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Design, Kinematics and Analysis of the Instantaneous Effect of Uneven Surface on the Kinematics of Patients Amputated Below the Knee and Checking their Postural and Movement Compatibility

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Abstract **Original Research Article**

This study explores the design and kinematic analysis of below-knee amputees navigating uneven surfaces, focusing on the instantaneous effects of surface irregularities on their movement patterns and postural stability. The research aims to assess the compatibility of prosthetic designs with real-world terrain challenges, highlighting how uneven surfaces influence gait dynamics, joint motion, and overall mobility. By examining the kinematic parameters—such as stride length, joint angles, and body posture—this study evaluates the ability of prosthetic systems to adapt to abrupt changes in surface conditions. In fact, for each patient, the number of steps in each path for both legs and the path was examined as a fixed parameter, the frequency of changes (flexion and extension) in the knee joint as a variable, and the criterion for examining symmetry. KINOVEA, version 0.9.5, was used for biomechanical analysis using specific parameters to derive the kinematic parameters in the research. The results showed that the changes in walking speed for both subjects after the moment training had changed compared to the first walking on a stable surface. The asymmetry score of the frequency of angular changes in flexion and extension of the knee joint during a walking cycle for both subjects did not improve compared to the first walk on a regular surface. The analysis also addresses the impact of such surfaces on balance control and movement fluidity, aiming to inform the development of more adaptive prosthetic technologies. The findings reveal key insights into the kinematic discrepancies between walking on even and uneven terrains, offering valuable data for enhancing prosthetic limb design to improve postural alignment, safety, and comfort for below-knee amputees.

Keywords: Knee Amputation, Gait Analysis, Prosthesis, Kinovea, Kinematic

1. INTRODUCTION

Amputations are increasing rapidly. The number of amputees in the United States is currently 1.6 million, which is projected to double by 2050 [1]. In the anatomical situation, a below-the-knee amputation is a significant event that inevitably leads to movement disorders. Prostheses are designed to help restore at least some lost mobility [2]. Mobility is vital in improving the quality of life for people with lower extremity amputations. Walking is greatly affected by the mechanical movement of the foot prosthesis [3]. One of the reasons for the loss of social status and independence is related to the decrease in physical function caused by walking problems. One of the most basic and important activities that can increase physical fitness is walking [4]. An important factor in reducing the speed of development of physical disabilities is corrective sports interventions for older people [5]. Exercise by understanding familiar movement-canto improves walking performance through regular and timed practice and repetition of movements [6]. After lower limb amputation, functional mobility and quality of life improvement are very significant. Appropriate prostheses are recommended after amputation, the use of prostheses, physiotherapy, and rehabilitation to achieve recovery after amputation surgery. Rehabilitation is a set of treatments to increase comfort in life after amputation [7]. However, walking on a slope or uneven ground as part of an independent social walk is still daunting for amputated people [2]. Fixed prostheses are traditionally used to compensate for amputation function. Most people with amputations have asymmetrical gait due to the nature of their prosthesis [8]. Asymmetric walking leads to degenerative changes in the joints [9], spinal deviation [10], and pain in the other limb [11]. The symmetrical function of the lower limb is kinematically dependent on the prosthesis with their biological counterparts. Improving the kinematic settings in the prosthesis reduces the asymmetry in the limb during walking. Active prosthesis stabilizes walking and reduces asymmetry [12] and metabolic costs in walking [13]. One of the reasons for the increase in asymmetry is the lack of communication between the nervous system and the prosthesis [14]. Asymmetry is a significant factor in losing balance and falling to the ground [15]. In a stage of rehabilitation, one of the crucial criteria in assessing the health of prosthetic joints is the symmetry criterion [16]. One of the essential factors in improving and increasing symmetry during walking and standing is the use of orthosis [17], but it cannot improve dynamic balance [18]. One of the most used devices in rehabilitation centers is the treadmill. The use of treadmills in rehabilitation centers for patients has increased the speed and symmetry of walking [19, 20]. However, evidence suggests that neither a treadmill nor a treadmill exercise with a slit strap improves temporal asymmetry (e.g., standing and pre-rotation stages (dual support)) [20, 21]. However, inertial asymmetry may contribute to the asymmetric gait pattern [22]. However, the immediate effect of training on an uneven surface on the walking symmetry of people below the knee in the process of adapting to inclined walking has not been considered. This study was conducted to investigate the asymmetry parameters and to investigate the changes in kinematic parameters while walking on uneven and inclined surfaces. In particular, the three-dimensional kinematic patterns of the lower limbs, pelvis, and trunk when walking miles on uneven surfaces were examined. We examined the schematic changes in walking in several steps. This process is designed to kinematically evaluate the effect of instantaneous exercise on walking on a regular surface. This study is an experimental laboratory study on the kinematics of amputation below the knee, which is uneven by walking on a special variable ramp from the ground.

