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Mechanical Analysis Loads of Prosthetic Ankle Foot and Most Angle Effect during Walking Movement

Huda Falih Mahdi Mohammed Ali, Mays Hussein Ali Jasem,
Safa Masrahed Mohammed Masrahed, Ghada Ahmed Hussein Abdelhamid
Al-mustaqbal University College Bio Medical Engineering Department

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Annotation: A prosthesis is a device designed to replace a missing part of the body or to make a part of the bodywork better. Diseased or missing, arms, hands, legs, or prosthetic devices commonly replace joints. The computational prediction method is one of the fundamental steps in manufacturing medical devices. The prosthetic models were drawn using SOLIDWORKS 2016. The prosthetic mechanical load's performance at different walking angles of mechanical was analyzed using numerical software called ANSYS 19. The results were statically analyzed by applying multi-criteria decision- making (MCDM). The analysis showed that for a vertical load of 120 N there was a maximum stress observed of 62.89 MPa at the first angle of heel-strike which is 19.81°. The mid-section of the foot where the three sections meet. The maximum weightage of mechanical loading modes criteria was observed for H1 by 0.33, followed T1 with 0.35. The lowest values have been taken for H4, and H3. The best angle performance was observed under mechanical load modes via applying the VIKOR method with AHP weights for each criterion in angle H4 (3.44 °) followed by H3 and, T3 for models. Then, the fourth angle was taken for T2 for. The sequence was followed for each of H2, T1 and H1.

1. Introduction

In the United States, there is currently an estimated 2 million people living with an amputation and this number expected to reach 3.6 million by 2050. Currently, the leading cause of amputation in the U.S are dysvascular diseases that originate from underlying conditions such as diabetes mellitus which account for 54% amputations and 97% of lower limb amputations [1], [2]. To improve rehabilitation techniques and assistive technologies for this growing population of lower limb amputees, a significant body of literature been developed in the field of biomechanics and medical design with the goal of restoring function and independence to an amputee. To this end, investigations on lower limb prosthetic device have identified several key design parameters including, the roll-over shape [3], the viscous behavior, the component stiffness, and the elastic energy return during push-off [4].

Figure 1.1: Freedom Innovations' Renegade prosthetic foot [5]

However, many gaits analysis studies that examine the performance of existing prosthetic devices fail to report these response parameters making it difficult to interrupt their influence on a specific amputee. This is largely due to the lack of standardization in reporting the mechanical response of prosthetic devices. While several researchers have independently examined the effects of the roll-over shape [6] and the stiffness [7] these prototype designs do not fully report all of the response parameters. To improve the mechanical characterization and design process of lower limb prosthetics this paper will consist of two parts.

Figure 2: TLM Prosthetics' TaiLor-Made foot [8]

First mechanical testing will be conducted to evaluate the stiffness, energy return, and viscous properties of a used, but in good condition Freedom Innovations Renegade foot (Figure 1.1), as well as, a prototype foot called the TaiLor Made that was developed by TLM Prosthetics and allows for the clinicians to independently select the stiffness of the toe, heel, and three internal compressive springs in base chamber shown in Figure 2.2. Finally, this project will offer an approach to understand the mechanical loads performance of prosthetic feet with a designed mechanical response using finite element simulations in ANSYS. This process will allow for faster product development and potentially lead to additional insight on the influence the prosthetic device has on the biomechanics of amputee.

CHAPTER THREE

Methodology

2.1 Methodology

The computational prediction method is one of the fundamental steps in the manufacture medical devices. This chapter discusses the steps of the methodology to improve the understanding of mechanical performance of prosthetic ankle foot. The prosthetic models were drawn using SOLIDWORKS 2016 (Dassault Systèmes SolidWorks Corporation, Waltham, Massachusetts, United States) software. As well as the prosthetic mechanical loads performance of different walking angles of mechanical were analyzed using a numerical software called ANSYS 19 (Canonsburg, Pennsylvania, United States). The results were statically analyzed by applying multi criteria decision-making (MCDM).

1. Mapping the Study Flow Chart

The study process steps to approve of mechanical durability as well as the performance of prosthetic using as illustrated in Figure 3.1. The porous of the optimization is to enhance some points by make some changes in the prostheses leg. In order to make these changes and improvements in the prosthesis, data collected at first from a specialized center in the manufacture and innovation of prosthetics. After checking and doing the calculations in order to find out which prosthesis was the most made, it concluded that the prosthetic ankle is the most prosthetic limb made. The artificial ankle made after taking accurate measurements from a normal human foot by a local blacksmith.

