Influence of Link Dimensions on Parameters of Trace in a Klann Mechanism

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Abstract - *The invention, modification and development in the mode of transport has lept a very long way since 3500 BC and turned into an integral part of living. Legs used to be the natural mode of transportation for most animals across the planet's surface. A walking mechanism like the Klann or Jensen could find applications in an arena where wheels cannot be used. A careful analysis of the nature of the mechanism and its construction is imperative before the use of such mechanisms. The most common analysis on the Klann mechanism relates to that of stress. However, there is a need to analyze the effect of individual links making up the mechanism. One of the major characteristics of a walking mechanism is its trace and related parameters. These are typically evaluated using analytical methods. The use of powerful simulation tools and data analysis software can help generate these parameters with relative ease. The effect of the dimensions making up the Klann mechanism is examined taking one dimension at a time. The decomposition of effect of the individual links on the motion of the foot makes it easier to modify any dimension instantaneously rather than synthesizing a new mechanism that serves the specified purpose. On comparing the traces of foot for a number of configurations of the system, it is found that the crank and frame lengths play a significant role in the average velocity and stride length while the couple angle plays an important role in the step height.*

Key Words: **Stride Length, Step Height, Average Velocity, Jerk, Indeterminate Structures.**

1. INTRODUCTION

The Klann mechanism is a walking mechanism used as an alternative for wheels (V, U, Kumar, & S, 2015). It uses the rotary motion of a prime mover like a motor or an engine to produce a walking motion. Usually, about half of the rotation is used for the linear motion that propels the body forward, and the rest to restore to the initial position. This finds applications in uneven terrain where wheels may not be suitable. This mechanism is similar though not the same as the Jensen mechanism; Jensen is a more advanced mechanism in comparison to Klann (Bhongale, Pal, Lingawar, & Hiwarkhade, 2018).

1.1 Description of Klann Mechanism

The Klann mechanism is made up of 6 links as shown in Fig - 1. It is a planar mechanism which means that all links move relative to each other in parallel planes. It consists of the crank which is connected to the prime mover, two rockers, a coupler, leg and the frame. The frame connects the crank and the two rockers at its pivot. It should be noted that the crank is capable of complete rotation whereas the two rockers oscillate.

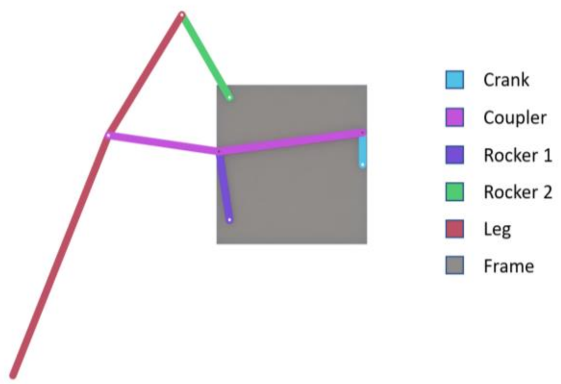

Fig - 1: Representation of a Klann Mechanism

The Klann mechanism consists of 7 binary joints; hence, the degree of freedom of the mechanism is 1(Mane, Barje, Kurale, Oulkar, & Waghmare, 2019). This implies that the rotation of the crank alone can produce a unique part in the foot.

1.2 About the Study

The aim of the analysis is to determine the most influential links for the path of the foot. All the links do not contribute equally to the path of the foot; changing one dimension of a link may have a more profound effect on the path than another. In the analysis, an attempt is made to determine the effect of change of dimension(s) of each link. To achieve this, the dimension of one link is changed at a time keeping the dimensions of all other links constant.

2. UNIVERSAL KLANN MECHANISM

The dimensions of the Klann mechanism that is most widely used (referred to as parent in this paper) is presented in Table - 1(Teli, Agarwal, Bagul, Badawane, & Bandre, 2019). A more important parameter than the absolute magnitude of the dimensions is their link ratios. Two Klann mechanisms possessing the same dimension ratios but different magnitudes of dimension will trace a path that are scaled versions of each other (Desai, Annigeri, & A, 2019).

The Klann mechanism can be considered to be made of two four bar mechanisms. The first is made by D8(grounded link), D1, D3 and D2. The second is made by the closing side of the triangle consisting of D2 and D4 (imaginary link), D6, D5, and D10 (grounded link). The motion of the foot is governed by the properties of these four bar mechanisms (NIT-K, 2016).

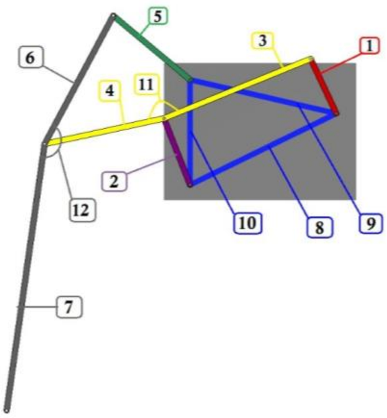

Fig - 2: Assigned Dimension Numbers

Table - 1: Dimensions of Parent

Dimension	Name	Magnitude
D1	Crank	110mm
D2	Rocker 1	130mm
D3	Coupler	288mm
D4	Coupler	222mm
D5	Rocker 2	182mm
D6	Leg	265mm
D7	Leg	490mm
D8	Frame	296.241mm
D9	Frame	273.16mm
D10	Frame	191.45mm
D11	Coupler Angle	170°
D12	Leg Angle	160°

3. CONDUCT OF ANALYSIS

The analysis is conducted on *Autodesk Inventor* for the simulations and *MATLAB* for data interpretation.