2. METHODS

Table 1. Basic information about the participants

Subject	Gender	Weight	Height	Age	Affected side
A	Male	70 KG	160	40	Right foot
B	Male	85 KG	190	35	Left foot

Participants

Two patients with amputation below the knee participated in this phase of the study. Table 1 shows the characteristics of volunteers in this study. The main criterion for selecting the subjects was that the participants spent at least a few months of the initial rehabilitation period so they could walk easily without assistance. The main criterion for selecting subjects is people below the knee.

Design and Study Method

The study design was a case study, and both patients gave their informed consent to participate. At first, we designed a device to evaluate and measure the amount of force on the foot during movements. The device has mechanical, electrical, and sensor parts. Also, it has a load cell that consists of a strain gauge connected to a metal holder and side connections. The test was performed in the Helal-e-Ahmar rehabilitation center[1] under the supervision of a prosthetist. According to the algorithm presented in Figure 1, after connecting the markers to the pelvic, knee, and ankle joints, the subjects walked 5 meters separately in three round-trip stages in the first stage. Experimental gait for data processing was measured using the Kinovea motion analysis system version 9.5. Outcome measures were compared during the first normal surface walk with and on the average surface after performing an open exercise on a rough surface for each patient .

Procedures

Participants were instructed in test instructions. This study aimed to investigate the effect of momentary exercise on uneven ramps on gait symmetry. In this regard, for this test, each subject, as mentioned in Algorithm, was performed in three separate steps in a 12-meter corridor in the Helal-e-Ahmar rehabilitation clinic. In the next part, it returns to normal with the same initial conditions. The experiment was performed in three separate steps. This experiment is known for the effect of exercise on balance and the ability of amputated people to walk [23].

[1] https://rehab.rcs.ir/

The executable algorithm in this article:

1. Walking on a regular surface (A1)
2. Walking on an uneven surface, two-part uneven, sloping surface (instant practice)
3. Walking on a regular surface after each walk on a rough surface (A2)
4. Comparison of kinematic parameters of the frequency of knee joint changes in the first and third stages

A B C

Figure 1. How to practice patient walking (B) and video accuracy (C) and uneven surface training environment (A)

Participants did not need help to walk. In this study, the prosthesis used for both subjects had stable ankle movement, meaning it did not deform when standing. As shown in Figure 1, labels were placed on both feet in specific sections as markers to collect kinematic information. The distance considered in this experiment for exercise and the expected level was 5 m. A 13-pixel camera was used to receive kinematic information. Training speed was based on personal preferences. The important thing about exercise was that the number of back-and-forth steps was the same. Three light-reflecting markers were used on both feet to identify essential and unobtrusive points of the gait pattern. After placing the markers and filming the subject for testing, they started walking in a specific place. Each subject completed a maximum of 3 separate steps of the 4-meter path for walking, of which two complete walking cycles were selected for analysis by KINOVEA[2] motion analysis software, and the angular changes of the knee joint were used in the calculations. For calculating the frequency of changes in the knee joint angle, the time elapsed for walking with a fixed number of steps in the reciprocating path was calculated and divided by the time (in seconds) elapsed. The symmetry parameter of walking was used to measure the effect of instantaneous exercise on the movement of knee-amputated individuals. Formula 1 was used to calculate the asymmetry index [8].