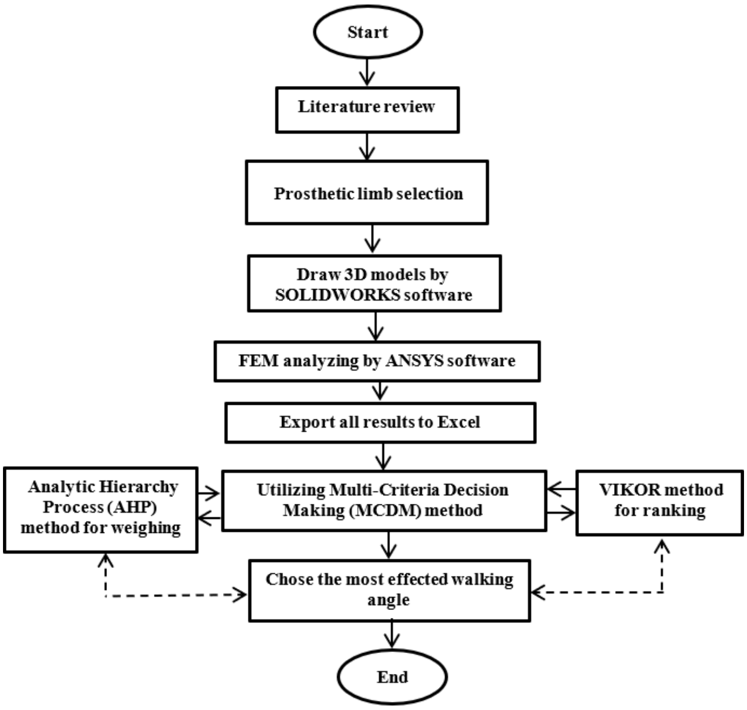


Figure 3.1: Mapping of the study flow chart

The same measurements used for the design of the artificial ankle in the 2016 version of the SOLIDWORKS program. The artificial ankle tests the same movement that the natural ankle moves. The angles of movement that the artificial ankle moves also made in the SOLIDWORKS program. A simulation of the loads carried out in the ANSYS program; the loads that the artificial ankle bears during movement. After carrying out many loads on the ankle and simulating it, the area where the limb needs improvement.

2. Prosthetic limb selection

Before starting the development process of the prosthetic limb, we must find the most widely used and widespread type of limb now (our region). Therefore, after many preliminary researches, a smart center that manufactures smart limbs, called Al-Wraith Darmian Center for Smart Limbs. We submitted a request in order to obtain data related to the most frequently used prosthetic limb, and according to the attached evidence, we find that the most used limb is the prosthetic ankle. According to the data taken, the development will be on problems related to the prosthetic ankle, ways to develop it, get rid of some problems and improve the limb in general.