The mechanism is designed in *Autodesk Inventor* with appropriate dimensions and kinematic analysis is conducted. To conduct this analysis, the dynamic simulation tool of Inventor is used. Parameters such as Position, Velocity, and Acceleration are recorded. A snip of the Inventor environment during the study is shown in Fig - 3. Fig – 4 shows the working environment of *MATLAB.*

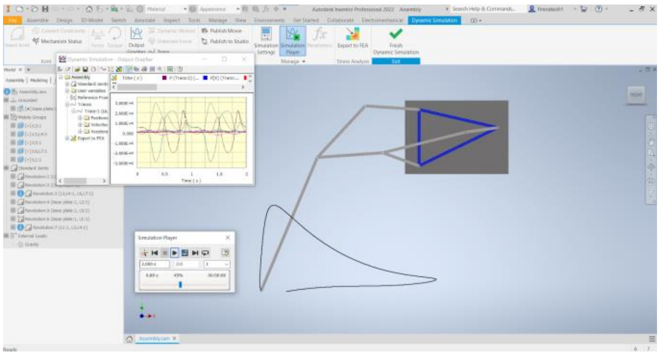

Fig - 3: *Autodesk Inventor* Environment

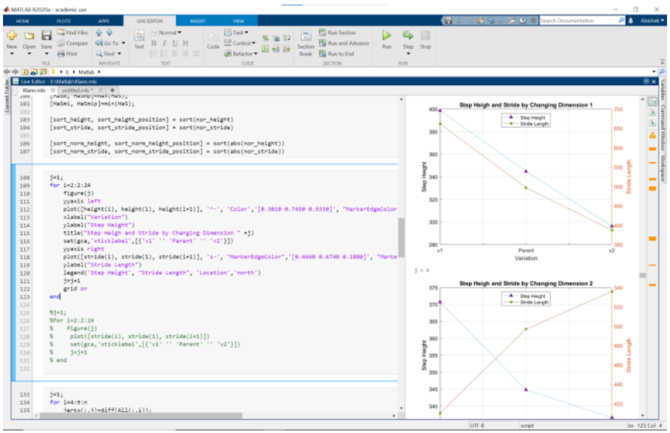

Fig - 4: MATLAB Environment

The imposed motion is set to constant velocity with a magnitude of 2π rad/s (360 deg/s). The time of study is set to 2 seconds with 200 data points. This yields 100 data points per cycle. The position (with respect to the grounded link - the frame), velocity and acceleration of the foot of the leg are recorded. The jerk of the same is calculated on MATLAB using the acceleration that was previously recorded. The x and y components of the jerk are calculated individually and the resultant (net jerk) is calculated from the same. Fig - 5 shows the MATLAB code to calculate the jerk.

```
j=1;
for i=4:9:n
    jerkx(:,j)=diff(All(:,i));
    jerky(:,j)=diff(All(:,i+1));
    j=j+1;
end

jerk = ((jerkx).^2+(jerky).^2).^0.5
```

Fig - 5: *MATLAB* Code for Jerk

4. PARAMETERS MEASURED

Stride Length: It is the distance for which the foot traces a linear path. This usually corresponds to about half the rotation of the crank. An ideal mechanism would have a straight line during its stride. A relatively smooth terrain would maximize this parameter to achieve faster speeds (N, R M, & B, 2019).

Step Height: It is the height to which the foot rises from the ground (end of the stride) during a cycle while returning to its initial stride position. A rough terrain would require greater step height to move over rocks and rubble. The stride length and step height are shown in Fig - 6.

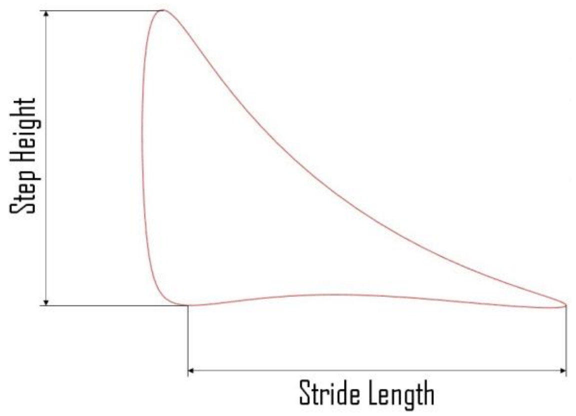

Fig - 6: Stride Length and Step Height

Average velocity: This is the velocity with which the body that bears the mechanism (usually has 6 to 8 Klann mechanisms with synchronized movement) walks. It is calculated as the stride length moved per unit time (stride length/time taken for stride).

5. PRE-PROCESSING OF DATA

The data obtained needs to undergo some level of processing before it can be used to generate plots. Two important steps are: 1. Normalization of data and 2. Rotation of cartesian coordinates.

Normalization of data:
The data obtained for position is with respect to the frame. Since the frame is away from the foot of the link, all values are shifted by an equal but large distance. This makes the usage of this data difficult. To eliminate this, all the points of the data are subtracted by their mean values.

Rotation of axes:
It is desirable to obtain a Klann mechanism that has a linear stride (line joining start of stride to end of stride) parallel to the horizontal. However, a change in the position or configuration of the frame would result in a stride that is inclined to the horizontal. To achieve horizontal stride, the configuration should be rotated by the slope (angle of inclination), in the opposite direction. Additionally, this facilitates the easy calculation of stride length and step height.

Fig - 7 represents the path traced before the rotation of axes and after rotation of the axes. It is generated by plotting the y position of the foot against the x position. It can be seen that the nature of the graphs remains the same; it is only rotated to make the stride parallel to horizontal.

6. INTERPRETATION OF MOTION OF PARENT

Using the data recorded, the plots of velocity, acceleration and jerk of the foot are generated and shown.