$$Asymmetry = abs\left(\frac{left-right}{(left+right)*0.5}\right) \qquad (1)$$

Rotation values were omitted from gait analysis to focus strategy development and focus more on gait parameters. The first and last 4.3 meters of walking represent the maximum walking distance required to reach a steady state of walking speed or a complete stop [24]. Each stage of training took place on a rough surface for walking separately and in three separate stages. Descriptive statistics were used to calculate the data's mean and standard deviation, and inferential statistics were used to compare the groups. One_Sample_Kolmogorov_Smirnov test was also used to examine the normal distribution of data [25]. Descriptive statistics were used to determine the effect of instant training challenges on uneven surfaces on kinematic gait parameters. Paired T-test was used to evaluate the impact of uneven surface instantaneous training on gait symmetry on normal surfaces before and after exercise. The significance level was considered for all calculations $P>0.05$. For performing paired T-test, the distribution of input data was first normalized. All calculations were performed using Excel and SPSS software version 26. Since the mean step length at each stage of the experiment varied between the two participants in the present study, we removed some data from the analysis to ensure a stable gait status was obtained for all participants.

3. RESULTS

The diagram of the amplitude of the kinematic changes of the raw data collected during the experimental stages for both patients, taken from both feet, is shown in Figure 2 .The results of the normal distribution of raw data using the

[2] https://www.kinovea.org

One_Sample_Kolmogorov_Smirnov test are shown in Table 2 in terms of symmetry changes (Sig= 0.05 ≥P). Therefore, the kinematic changes of the normal distribution are not. In this regard, the statistical analysis of Table 3 is visible for both patients. In descriptive statistical analysis, the frequency of output changes can be seen in Figure 3. To compare the effect of surface in the practice mode instantaneously after converting the data to a normal distribution, the results of paired T-test in the pre-test to post-test can be seen in Table 4. In the present study, the scores of symmetry changes between two patients were obtained through KINOVEA software. Then therapeutic intervention was performed on them, and in the post-test, the scores of symmetry changes in this group were re-recorded. In the next step, using paired T-test, the post-test score was compared with the pre-test to determine whether there was a change in symmetry changes after treatment (Table 4). Both patients did not need help walking. During the period of walking after the uneven surface, the symmetry of the knee joint changes in three separate cycles.

Case A

As can be seen in the above argument, the average score of symmetry changes in the pre-test was 4.64%, which increased to 2.71% in the post-test, and this increase is also statistically significant (Sig= 0.05 ≥P). When case A used a rough surface, the average walking speed increased by 9.2%, according to Table 4.

Case B

As can be seen in the above argument, the average score of symmetry changes in the pre-test was 3.48%, which increased to 1.2% in the post-test, and this increase is also statistically significant (Sig= 0.05 ≥P). When case B used a rough surface, the average walking speed decreased by 8.9%, according to Table 4.