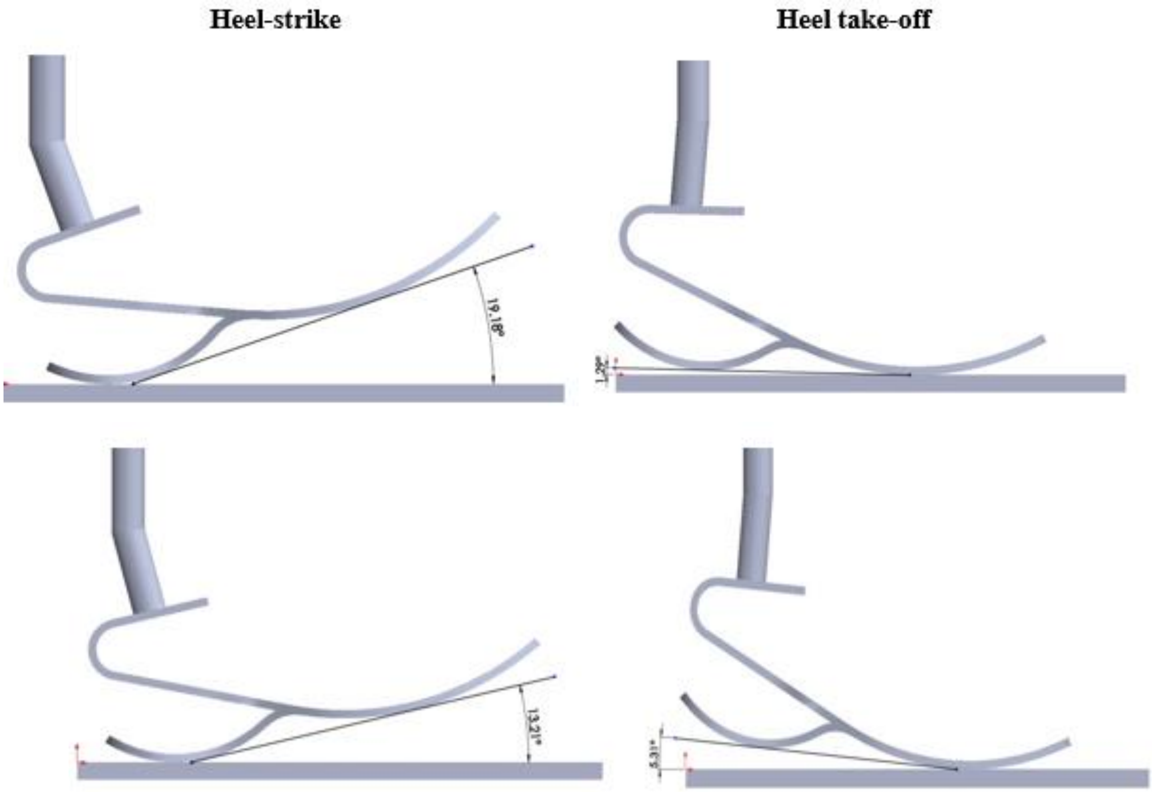
3. Computational Process

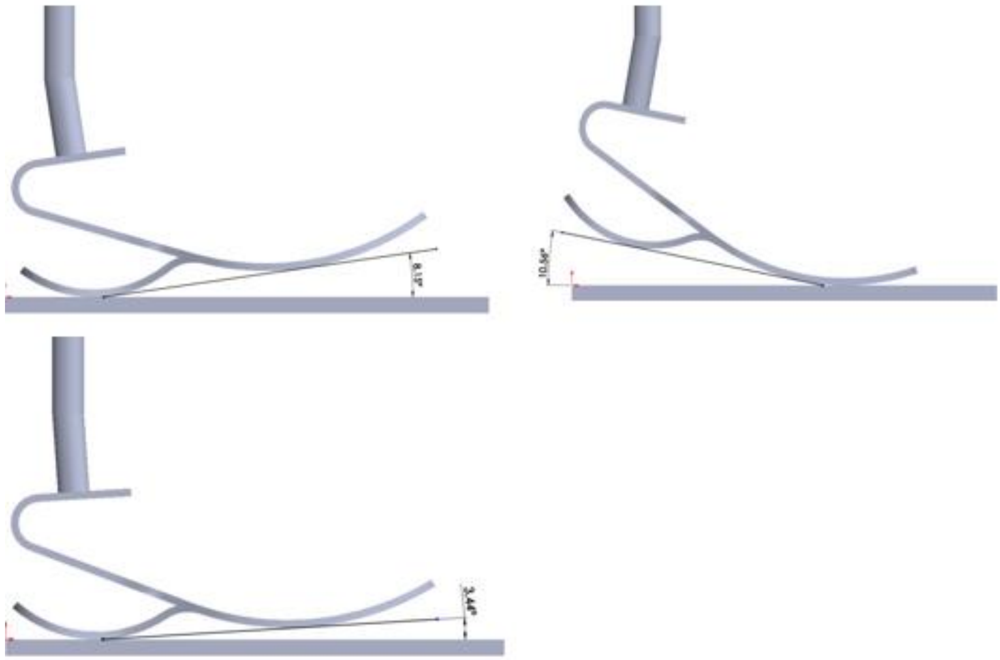
Improving a prosthesis made in very large quantities for many patients who suffer from amputation of the ankle of the foot. This development was carried out with an extensive study and using scientific and computerized methods, using engineering programs in order to suggest improvement to it, also to allow subsequent studies in order to make other necessary improvements on the prosthesis’s ankle.

4. Mechanical Loads Scenarios

The foot models were designed on SOLIDWORKS. The ankle joints and toe joints were replaced by compliant joints to make a single piece design with reduced weight and increased strength. In order to ensure that the operation of the compliant foot was similar to a natural foot, a video of operation of foot during normal walking was analyzed and the different angles between the base of the foot and the calf was noted as shown in Table 3.1. [63].

Table 3.1: Prosthetic-foot angles during foot walking movement





All this was done to ensure that the feeling of the compliant foot would be the same as that of a real foot and the wearer would not feel any discomfort. This information was then used to calculate the amount of stress exerted on the foot during different phase's angles of normal walking. Simulations were performed on it such that the part does not break on load application. The stress analysis of the foot was done on Ansys. The maximum von Mises equivalent stress that was induced was produced in MPa units and it was produced at the mid-section where the heel meets the main part of the foot. The force applied equal to the 120 N in vertical direction load that related to simulate the real of human weight.

5. Multi-Criteria Decision Making (MCDM)

However, after collecting data that resulted from previous mechanical loading modes, for different walking angles, to rank and calculate the best and worst angle performance results, the MCDM method was applied. In the case of giving weight importance for each angle (19.18, 13.21, 8.15, 3.44, 1.29, 5.31, and 10.56 degree) the Analytical Hierarchy Process (AHP) [41], [64] was used. As well as, in the case of giving ranking for each angle the VIKOR method [38] was performed, as clarified in next subtopic.

1. Analytic Hierarchy Process (AHP)

After collecting all the required data related to the chosen criteria, so, the AHP method is the first step in weighing each criterion through several steps, as explained in (Figure 3.4).