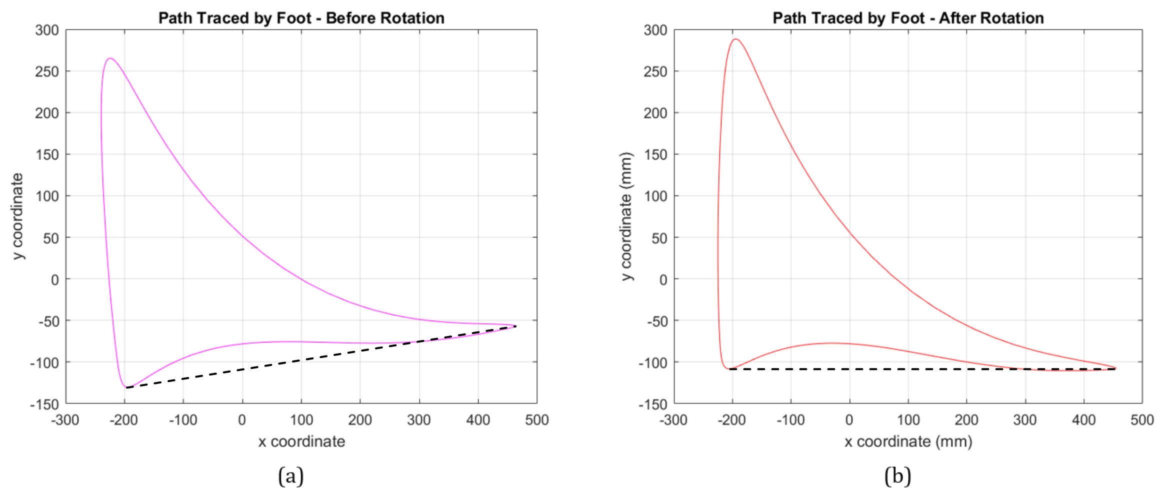

Fig - 7: Comparison of Trace Before and After Rotation

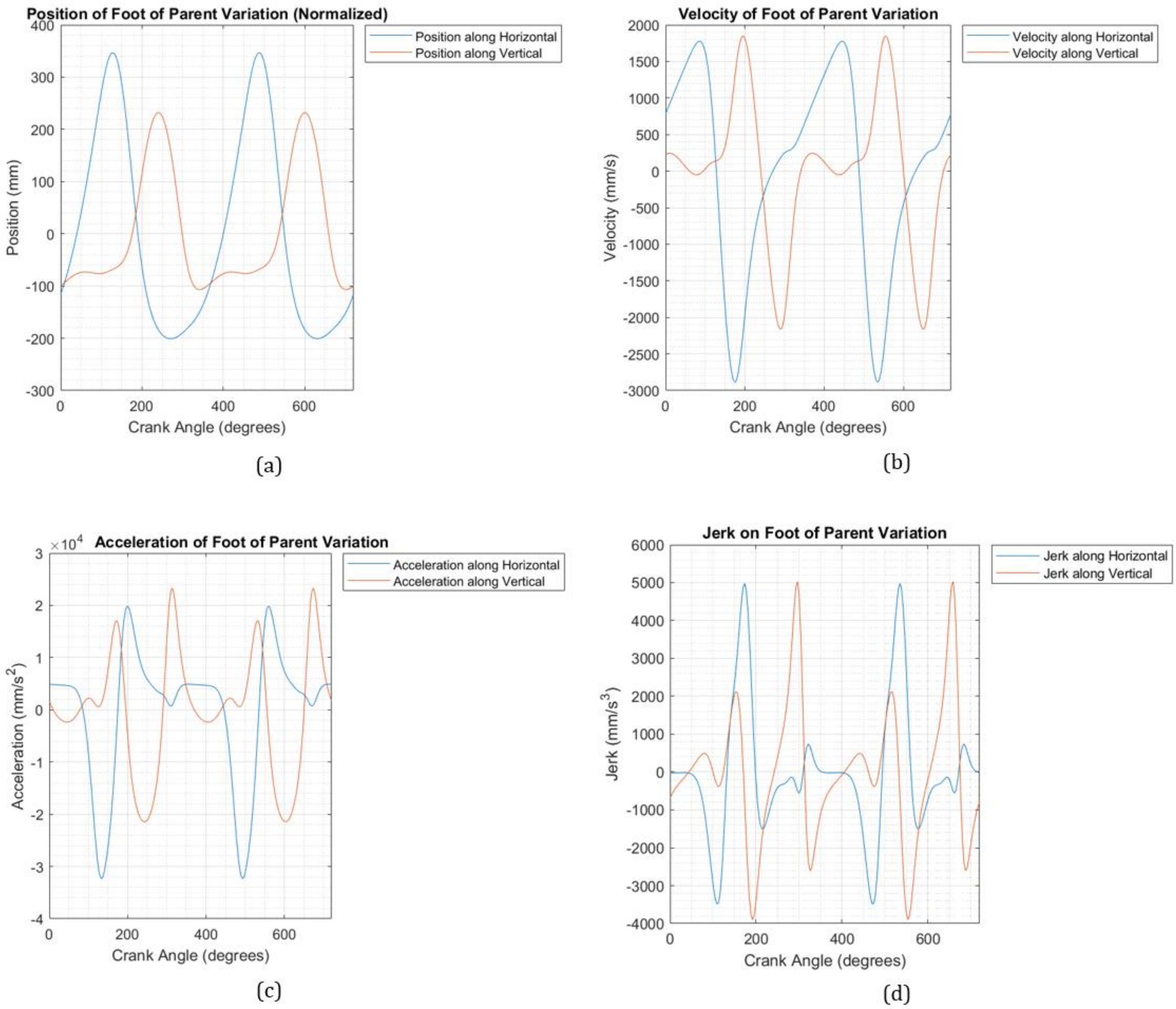

Fig - 8: Kinematic plots of Parent

Fig - 8(b) shows the plot of velocity against the crank angle. The x-component and y-component are plotted separately; the x-component contributes to the stride. Similarly, the acceleration and jerk (rate of change in acceleration) are plotted in Fig - 8(c) and Fig - 8(d) respectively. It is important to minimize jerk (by using appropriate length ratios) for high-speed application since it can lead to heavy vibrations and wear when not controlled.

7. VARIATIONS OF THE MECHANISM

As mentioned previously, the aim is to observe the effect of change of one dimension in the parameters of the path of the foot (Ben & Wade, n.d.). To achieve this, one dimension is taken at a time; the change is positive in the first case and negative in the second case. That is, the first variation of each dimension is a proportional increase in the dimension and the second is a proportional decrease of the same. The effect of increasing all dimensions by a constant amount may have a severe effect on the parameters for one dimension and a very mild effect on the other. Therefore, the dimensions are changed proportionally rather than by a constant amount.

The proportional change is 10% for most of the dimensions. Some dimensions exhibit unpredictable behaviour by a 10% change; the acceleration in these tends to infinity. For these cases, the dimensions are changed to make the acceleration within predictable (finite values) limits. Fig – 15 shows the problem that arises due the issue described above.