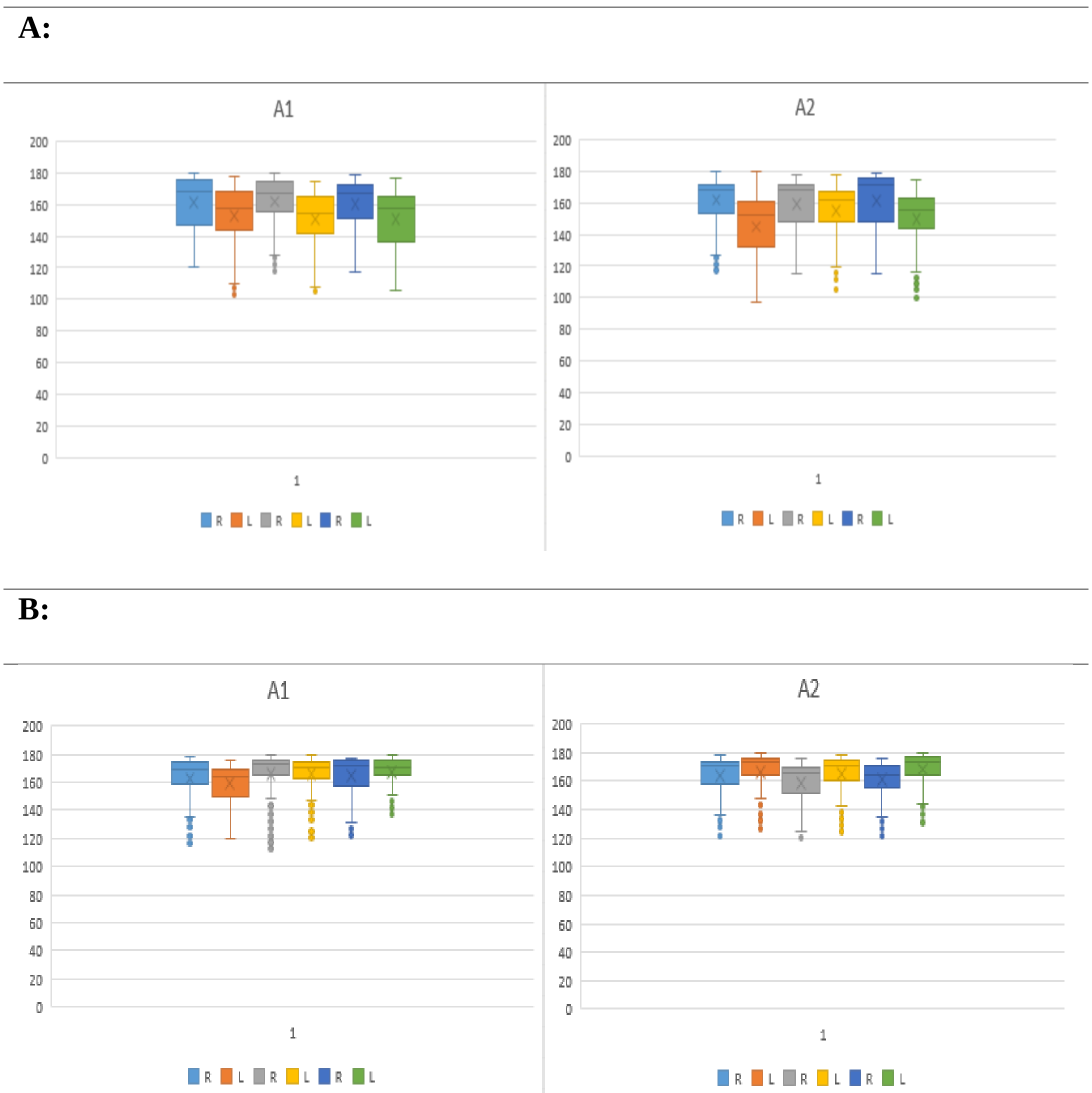

Figure 2. The range of angular changes of the right knee joint (R) and left leg for the patient (L) and the patient (A & B) at the first normal level (A1) and the normal level after uneven walking (A2)

Table 2. One-Sample Kolmogorov-Smirnov Test

Subject		A					
Foot & levels		LR1	LR2	LR3	LR4	LR5	LR6
N		139	139	139	139	139	139
Normal Parameters[a,b]	Mean	0.046	0.061	0.051	0.107	0.027	0.073
	Std. Deviation	0.018	0.017	0.022	0.054	0.011	0.017
Most Extreme Differences	Absolute	0.135	0.157	0.083	0.188	0.199	0.201
	Positive	0.094	0.076	0.083	0.188	0.106	0.099
	Negative	-0.135	-0.157	-0.065	-0.158	-0.199	-0.201
Test Statistic		0.135	0.157	0.083	0.188	0.199	0.201
Asymp. Sig. (2-tailed)		.000[c]	.000[c]	.021[c]	.000[c]	.000[c]	.000[c]
Subject		B					
Foot & levels		LR1	LR2	LR3	LR4	LR5	LR6
N		139	139	139	139	139	139
Normal Parameters[b]	Mean	0.034	0.009	0.005	0.010	0.035	0.043
	Std.Deviation	0.016	0.006	0.003	0.005	0.012	0.014
Most Extreme Differences	Absolute	0.086	0.133	0.095	0.201	0.316	0.199
	Positive	0.086	0.133	0.095	0.201	0.316	0.104
	Negative	-0.058	-0.082	-0.078	-0.073	-0.185	-0.199
Test Statistic		0.086	0.133	0.095	0.201	0.316	0.199
Asymp. Sig. (2-tailed)		.013[c]	.000[c]	.004[c]	.000[c]	.000[c]	.000[c]

a. Test distribution is Normal.
b. Calculated from data.
c. Lilliefors Significance Correction.