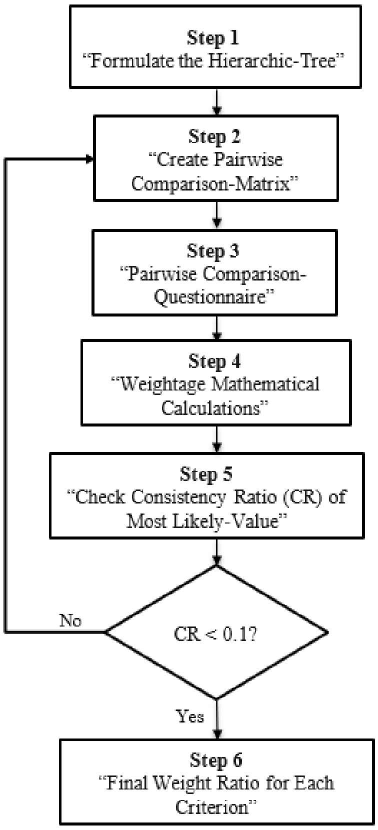


Figure 3.4: Flow chart steps of AHP method

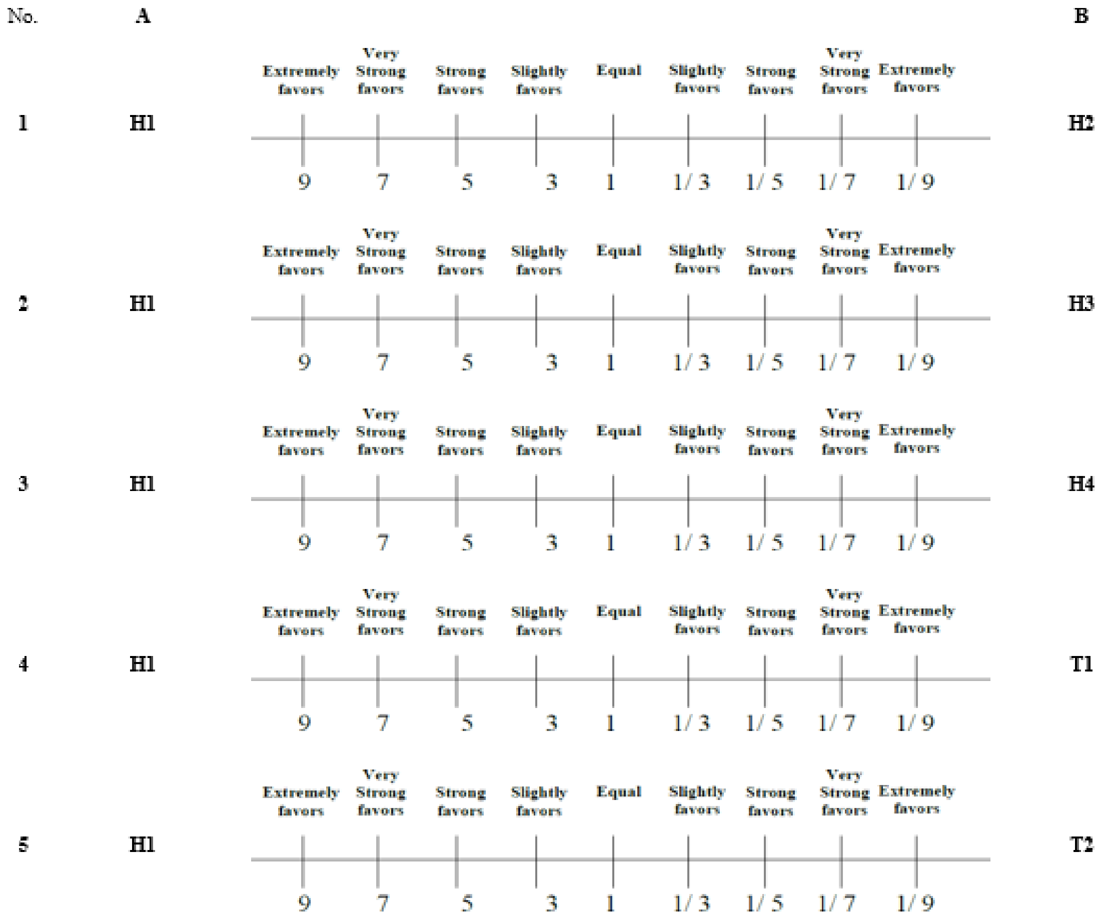


Figure 3.5: Example of pairwise-comparison-questionnaire

The second step is to prepare the pairwise-comparison-matrix, as such, in this study five criteria were used, so the matrix should be constructed. The third step was to prepare the pairwise-comparison-questionnaire; these questions were answered through an expert in the FPA stent area to give a relative relationship for each criterion as shown in Figure 3.5.

The fourth step was named as the normalized step, the sum of each column was calculated, and then each number in the matrix equation was divided into the sum of each column as shown in equation (3.1).

$$u_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} xij} \qquad (3.1)$$

where a_{ij} is the new values represented in normalized matrix, x_{ij} the number values.

The fifth step was to calculate the weight for each criterion, after calculating the normalized matrix, the values that were calculated from the sum of each row in the normalized matrix produce the aggregation values, the division of the aggregation values in the number of criteria (in this study 7) lead to result in the weight of each criterion (equation 3.2).

$$W_i = \sum_{j=1}^{n} a_{ij}/n \text{ and } \sum_{j=1}^{n} W_i = 1 \qquad (3.2)$$

Where: n= the number of compared elements.

For simplified the AHP method (up to the fifth step) and make it clear enough to the reader, the following steps were explained with mathematical calculations.

The sixth step was calculated the validity of expert answers via calculating of Consistency Ratio (CR), there are several steps to calculate CR as shown in equation (3.3) below:

$$CR = \frac{CI}{RI} \qquad (3.3)$$

where: *CI*= consistency index (equation 3.4) and;

RI= random consistency-index, its value depends on the number of criteria (Table 3. 2).

$$CI = \frac{\lambda - n}{n - 1} \qquad (3.4)$$

where: λ = Lambda and;

n = the number of criteria

Table 3. 2: Number of Criteria (n) with RI Values

Number of Criteria (n)	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

After calculating CR value, if CR equal or smaller to 10 % (CR ≤ 0.1) the expert opinion is acceptable, whereas, if CR greater than 10 % (CR > 0.1), so, the expert opinion needs to be revised.

2. VIKOR method

After measuring the weight of all the criteria using the AHP method used, the VIKOR method was used to rank the walking-angles due to its suitability to provide an accurate ranking with various criteria and alternatives Figure 3.6 summarizing VIKOR technique method steps.

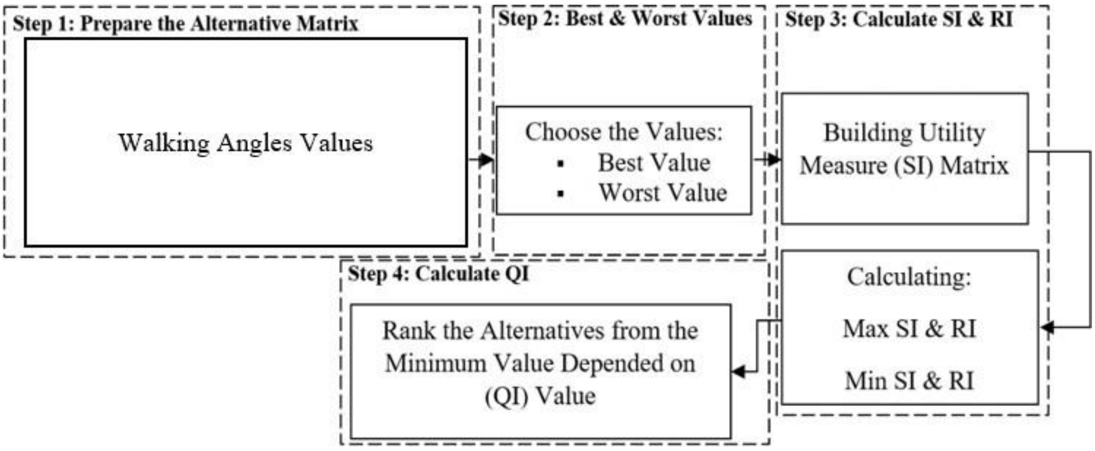


Figure 3. 6: VIKOR technique method steps

The first step has been carried out to construct the original matrix of the alternatives (walking-angles) under a fixed force value (120 N), as well as, the best value (f^*) has been defined for the lowest stress value for each criteria, whereas the worst value (f^-) has been defined for highest stress value.