As shown in Fig – 2, 12 dimensions are changed in total (10 lengths and 2 angles). Each has an increase and a decrease in value. This leads to 24 new variations. Therefore, the total number of variations are 25 (1 parent + 24 new variations)

Table – 2: New Dimensions

Variation Number	Dimension Changed	%Change	New Dimension	Variation Number	Dimension Changed	% Change	New Dimension
1	D1	10%	121	**13**	D7	10%	539
2	D1	-10%	99	**14**	D7	-10%	441
3	D2	10%	143	**15**	D8	2.96%	305
4	D2	-3.85%	125	**16**	D8	-7.17%	275
5	D3	2.50%	295.2	**17**	D9	10%	300.476
6	D3	-2.50%	280.8	**18**	D9	-10%	245.844
7	D4	10%	244.2	**19**	D10	10%	210.595
8	D4	-10%	199.8	**20**	D10	-10%	172.305
9	D5	10%	200.2	**21**	D11	10%	187°
10	D5	-10%	163.8	**22**	D11	-10%	153°
11	D6	10%	291.5	**23**	D12	10%	176°
12	D6	-10%	238.5	**24**	D12	-10%	144°

Dimensions 2, 3 and 8 show indeterminate behavior. In the case of D3 which is a coupler (Link 3), it can be seen from the table that the dimension is changed only by 2.5%. Similarly, D3 and D8 are changed suitably.

8. OBSERVATION

To calculate the stride, the difference between values corresponding to maximum x-coordinate (end of stride) and x-coordinate for minimum y when x is negative (start of stride) is found. This condition makes a simplification in the calculation of approximate stride. For stride, only the horizontal distance between the start of stride and end of stride is considered.

Step height involves the distance between the maximum and minimum y-coordinates achieved (since the plot has been rotated).

Average velocity is found as the stride length per unit time. The time considered here is that taken between the start of stride and end of stride; not the entire cycle.

The parent variation has a stride length of 497.062 mm. An increase in D1 (crank) by 10% leads to a 661.992 mm stride which corresponds to the maximum stride out of all variations. 360.098 mm stride by changing D11 (coupler angle) corresponds to the minimum stride. The maximum step height is 465.308 mm by varying D11 (coupler angle) as against 342.749 mm of the parent variation. The minimum step height is achieved by a negative change in the same dimension corresponding to a value of 265.339 mm. The maximum average velocity is achieved by an increase in D8 (frame) with a value 1.498 m/s and a minimum of 0.624 m/s for a decrease in D1 (crank). The average velocity of the parent is 0.842 m/s.

A more significant parameter than the absolute change is the relative change of the above parameters with respect to the proportional change in the dimensions. The percentage change in parameter (stride, height, average velocity) divided by the percentage change in the dimension. The percentage change in the parameter is calculated as the difference between the parameter in the new configuration and the parent divided by that of the parent times 100.

The parameters found in Table – 4 are abbreviated as:
CPCD – Percentage Change in Parameter per percentage Change in Dimensions

- CSCD – Percentage Change in Stride length per percentage Change in Dimensions
- CHCD – Percentage Change in step Height per percentage Change in Dimensions
- CVCD – Percentage Change in average Velocity per percentage Change in Dimensions

$$CSCD = \frac{\textit{Percentage Change in Stride}}{\textit{Percentage Change in Dimension}}$$

$$\textit{Percentage Change in Stride} = \frac{\textit{Stride in Variation} - \textit{Stride in Parent}}{\textit{Stride in Parent}} * 100$$

$$CHCD = \frac{\textit{Percentage Change in Height}}{\textit{Percentage Change in Dimension}}$$

$$\textit{Percentage Change in Height} = \frac{\textit{Height in Variation} - \textit{Height in Parent}}{\textit{Height in Parent}} * 100$$

$$CVCD = \frac{\textit{Percentage Change in Average Velocity}}{\textit{Percentage Change in Dimension}}$$

$$\textit{Percentage Change in Velocity} = \frac{\textit{Velocity in Variation} - \textit{Velocity in Parent}}{\textit{Velocity in Parent}} * 100$$

Fig - 9: Formulae for CPCDs

When CPCD is negative (refer Table - 4), an increase in the dimension corresponds to a decrease in the parameter. CSCD is maximum for an increase in D8 (frame) with a value of 5.940 and minimum of -5.319 for D3 (rocker). CHCD is maximum for increase in D12 (Angle in leg) with a value of 1.897 and minimum of -3.576 for a negative change in D11 (Coupler angle)

Table – 3: Calculated Parameters

Variation Number	Dimension Changed	CSCD	CHCD	CVCD	Variation Number	Dimension Changed	CSCD	CHCD	CVCD
1	D1	3.318	1.5	3.785	**13**	D7	0.579	0.402	0.579
2	D1	2.212	1.384	2.589	**14**	D7	0.578	0.405	0.578
3	D2	-1.746	0.802	-2.145	**15**	D8	5.94	-2.651	26.331
4	D2	-2.041	0.69	-2.524	**16**	D8	3.774	-2.784	3.229
5	D3	-4.105	0.402	-3.486	**17**	D9	-0.018	1.67	4.364
6	D3	-5.319	0.194	-3.833	**18**	D9	-0.175	1.068	-0.175
7	D4	0.032	0.308	-0.297	**19**	D10	0.615	-1.138	0.615
8	D4	-0.041	0.322	-0.214	**20**	D10	0.698	-1.066	0.853
9	D5	0.316	-0.686	0.316	**21**	D11	1.533	-2.259	6.596
10	D5	0.288	-0.64	0.45	**22**	D11	2.755	-3.576	-0.425
11	D6	-1.287	1.315	-1.287	**23**	D12	-0.339	1.337	-0.5
12	D6	-1.377	1.118	-1.187	**24**	D12	-0.151	1.897	-0.326

9. TRACES OF FOOT

In the plots of the trace, the parent is represented with a dashed blue curve. The effect of increase in a particular dimension (Variation 1) and that of decrease in a particular dimension (Variation 2) are plotted in Fig - 10 in the same graph for the ease of comparison.

