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Analysis and Investigation of the Moment Effect of Walking on a Hybrid Rough Surface and Walking of a Transtibial Amputee While Walking on a Slope with a Unity Suspension System

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Abstract **Original Research Article**

This study presents a comprehensive analysis of the moment effects experienced during walking on hybrid rough surfaces and slope walking by transtibial amputees using a unity suspension system. The research investigates the mechanical behavior and gait dynamics, focusing on the interaction between the prosthetic limb and uneven terrains. By comparing the moments generated at the knee and ankle joints during level-ground and slope walking, the study highlights how the hybrid surface affects stability, load distribution, and energy consumption. Special attention is given to the unity suspension system, which provides enhanced vacuum-assisted suspension to maintain socket fit and limb control. In this regard, this study investigated the effect of momentary training on the surface (uneven-inclined) on biomechanical parameters such as force, the angular velocity of the knee joint, torque, and strength of the knee joint of below-the-knee amputation patients. This study aims to determine the effect of uneven, sloping surfaces on kinetic and kinematic quantities after short walking on a flat surface. Knee joint design can significantly improve gait quality, and there is limited information to guide selection. This study was conducted as a case study on two below-the-knee amputee patients. A wearable sensor with a load cell extracted the amputated knee joint's kinetic data (force, torque, power). In this regard, KINOVEA software has been used to extract kinematic data (frequency of changes in the knee joint angle and angular velocity, flexion, and extension of the amputated knee joint). After the initial pre-processing, the extracted data has been analyzed and compared using statistical methods. In the research, our findings have shown statistically significant changes. These findings have implications for optimizing prosthetic components to improve mobility and comfort for individuals with transtibial amputations.

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

1. INTRODUCTION

The growth rate of amputees is increasing. Nearly 1.6 million people in the United States have amputations, and projections indicate a doubling by 2050 [1]. Definitely, in the anatomical situation, amputation is an important issue. The prosthesis has improved movement disorders caused after amputation [2]. One essential factor in improving amputees' quality of life is mobility. The mechanical movement of the foot prosthesis significantly affects the type of walking [3] .Walking problems reduce physical performance and cause a loss of independence in social activities. The basis of daily life is walking, and the ability to walk (for example, a change in walking speed) can be used to increase physical capacity [4]. Sports interventions are a means to reduce or delay physical disability [5]. Exercise with a learned movement sequence is possible with the aim of improving the walking pattern through timed walking training [6]. Improving the quality of life and comfort in lower limb mobility after amputation is very important. Rehabilitation aims to recover after amputation to enhance the quality of life after disability [7]. However, walking independently and unaided for people with amputations on uneven and steep paths is a daunting societal issue [2]. The physical activity of walking stimulates different body parts [8].

Movement is a primary and vital issue in life. Daily movement is much more important than exercise, and with the advancement of technology, prostheses play an essential role in rehabilitation and have improved biological function in different body parts. Unequal weight distribution in people with transfemoral amputation is necessary for various skeletal and muscular complications [9, 10].

Extensive research is being done to improve the performance of the knee joint prosthesis. The most critical process in rehabilitation is related to adapting the artificial leg to the amputee. Mechanical and microprocessor-controlled prostheses are two common prostheses available in the market [11]. The difference between using a passive prosthesis and its intelligent type in the walking cycle of amputees is almost tiny. The torques above the knee and below the knee and the range of motion of the knee joint are different in people with normal physical strength [11-13].

Amputees can maintain their strength by changing their lifestyle [14]. Evaluation and analysis of gait and human kinesiology have been used in essential fields such as medicine, ergonomics, and sports [15, 16]. Most people at risk of falling during daily activities have a lower limb prosthesis. Walking on uneven ground is an essential factor that aggravates the risk of falling [17]. Uneven terrain is challenging for people with prostheses to navigate [18]. One thing that reduces users' stability on uneven ground is the changes made in the axial movement of the whole body during walking [19]. Investigations on kinematic changes in rough terrain for amputees with prostheses have been conducted [20, 21]. However, many studies have yet to be performed on the differences in the kinetics of the knee joint on the uneven surface. In this regard, changes in toe joint adduction kinetics in unilateral below-the-knee amputees were investigated while walking on an uneven surface. Biomechanical adaptations when walking on uneven surfaces are similar between able-bodied and amputee subjects [22]. Adding a toe joint improved the performance of the passive prosthesis on rough terrain (increased walking speed and reduced metabolic costs) [23].