The second step has calculated the Measure of utility (SI) by applying equation (3.6), then, the value of the Repentance Measure (RI) was calculated, which RI value represents the maximum value in the row matrix SI using equation (3.7).

$$SI = \sum_{i=1}^{n} weight\ of\ AHP * (f_i^* - fij)/(f_i^* - f_i^-) \quad (3.6)$$

$$RI = \max_i Value\ of\ SI\ row\ matrix \quad (3.7)$$

Where: j=1,2, 3…J and,

i=1,2,3…n.

The third step was calculated the ranking value (QI) for each alternative via applying equation (3.8).

$$QI = \frac{v(S_j - S^*)}{S^- - S^*} + \frac{(1-v)(R_j - R^*)}{(R^- - R^*)} \quad (3.8)$$

Where:

$S^* = min_j S_j$, $S^- = max_j S_j$

$R^* = min_j R_j$, $R^- = max_j R_j$

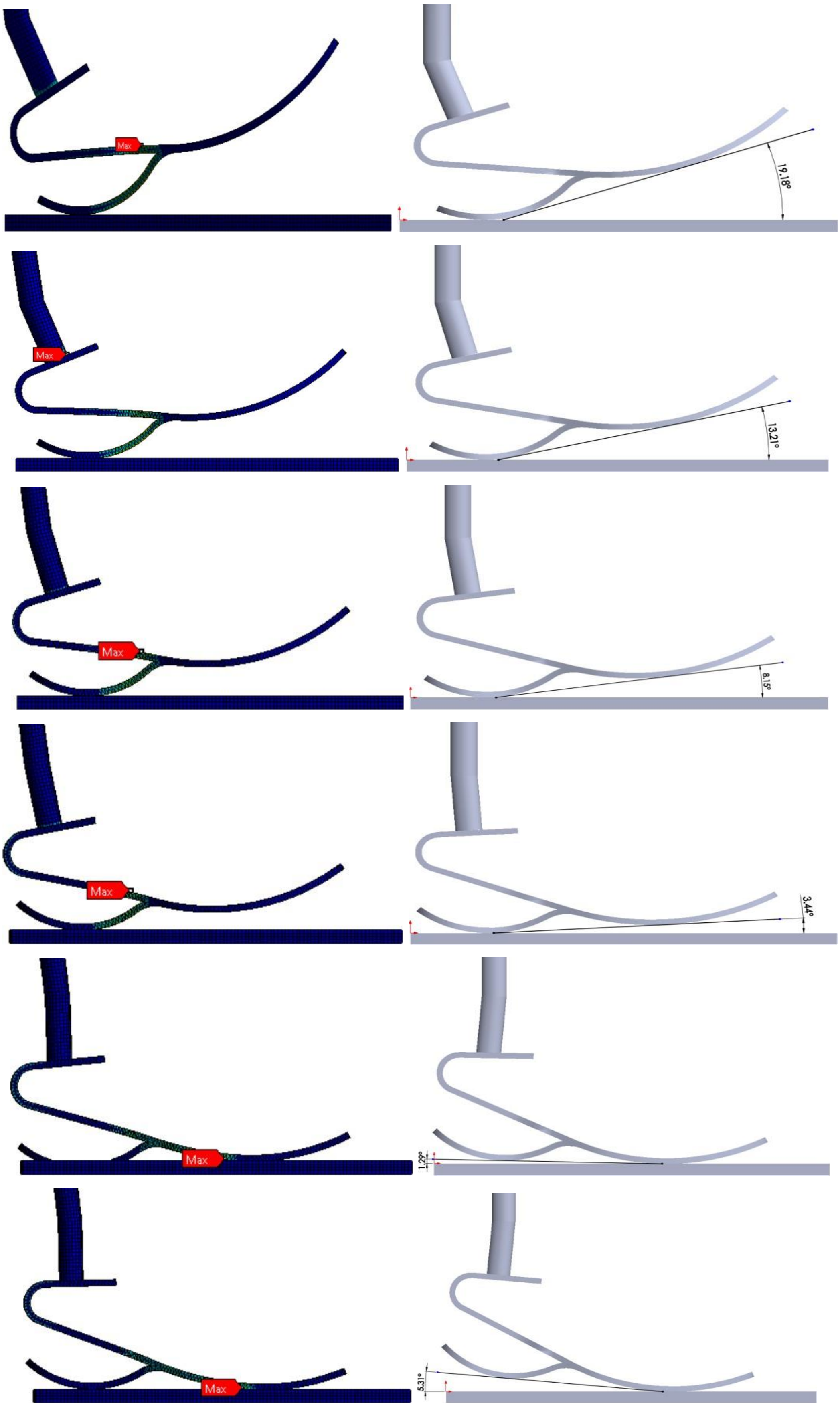
v = the weight of the strategy of ‘the majority of criteria’ (or ‘the maximum group-utility’); here, v = 0.5. The final step was ascending-order of QI values, which means the lowest value of alternative take the first rank (best rank), and so on.