The effect of change of the crank length (D1) is that of scaling. An increase in the crank length leads to an increase in the stride, height, and the average velocity. The nature of the path traced is approximately the same. An increase in the length of rocker 1 (D2) leads to an increase in the height and a decrease in stride; this leads to a decrease in the average velocity. An opposite effect is found for a decrease in the length of rocker 1. The step heights remain approximately the same for both the variations of coupler link(D3). A decrease in stride and average velocity is observed for an increase in this dimension. The slope of the return stroke also changes considerably.

A change in the coupler to leg link (D4) and Rocker 2 (D5) has negligible effect on the parameters; although, a slight increase in the stride and average velocity is observed for an increase in these dimensions. The plots show notable changes for a change in the dimension of the leg (D6). For an increase in this dimension, the stride and average velocity decrease with an increase in the step height. It also shows an undesirable bump during the stride. This may lead to bumpy functioning of the system. A decrease in this dimension leads to a smoother stride with increased average velocity and decreased height. A change in the lengths of the leg to foot dimension (D7) results in a precisely scaled version of the parent.

For an increase in the length of the frame between the pivots of crank and rocker 1 (D8), an increase in the average velocity and stride is observed; the stride is relatively smooth. A decrease in this dimension leads to striking differences in the trace as can be seen in the plots. A decrease in this dimension produces the undesirable effect of bump on the stride. The height of stride shows an increase for an increase in the length of the frame connecting the crank and rocker 2 (D9). The stride length and average velocity do not show significant change. A change in the length between the pivot of the two rockers (D10) shows an opposite trend to that shown by D9.

Dimensions D11 and D12 correspond to angles. D11 is the coupler angle and D12, the leg angle. The coupler angle has a profound effect on the nature of the path traced. An increase in the coupler angle (a straight coupler) has a large stride and average velocity with a decrease in the step height. A decrease in coupler angle increases the step height. The stride length is small with a bump. Thus, the coupler angle should be maintained at the optimum level (165° to 175°). The effect of D12 can be seen in the trace plotted.

It can be observed that a decrease in stride is associated with an increase in step height in general. Exceptions to this are exhibited by D1 and D7.

10. MOST INFLUENTIAL PARAMETERS

Given the numerical data for various parameters along with its CPCDs, the aim, (as previously stated), is to determine the dimensions that have the most significant effect on motion of the foot. In order to achieve that, the change of the parameter per unit change in dimension should be relatively larger. Hence, from Table - 3 it can be noted that the CPCD is relatively large for the dimensions D1, D2, D3, D8, D11 for both CSCD and CVCD. D1, D8, D9, D11, D12 for CHCD

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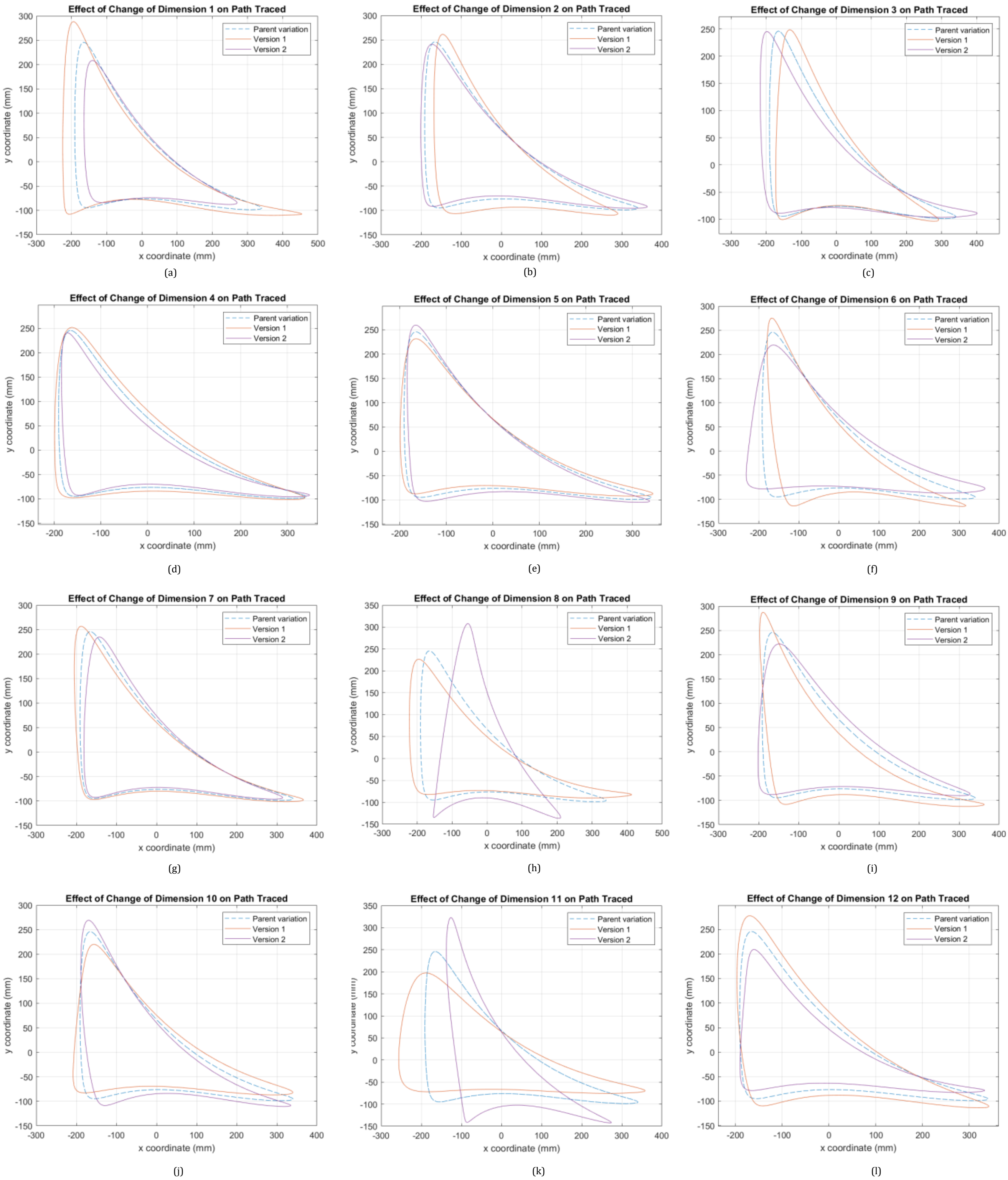