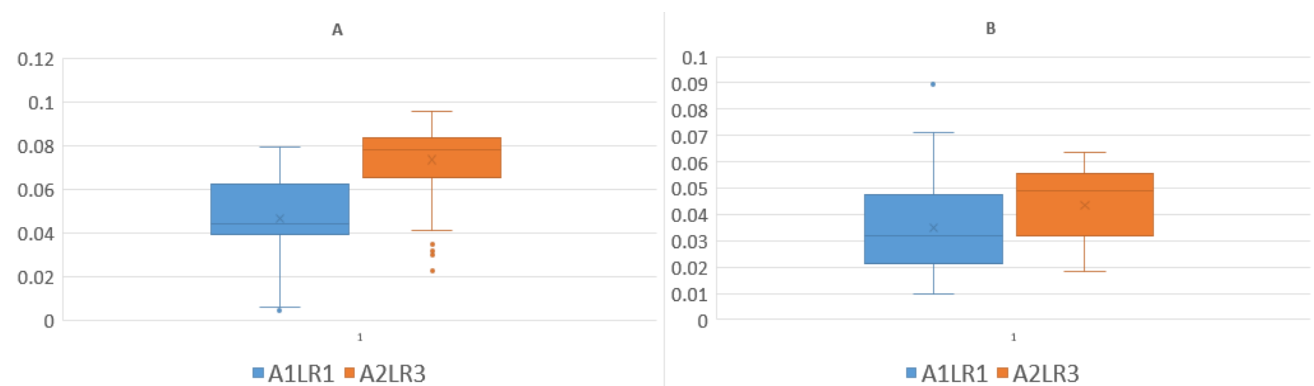

Figure 3. Shows the amplitude of changes in the angular symmetry of the knee joint in the normal gait of the first stage (A1LR1) and the amplitude of changes in the angular balance of the knee joint in normal gait after the instantaneous exercise of the third stage (A2LR3). And Patients (A & B)

Table 3. Kinematics of frequency symmetry of knee joint changes in the area of unilateral amputation of the lower knee

Subject	plane	A1				A2			
	levels	1	2	3	Average	1	2	3	Average
	foot	LR	LR	LR		LR	LR	LR	
A	Mean	0.046	0.061	0.051	0.052	0.107	0.027	0.073	0.069
	Standard Error	0.001	0.001	0.001	0.001	0.004	0.000	0.001	0.001
	Median	0.043	0.065	0.051	0.053	0.093	0.030	0.078	0.067
	Standard Deviation	0.018	0.017	0.022	0.019	0.054	0.011	0.017	0.027
	Sample Variance	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.000
	Kurtosis	-0.103	-0.112	-0.179	-0.131	0.543	0.263	0.708	0.504
	Skewness	-0.336	-0.381	0.275	-0.147	0.973	-1.038	-1.156	-0.407
	Range	0.075	0.079	0.096	0.083	0.248	0.041	0.072	0.120
	Walking speed (m/s)	0.631	0.588	0.619	0.612	0.779	0.674	0.660	0.704
B	Mean	0.034	0.009	0.005	0.016	0.010	0.035	0.043	0.029
	Standard Error	0.001	0.000	0.000	0.000	0.000	0.001	0.001	0.000
	Median	0.032	0.007	0.005	0.014	0.009	0.030	0.048	0.029
	Standard Deviation	0.016	0.006	0.003	0.008	0.005	0.012	0.014	0.010
	Sample Variance	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Kurtosis	0.521	-1.135	-0.720	-0.444	2.200	1.400	-1.279	0.773
	Skewness	0.689	0.341	0.331	0.453	1.446	1.533	-0.490	0.829
	Range	0.080	0.021	0.0146	0.038	0.026	0.057	0.044	0.042
	Walking speed (m/s)	0.869	0.606	0.588	0.687	0.566	0.649	0.579	0.598