1. Results and Discussions

The main objectives of this study were; first, to analysis the mechanical performance of prosthetics models by comparing via different walking angles, second, to give weights for the most importance and less importance effecting angles, thirdly, propose a mathematical approach to choose the best mechanical performance in different walking angles.

2. Mechanical performance of prosthetic foot

The FEA analysis was done on Ansys software and the resulting images are provided in Figure 4.1 and Table 4.1.



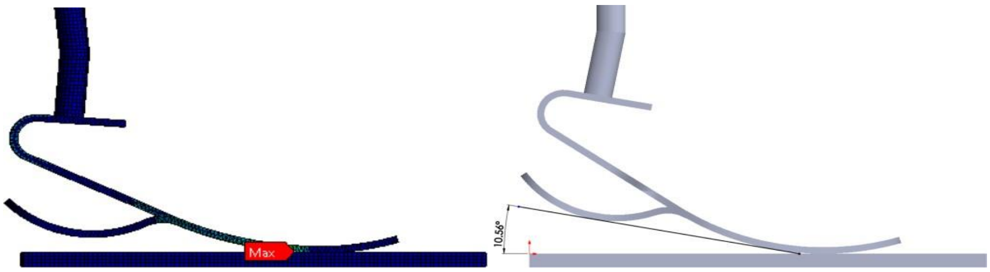


Figure 4.1: Comparison of FEM prosthetic foot angles with real foot movement

The analysis showed that for a vertical load of 120 N there was a maximum stress observed of 62.89 MPa at the first angle of heel-strike which is 19.81 °. The mid-section of the foot where the three sections meet. This area suggested to improve the mechanical performance by increasing the thickness to reduce the stress developed at this point. This modification was important as this region was acting as a stress concentration region and thus would be prone to failure.

Table 4.1: von Mises stress values with different walking angles

Angle values (°)		von Mises stress values (MPa)
1	19.18	62.89
2	13.21	53.30
3	8.15	48.13
4	3.44	41.88
5	1.29	43.63
6	5.31	47.65
7	10.56	57.62

The maximum concentrations values were observed at the center point of the prosthetic foot during the heel-strike while at the take-off the concentrations stress values have been observed at the toe region. That give a good understanding about the most loaded regions most be improved to enhance the mechanical loaded parts.

3. Multi-criteria decision-making (MCDM)

The use of MCDM was applied in two steps; firstly, to weigh each of these walking angles (heel-strike and take-off), the coherent mathematical approach using the Analytical Hierarchy Process (AHP) method was proposed; secondly, to give ranking for each of these angles with mechanical performance to choose the most critical angle, the VIKOR method was used, as explained in the following sections.

1. Analytical hierarchy process (AHP)

The mathematical approach of the weighting process via using of AHP started by preparing the matrix of comparison by pairs, this matrix depended on the answers of the experts, it is good to mention that, not all these experts responded, as well as some of them their answers were not valid, finally, only one expert answer was chosen to give a peer comparison questionnaire, the expert answers was illustrated in Figure 4.2.

No.	A										B
1	H1	Extremely favors	Very Strong favors	Strong favors	Slightly favors	Equal	Slightly favors	Strong favors	Very Strong favors	Extremely favors	H2
		9	7	5	3	1	1/ 3	1/ 5	1/ 7	1/ 9	
2	H1	Extremely favors	Very Strong favors	Strong favors	Slightly favors	Equal	Slightly favors	Strong favors	Very Strong favors	Extremely favors	H3
		9	7	5	3	1	1/ 3	1/ 5	1/ 7	1/ 9	
3	H1	Extremely favors	Very Strong favors	Strong favors	Slightly favors	Equal	Slightly favors	Strong favors	Very Strong favors	Extremely favors	H4
		9	7	5	3	1	1/ 3	1/ 5	1/ 7	1/ 9	
4	H1	Extremely favors	Very Strong favors	Strong favors	Slightly favors	Equal	Slightly favors	Strong favors	Very Strong favors	Extremely favors	T1
		9	7	5	3	1	1/ 3	1/ 5	1/ 7	1/ 9	
5	H1	Extremely favors	Very Strong favors	Strong favors	Slightly favors	Equal	Slightly favors	Strong favors	Very Strong favors	Extremely favors	T2
		9	7	5	3	1	1/ 3	1/ 5	1/ 7	1/ 9	
6	H1	Extremely favors	Very Strong favors	Strong favors	Slightly favors	Equal	Slightly favors	Strong favors	Very Strong favors	Extremely favors	T3
		9	7	5	3	1	1/ 3	1/ 5	1/ 7	1/ 9	
7	H2	Extremely favors	Very Strong favors	Strong favors	Slightly favors	Equal	Slightly favors	Strong favors	Very Strong favors	Extremely favors	H3
		9	7	5	3	1	1/ 3	1/ 5	1/ 7	1/ 9	
8	H2	Extremely favors	Very Strong favors	Strong favors	Slightly favors	Equal	Slightly favors	Strong favors	Very Strong favors	Extremely favors	H4
		9	7	5	3	1	1/ 3	1/ 5	1/ 7	1/ 9	
9	H2	Extremely favors	Very Strong favors	Strong favors	Slightly favors	Equal	Slightly favors	Strong favors	Very Strong favors	Extremely favors	T1
		9	7	5	3	1	1/ 3	1/ 5	1/ 7	1/ 9	
10	H2	Extremely favors	Very Strong favors	Strong favors	Slightly favors	Equal	Slightly favors	Strong favors	Very Strong favors	Extremely favors	T2
		9	7	5	3	1	1/ 3	1/ 5	1/ 7	1/ 9	
11	H2	Extremely favors	Very Strong favors	Strong favors	Slightly favors	Equal	Slightly favors	Strong favors	Very Strong favors	Extremely favors	T3
		9	7	5	3	1	1/ 3	1/ 5	1/ 7	1/ 9	