Fig - 10: Traces of Foot

10.1 Effect of D1

It can be seen from Fig – 11(a) that an increase in the crank length (D1) leads to an approximately scaled up version of the original path. A similar trend can be observed with a decrease in dimension. This shows that the foot is about 50 to 450mm away from the centre of the locus. The area enclosed by the path of foot trace is also scaled according to the change in dimension (scaled up for an increase and scaled down for a decrease) thereby increasing both stride length and step height. It should be noted that for all versions the time period is maintained constant. So, an increase/decrease in the plot length increases/decreases the velocity respectively which can be observed in Fig – 11(b).

In the acceleration and jerk plots, an increase in the dimension results in a sudden rise in magnitude at crank angles near 100^{o} and 450^{o}. Therefore, a further increase in dimension causes the magnitude to reach larger values resulting in disturbing vibrations that leads to instability (Sheba, Elara, Martínez-García, & Tan-Phuc, 2016).

10.2 Effect of D8

In case of D8 (Fig – 12), an increase in dimension (version 1) causes an increase in stride length and decrease in step height; similar is the case for version 2 where decrease in dimension decreases the stride length and increases the step height. It can be concluded that the consequence of the inverse proportional behaviour of stride length and step height results in the area approximately remaining constant.

The acceleration and jerk reach sharp extremes for both increase and decrease in dimension. Hence it can be concluded that any change in the dimension introduces vibration to the system.

10.3 Effect of D11

For D11 (Fig – 13), when angle of the coupler (parent having 170^{o}) tends to a reflex property (greater than 180^{o}) which corresponds to version 1, the stride length and step height increases and decreases respectively; and when reduces to obtuse angles (less than 180^{o}), the stride length and step height decreases and increases respectively, exhibiting the properties similar to D8 (where area approximately remains constant).

The acceleration and jerk plots indicate that a decrease in dimension causes steep increase in magnitude whereas an increase in dimension reduces the magnitude. Hence a decrease in dimension (version 2) introduces vibrations to the system.