A1 & A2 = Plane
A1 LR1= Symmetry of changes in knee joint angle the first movement
A2 LR3= Symmetry of changes in knee joint angle the third movement

Table 4. Paired t-test in the pre-test to post-test

Paired Samples Statistics					
Subject	***Plane & Foot & Levels***	***Mean***	***N***	***Std. Deviation***	***Std. Error Mean***
A	A1 LR1	.0464	137	.01772	.00151
	A2 LR3	.0735	137	.01685	.00144
B	A1 LR1	.0348	137	.01570	.00134
	A2 LR3	.0435	137	.01416	.00121

Paired Samples Correlations				***Paired Samples Test***							
Subject	***Plane & Foot & Levels***	***Correlation***	***Sig.***	***Paired Differences***					***t***	***df***	***Sig. (2-tailed)***
				Mean	***Std. Deviation***	***Std. Error Mean***	***95% Confidence Interval of the Difference***				
							Lower	***Upper***			
A	A1 LR1 & A2 LR3	.365	.000	.027	.019	.001	0.023	0.030	16.233	136	.000
B	A1 LR1 & A2 LR3	.665	.000	.008	.012	.001	0.006	0.010	8.255	136	.000

A1 & A2 = Plane
A1 LR1= Symmetry of changes in knee joint angle the first movement
A2 LR3= Symmetry of changes in knee joint angle the third movement

4. DISCUSSION

Walking is the most essential human movement. This study aimed to evaluate the effect of instantaneous exercise on the walking of amputees below the knee. As shown in the results section, a significant difference was found between the two patients. There is also a significant difference in different levels in each stage; the results show that the symmetry index increases slightly.

The increase in the symmetry index means that increasing the angular changes in the knee joint in momentary exercises on a rough surface causes a slight tendency to shift more weight towards the amputated limb than the other limb. This study investigated the effect of instantaneous training on the rate of knee joint changes (flexion and extension). The frequency of knee joint changes in terms of symmetry in both legs was assessed.

In this regard, the amount of symmetry in the number of changes in the knee joint was examined in this study. In fact, for each patient, the number of steps in each path for both legs and the way was examined as a fixed parameter, and the frequency of changes in the knee joint as a variable and the criterion for examining symmetry. The results of published studies examining the relationship between lower limb inertia and the metabolic cost of walking in unilateral amputations [22, 26] show that the metabolic cost of walking increases with increasing lower limb inertia.

In the study by Mattes et al. [22], adding 0.85 kg to the amputated distal limb did not affect the recovery of the metabolic costs of walking. However, by adding 1.70 kg, the metabolic cost has increased by 6%. Changing the inertial properties of the limb changes the oscillation period described by a simple pendulum model, indicating an increase or decrease in walking time [22, 26].

Changes in this index can mean the loss of balance of the subjects in stressful situations and confirm the studies in the literature. We observed similar values between the right and left foot in standard conditions from the data analysis related to the single phase of the walking cycle (when the whole body weight is placed only on one of the two lower limbs).

While under stress, there is a tendency to do more on the unsteady foot. The global symmetry index increases in both patients after the test, meaning that the corresponding support and right and left limb flight phases tend to deviate from normal values. The results are contrary to the findings[27]. The results of spatiotemporal parameters of patients with amputation below the knee are consistent with

the asymmetries reported in the literature [28]. Changes in walking speed, statistical differences (Table 2), and symmetry measurements show that these parameters are related to the length of the remaining limb and prove that the patient is more unstable [29].
One of the goals of this study is to show the importance of level challenges used in rehabilitation exercises in future studies. This study has limitations; Because of the movement of the skin (soft tissue), markers affect the parameters and size of the kinematic parameter estimation in the evaluation of movement artifacts [30]. This is a case report of changes in the kinematic parameters of walking. On the other hand, more studies are needed to evaluate clinical parameters influenced by momentary exercise.

5. CONCLUSION

During the walking of the subject (amputation), the average score of measuring the asymmetry of the angular changes of the knee joint during the walking cycle increased compared to walking on the natural surface of the first stage. If the mean change in walking speed is considered as walking improvement, it was variable for both patients. These movement changes show the rapid effect of the type of exercise on the improvement or lack of progress of the patient's rehabilitation.

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