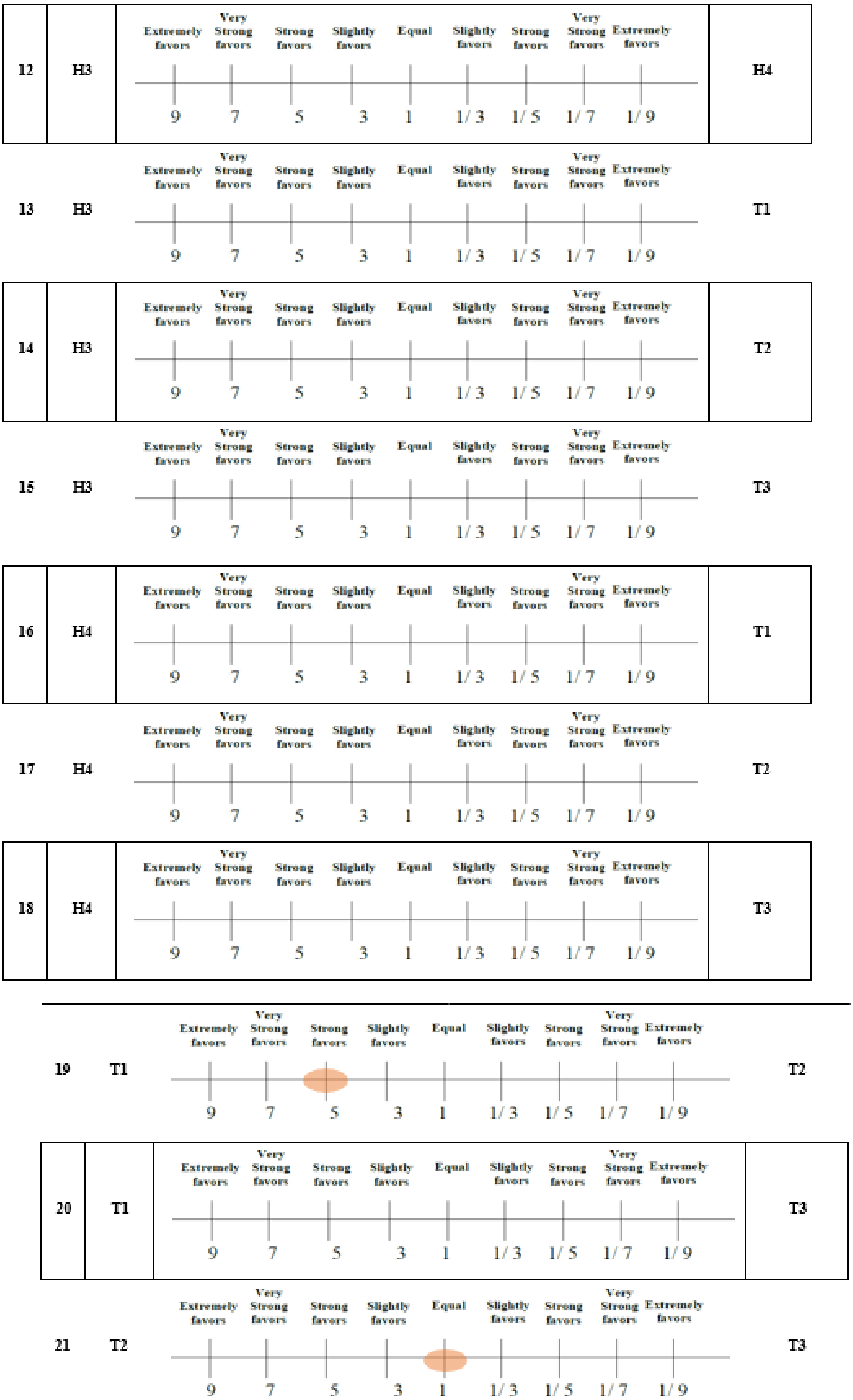


Figure 4.2: The expert answers

After obtaining the expert's answers, the first step, preparing the original matrix of comparison by pairs as it was clarified in equation (4.1), the summation of each column was calculated.

	H1	H2	H3	H4	T1	T2	T3
H1	**1**	**5**	**9**	**9**	**1**	**5**	**7**
H2	**0.2**	**1**	**1**	**1**	**0.14**	**1**	**0.33**
H3	**0.11**	**1**	**1**	**1**	**0.11**	**0.14**	**1**
H4	**0.11**	**1**	**1**	**1**	**0.11**	**0.33**	**0.33**
T1	**1**	**7**	**9**	**9**	**1**	**5**	**7**
T2	**0.2**	**1**	**7**	**3**	**0.2**	**1**	**1**
T3	**0.14**	**3**	**7**	**3**	**0.14**	**1**	**1**

(4.1)

The second step was to prepare the normalized matrix, dividing each value in the original matrix on the sum of each column, after that, the aggregation value for each row was calculated by calculating the sum of each row. The third step was to calculate the weight value for each criterion, by dividing each of the aggregation values on the total criterion number (seven criteria when used) as shown in Table 4.2.

Table 4.2: Step of weightage calculation

Criteria	Weight = $\frac{\text{Aggregation value}}{\text{No.of criteria}}$
H1	0.336271
H2	0.047926
H3	0.037979
H4	0.034574
T1	0.351308
T2	0.091592
T3	0.10035

* H: Heel strike angle
T: Take-off

now by applying each equation, the results were summarized in Table 4.3.

