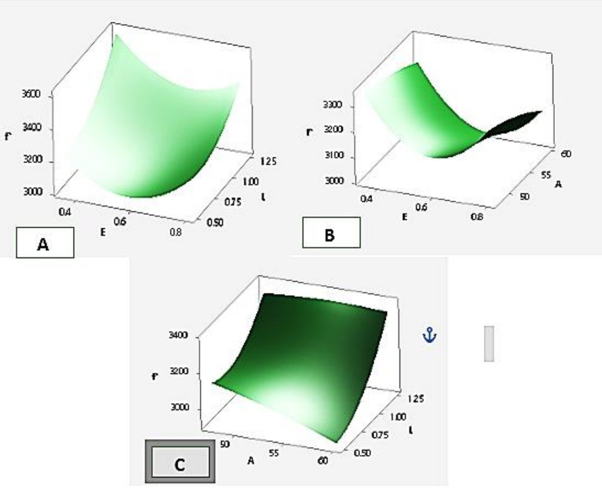

Fig. 3. Combination effects on impact loading rate (A) E; L vs F` (hold A=53.7). (B) E; A vs F` (hold L=0.875). (C) A; L vs F` (hold E=0.575).

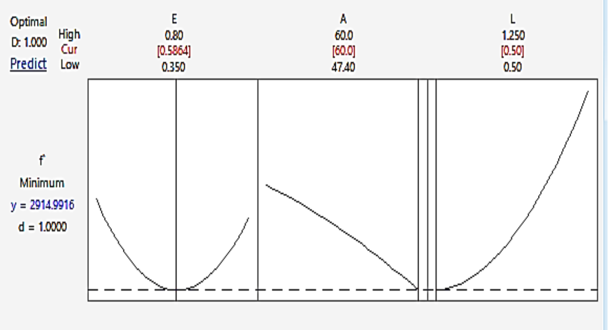

Fig. 4. Multi response optimisation by DFA. The upper left corner and top row display the composite desirability D. Each of the remaining rows represents a response variable. The numbers at the top of each column represent the maximum and lowest modulus of elasticity variable settings employed in the experimental design. The columns stand for different variables, while the vertical red lines indicate the modulus of elasticity settings. Not to mention, the most current answer values are shown by the blue horizontal lines.

4. Conclusions

In light of the experimental findings, the conclusions are as follows:

- The results have been greatly influenced by the choice of input parameters.
- The created model exhibits high predictive accuracy when applied to the experimental data.
- The impact loading rate is strongly influenced by the height (the slight increase in the mean of F` of 246.02 BW/s) and elastic modulus than by other factors.
- The optimal heel design can be obtained using modulus of elasticity of 0.5864 MPa, area of 60.0 cm^2 and height of 0.50 cm to provide the lowest impact loading rate and reduce impact during the heel strike, leading to a comfortable gait with less impact side effect on the knee joint.

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قياس معدل الصدمة لتصاميم مختلفة لكعب حذاء لمبتور تحت الركبة

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المستخلص

يتعرض البشر لقمم الاصطدام بسبب الضغوط المتكررة التي توضع على الكعب أثناء المشي، والتي تتميز بمعدلات وقيم للتحميل. يتم نقل الزخم من الأرض لإنشاء قمم الصدمات عند الكتلة الفعالة، أو جزء الجسم الذي يتوقف عن الحركة عند تلك النقطة. يمكن أن يكون لتبادل الزخم بين عدة أطراف تأثير على هذا، بما في ذلك صلابة أحذية الكعب. هدف هذه الدراسة إلى تحسين فهمنا لكيفية إنتاج الجسم لقمم الاصطدام وكيف تؤثر صلابة وخصائص كعب الحذاء على معلمات: قمة الاصطدام الكبرى (Fmax)، ومعدل قوة الاصطدام ('F)، يتم تقديم وتقييم نموذج كعب الحذاء، ومن المتوقع أن يكون لدى المشاة الذين يرتدون كعوبًا أقل صلابة كتلة فعالة ونبضة رأسية اقل. تم الاستعانة بمتطوع ذكر بالغ مبتور الطرف الأسفل لتقييم هذا النموذج من خلال المشي في 15 تصميمًا مختلفًا للكعب. تم استخدام برنامج Minitab، الذي يطبق نهج سطح الاستجابة، للحصول على خصائص تصميم الحذاء. كان المتطوع يمشي على جهاز قياس قوة رد الفعل أثناء جمع بيانات القوة والعزوم ثلاثية الأبعاد. يتم إجراء تصميم مثالي للتجربة (DOE) باستخدام برنامج Minitab مرة أخرى لاقتراح أفضل تصميم لكعب الحذاء (اعتمادًا على المادة والابعاد) الذي يقلل من تأثير قوة الاصطدام. تظهر النتائج الإحصائية لبرنامج Minitab أن ارتفاع الكعب له تأثير أكثر أهمية ($p = 0.053$) على معدل قوة الاصطدام مقارنة بمعامل المرونة ومساحة المقطع العرضي. وفقًا لنتائج التحسين القائمة على تصميم سطح الاستجابة، فإن ارتداء كعب بمعامل مرونة 0.5864 ميجا باسكال ومساحة 60.0 سم^2 وارتفاع 0.50 سم قد يساعد في تحسين مشية المبتورين.