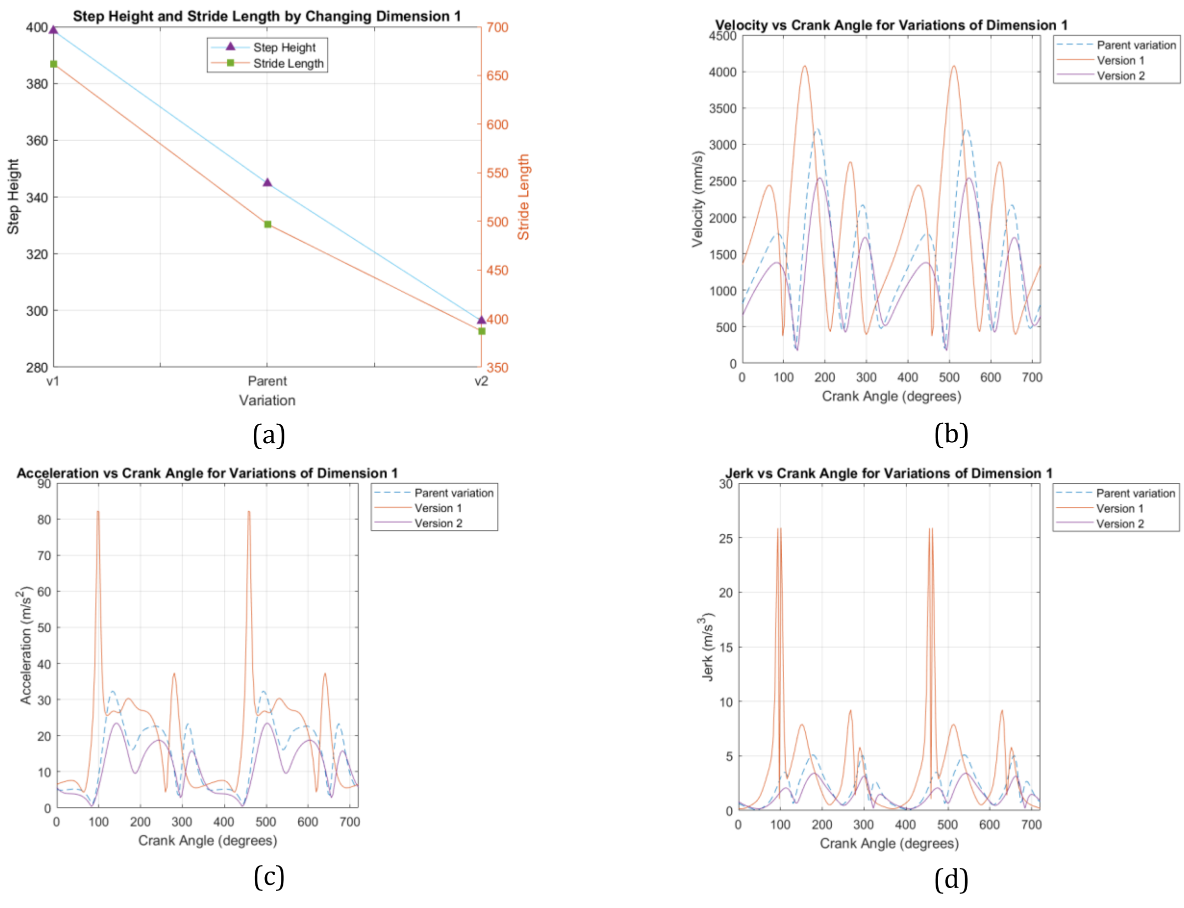
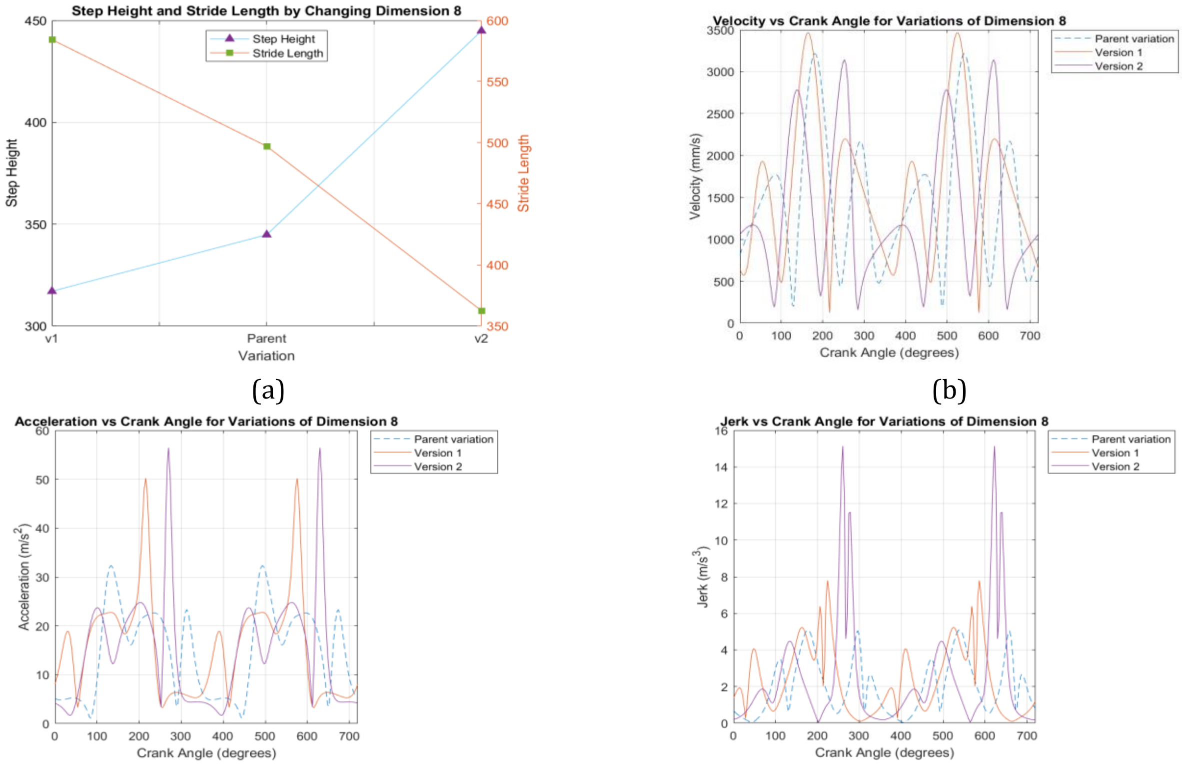
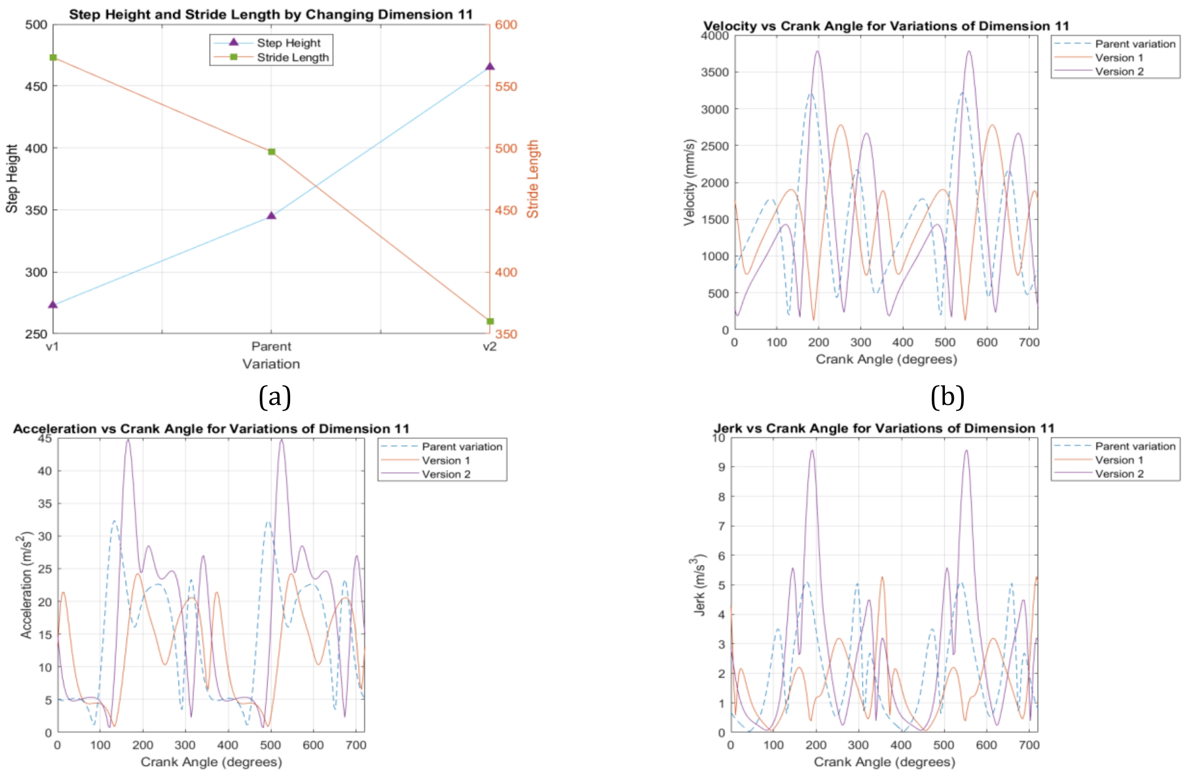