Table 4.3: Validation results of expert's answers

λ	CI	RI	$CR < 0.1$
8.05	0.17	6.10	**0.028**

The maximum weightage of mechanical loading modes criteria was observed for H1 by 0.33, followed T1 with 0.35.

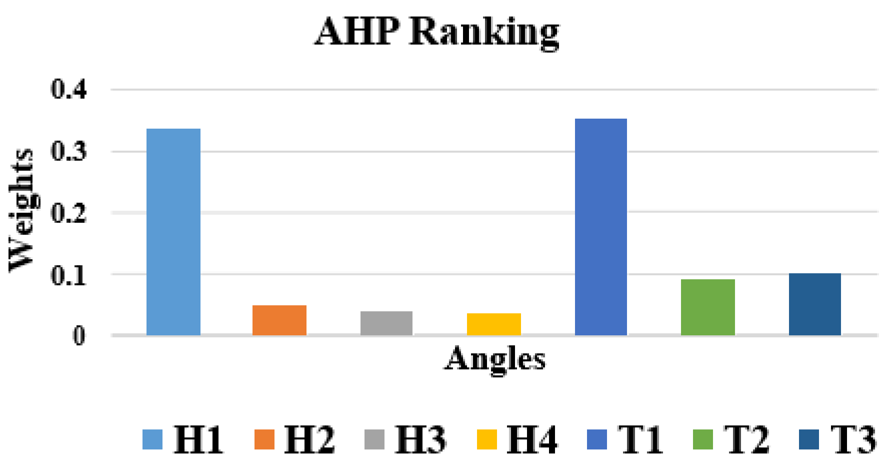


Figure 4.3: AHP final weightage score for each criteria

The lowest values have been taken for H4, and H3, respectively as illustrated in Figure

4.3. All mechanical loading modes weigh ready-to-use in the VIKOR method to give a ranking for each alternative as mathematically calculated in the next section.

5.2.2 VIKOR method for alternatives ranking

Test data for mechanical loading modes, as well as weight for each criterion have been calculated, after all previous tests and calculation steps, the mathematical approach process has been carried out for chosen appropriate of walking angle via applying the VIKOR method.

The first step was preparing the alternative matrix, for all mechanical loading modes under 120 N force, as well as, the best value (f^*) has been defined for the lowest stress value for each criteria, whereas the Worst value (f^-) has been defined for highest stress value. The second step was measured the utility (SI) matrix via multiplying the AHP weight for each criteria as it constructed The third step was calculated the value of the repentance measure (RI), which RI value represents the maximum value in the row of SI matrix. After that, in the fourth step, the maximum of each SI was calculated, and the IR was also calculated, as well as the minimum of SI and RI. Then, the final step was calculated ranking sequence for each alternative, the best ranked angles alternative, that alternative has the minimum QI value as it summarized in Table 4.4.

Table 5.7: QI of angles values and final net score ranking

Angles values (°)	Final Set	
	QI	Ranking
H1= 19.18	1	7
H2= 13.21	0.077467759	5
H3= 8.15	0.03354405	2
H4= 3.44	0	1
T1= 1.29	0.087018456	6
T2= 5.31	0.074802968	4
T3= 10.56	0.074687755	3

The best angle performance was observed under mechanical load modes via applying the VIKOR method with AHP weights for each criterion in angle H4 (3.44 °) followed by H3 and, T3 for models. Then, the fourth angle was taken for T2 for. The sequence was followed for each of H2, T1 and H1.

1. Conclusions

This chapter summarizes the conclusion of the present study, which explains the effect of the parameters, such as mechanical performance, and angles ranking on the patient stay period in hospital, and suggestions, as well as presenting the recommendations for future work.

1. Mechanical loads performance

The integrated compliant mechanism provides required flexibility to the foot, and ensures proper energy return making it easier to walk for the person wearing it and reduce the number of parts. The designed prosthetic was also simulated while walking to analyze the stress distribution. The analysis showed that for a vertical load of 120 N there was a maximum stress observed of 62.89 MPa at the first angle of heel-strike, which is 19.81 °. The mid-section of the foot where the three sections meet. This area suggested improving the mechanical performance by increasing the thickness to reduce the stress developed at this point.

2. Multi criteria decision making

The use of AHP was calculated based on the responses of experience to give weight to each criterion, depending on the AHP pair comparison questionnaire, the highest rank value was The maximum weightage of mechanical loading modes criteria was observed for H1 by 0.33, followed T1 with 0.35. The lowest values have been taken for H4, and H3, respectively. All mechanical loading modes weigh used in the VIKOR method to give a ranking for each alternative as mathematically calculated in the next section. The best angle performance was observed under mechanical load modes via applying the VIKOR method with AHP weights for each criterion in angle H4 (3.44 °) followed by H3 and, T3 for models. Then, the fourth angle weas taken for T2 for. The sequence was followed for each of H2, T1 and H1.

2. Recommendations

There are some recommended points further to the present study and suggested for future work as:

1. The optimal way to improve mechanical performance based on optimization of prosthetic foot models, as well as their using obstacles, is worth further examination.
2. The optimization based on parameterization that was performed in this study could be improved to focus on another alternative that could be parameterized.
3. Modify the peer comparison-questionnaire form and ask more than one expert to make a good assessment of the weight criteria.
4. Apply another MCDM method to evaluate the results of the VIKOR method, which could help give the researcher more flexibility and,
5. To design the experimental test to evaluate the numerical evaluation.

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