In connection with the pressure on the foot, many injuries and diseases are known from the medical point of view. Force per unit area is defined as pressure. There is a direct relationship between the surface pressure and the force on the human foot [24]. Recent studies have shown the importance of wearable electronic devices in improving human life [25]. Recently, in the study of A. M. Tahir et al., to detect vertical Ground Reaction Force (GRF), an intelligent shoe has been used for gait analysis. In shoe manufacturing, the load cell was used as an inexpensive alternative for calibrating shoe sensors [26]. G. Orekhov et al. analyzed the movement and compared the biomechanical values in below-the-knee amputees in elliptical and cycling exercises; the maximum compressive force of the knee was calculated using a load cell, abduction torque, and extension torque have been calculated [27]. However, the immediate effect of uneven and inclined surface exercises on the changes in kinetic and kinematic parameters of the knee joint in below-knee amputees while walking on a regular surface has yet to be investigated. In particular, the pattern of vertical GRF changes and the 3D kinematic patterns of the lower limb, pelvis, and trunk during walking on uneven surfaces were investigated. For this investigation, a wearable sensor has been designed and manufactured using a load cell. We examined the schematic changes in walking in several steps. In fact, in addition to the effect of the surface, the impact of the wearable sensor with the same structure as the shoe was investigated. This procedure evaluated the kinematic effect of momentary exercise on walking on a normal surface. This study is an experimental laboratory study on the kinetic and kinematic variables of below-the-knee amputees performing slow walking exercises on an uneven and sloping surface.

2 .METHODS

Participating People

In this phase of the study, two patients with below-knee amputation participated. Table 1 shows the essential characteristics of the people participating in the study. To select the subjects, the selection criterion was that the participants had at least a few months of initial rehabilitation. Issues could move easily without any assistance. For the selection of subjects, the main criterion was amputation below the knee.

Table 1. Important parameters of the participants

Subject	Gender	Weight(KG)	BMI	Age	Height(CM)	Affected side
A	Male	70	27.3	40	160	Right foot
B	Male	85	23.5	35	190	Left foot

Study and Design Method

This study has the structure of a case study, and each person has given their informed consent before starting the experiment. This test was performed under the supervision of a prosthetist in the Helal-e-Ahmar rehabilitation center [1]. 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.

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

Also, it has a load cell that consists of a strain gauge connected to a metal holder and side connections. To begin the trial, markers are attached to the ankle, knee, and hip .In the next step, the subjects used a wearable sensor with a 100 kg load cell to extract the vertical ground reaction force. To collect kinetic data in these sensors, a 24-bit hx711 converter is used to convert analog to digital data. At first, each subject walked 5 meters separately in three separate steps. Then KINOVEA[2] motion analysis software version 9.5 was used for kinematic analysis of data processing. In this regard, kinetic and kinematic data during initial walking on a normal surface and normal surface after walking on an uneven ramp were compared for each subject.

Approach

This study aims to investigate the gaps in the existing studies on the issue of whether momentary exercise on an uneven sloping surface affects the kinetic and kinematic parameters of normal walking on a normal surface. In this regard, information was collected from each person in three separate stages in a 12-meter corridor at the Red Crescent Rehabilitation Clinic as a subject. Then it returns to the original normal path with the same initial conditions. For this purpose, this test was conducted separately in three separate stages. This test was performed due to the importance of exercise on walking ability and balance [28] in people with unilateral amputation below the knee.

The following algorithm was used in this article:

1- Crossing the normal route (A1)
2- Crossing the uneven slope (quick moment exercise)
3- Crossing the normal route after each crossing in the second stage (A2)
4- Following the comparison between kinetic and kinematic parameters and examining the frequency of changes in the amputated knee joint between the first and third stages.

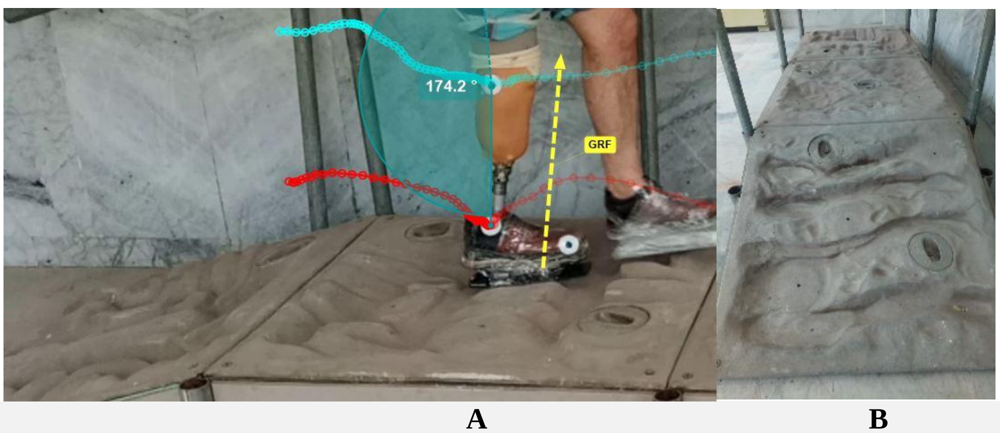

Figure 1. An example of instantaneous walking exercise form and kinematic extraction accuracy of patient walking exercise (A) rough ramp environment (B)

In this study, the participants did not need the help of another person to walk and move. The type of prosthesis used is fixed for each subject. Then, the motion marker tags visible in Figure 1 were used to collect kinematics (vertical ground reaction force (GRF)) after wearing the data collection shoes and kinematics. A normal area of 5 meters is considered for sports testing. A 13-megapixel camera was used to acquire kinematic data. GRF data collection was performed simultaneously with imaging in the same time frame. In this regard, the mechanical power parameter of the knee joint was used to compare and examine the effect of the surface. The power of the amputated leg joint is obtained from the following equation [29]:

$$p_j = M_j \times \omega_j \qquad (1)$$

M_j is the torque, and ω_j is the angular velocity obtained from the amputated knee joint.