Fig - 11: Effect of D1



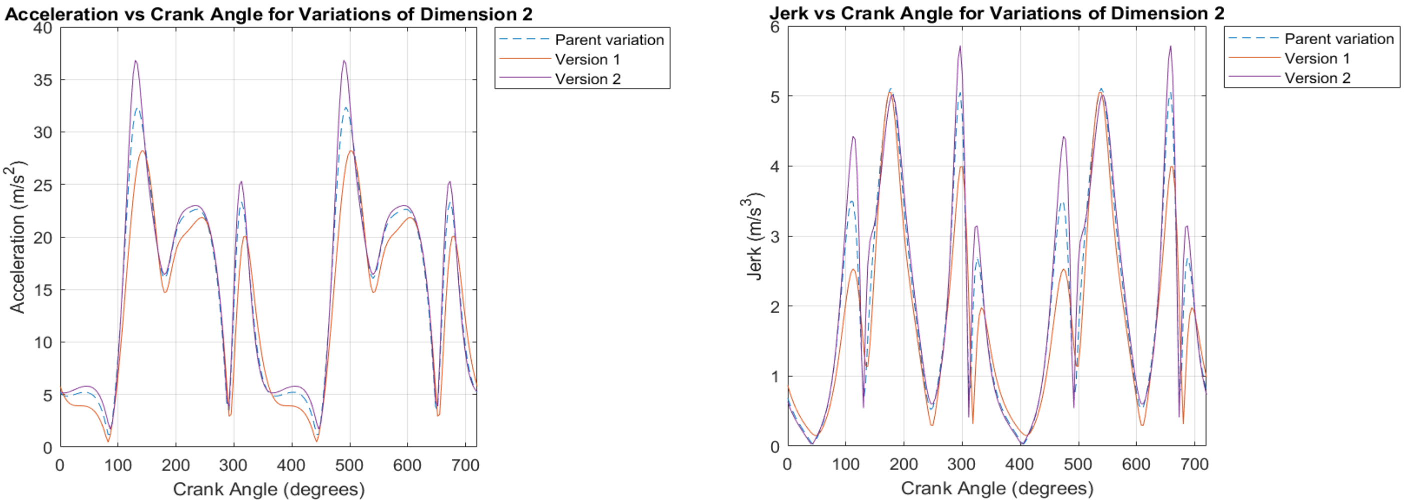
(a) (b) (c) (d)

Fig - 12: Effect of D8



(a) (b) (c) (d)

Fig - 13: Effect of D11



(a) (b)

Fig - 14: Acceleration and Jerk of Foot by Change of D2

11. SPECIAL CASES

Dimensions D2, D3 and D8 show infinite acceleration at the foot for large changes in the dimension. To restrict the acceleration to finite values, the change in dimensions is maintained at a small percentage (around 2 to 3%). The infinite values of acceleration signify increased inertia forces and such components will not serve their functionality in real life use. These configurations have a high probability of jamming; i.e., angle at joints reach 180^0 (collinear). This is highly undesirable since the probability of failure at the joints during operation is significant.

The acceleration curve for the two variations of D8 is shown in Fig - 14. It can be seen that the values of acceleration rise sharply (between 200° and 300° of crank). A higher change in the dimension (both reduction and increase) would lead to an asymptotic rise (circled red in Fig – 15) in the plots at these points. The position, velocity, acceleration, and jerk plots for D8 is shown.

A similar trend is observed in the case of D2 (version 2) and D3 (version 2). The rise for D2 is between 100° and 200° of crank and that between D3 is between 150° and 250° of crank.

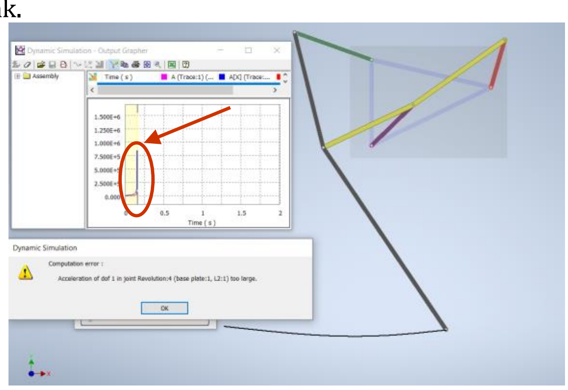


Fig - 125: Computation Error in *Autodesk Inventor*

12. INFERENCE

A walking mechanism finds its applications in a number of arenas. This requires the Klann mechanism to trace different paths with different parameters. To fulfill the specific conditions to be met, modifications to the link dimensions are to be made. In general, an increase in stride length is accompanied with a decrease in the step height. This is not true for dimensions that lead to scaling effect where both these parameters are increased or decreased at the same time.

13. SUGGESTED CHANGES

13.1 Stride Length, Step Height and Average Velocity

Table – 4: Suggested Changes

Modification	Stride length		Step Height		Average Velocity	
	Max	Min	Max	Min	Max	Min
Increase	D1 D8 D11	D2 D6 D12	D9 D1 D12	D11 D5 D8	D8 D11 D1	D2 D6 D3
Decrease	D6 D3 D2	D11 D8 D1	D11 D8 D10	D12 D1 D6	D6 D2 D3	D8 D1 D10

By referring to Table – 4, if there is a necessity to maximize the stride length, it is suggested (results from analysis) to either increase D1, D8 or D11 or decrease D6, D3 or D2. (Increase (Decrease) in D1(D6) has a more profound effect in comparison to D8(D3) and D11(D2)).

13.2 For Scaling

For parameters similar to the parent mechanism i.e., scaled version, D1, D7, D9 can be adopted.

14. CONCLUSION

The effect of change of dimensions of each link is observed and the most influential links are determined. It is important to understand the effect of each dimension on the path traced while designing a walking mechanism. This study has successfully analyzed the effect of both an increase and reduction of dimension on the path traced by the Klann mechanism. The effect of link lengths on the two most important parameters, the step height and stride length have been analyzed.

15. FUTURE SCOPE

The cumulative effect of change of more than one link at once can be studied. The torque requirements and forces on links can be analysed (MohdIsharudden, Mohamed, Rafaai, Wye Ho, & Kamarudin, 2020). The effect of the width and other structural properties on the links can be examined. The stresses and dimensional change for various positions of the crank can be investigated.

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