The vital point in this exercise was the number of steps taken on the way back and forth. Each subject starts training with a natural movement of their choice for walking training. Three markers have been used to identify essential walking patterns, and a portable battery-powered loadcell shoe to respond to the force applied to the ground during the exercise. Each subject has traveled in 3 stages (6

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

round trips). KINOVEA software was used to analyze the kinematic data of the amputated knee.

The shoes used in this experiment consist of static (the heel is placed) and dynamic (the toe is set). The effective part extracted in the cycle of movement steps of the vertical ground reaction force data is the front part of the shoe. To check the kinetics of the effect of exercise, the data extracted from the Excel 2021 software was used for pre-processing. Then, to obtain the frequency of changes in the angular velocity of the joint, the conversion of the frequency of changes in the angular velocity of the knee joint was calculated for walking, and the time spent on a round trip was calculated and divided by the time (in seconds). To focus more on valuable data on gait parameters, rotation values were excluded from the analysis. To reach a steady state, the first and last 4.3 meters of walking represent the maximum walking distance required from walking speed parameters or complete stopping [30]. The pattern used in the exercise on the uneven sloping surface has been examined in three separate stages. Inferential statistics were used to calculate the standard deviation, calculate the mean and compare the groups. Then, the normality of the data was checked using One_Sample_Kolmogorov_Smirnov test [31]. Descriptive statistics were used to investigate the effect of the study challenge. To investigate the effect of walking (immediate exercise) on an uneven sloping surface on a normal surface before and after training, the paired t-test was used. To use the statistical test (paired t-test), the data distribution was normalized at the beginning (significant level P>0.05). SPSS version 26 and Excel software were used for all calculations and analyses. Some data were excluded from the analysis to ensure the stable gait status of the participants.

3. RESULTS

First, the raw data collected after pre-processing was checked using the One_Sample_Kolmogorov_Smirnov test, the type of data distribution in terms of normality and abnormality. Data change condition (Sig=0.05 ≥P) was considered. Tables 2 and 3 show that the obtained results have a non-normal distribution. In this regard, from the point of view of descriptive statistics analysis, a comparison has been made between kinematic variables (angular velocity of the knee joint) and kinetic variables (power, force, torque of the knee joint) (see Table 4).

The following is to compare and check the number of changes before the test. After the test with the aim of the effect of the uneven sloping surface after converting the data to a normal distribution and checking the correlation (Table 5) of the output data, the paired T-test was used. The results can be seen in Table 6. In this research, first, kinematic data was extracted using KINOVEA software. Then the kinetic data was extracted using the wearable sensor. The changes in the data after transforming the data distribution into a normal distribution are shown in Figure 2.

Case A

According to the items mentioned above and Table 5, the correlation between the pre-test and post-test data, except for the force data, the correlation between the pre-test and post-test data is statistically significant. As can be seen in Tables 4 and 6, statistically significant changes (Sig=0.05 ≥P) between the mechanical power of the amputated knee joint before and after the test (increase in knee joint power) have been obtained.

Case B

The correlation between the pre-test and post-test variables is not significant regarding changes related to force. As shown in Tables 4 and 6, the mean knee joint mechanical strength change score in the pre-test and post-test is statistically increased (Sig=0.05 ≥P).

Table 2. One-Sample Kolmogorov-Smirnov Test

A		Force (N) A1-1	Torque (Nm) A1-1	Angular velocity (deg/s) A1-1	Power (W) A1-1	Force (N) A2-3	Torque (Nm) A2-3	Angular velocity (deg/s) A2-3	Power (W) A2-3
N		177	177	177	177	177	177	177	177
Normal Parameters,b	Mean	74.55	2.60	-0.39	-420.33	78.63	1.50	5.62	-54.95
	Std. Deviation	93.87	6.55	92.91	1231.68	39.12	5.19	110.00	746.96
Most Extreme Differences	Absolute	0.27	0.26	0.17	0.42	0.26	0.11	0.17	0.24
	Positive	0.27	0.26	0.15	0.27	0.26	0.11	0.17	0.21
	Negative	-0.21	-0.21	-0.17	-0.42	-0.12	-0.05	-0.14	-0.24
Test Statistic		0.27	0.26	0.17	0.42	0.26	0.11	0.17	0.24

Asymp. Sig. (2-tailed)	.00[c]	.00[c]	.00[c]	.00[c]	.00[c]	.00[c]	.00[c]	.00[c]

a. Test distribution is Normal.
b. Calculated from data.
c. Lilliefors Significance Correction.
A1 & A2 .Plane.
A. Subject.

Table 3. One-Sample Kolmogorov-Smirnov Test

B		**Force (N) A1-1**	**Torque (Nm) A1-1**	**Angular velocity (deg/s) A1-1**	**Power (W)A1-1**	**Force (N) A2-3**	**Torque (Nm) A2-3**	**Angular velocity (deg/s) A2-3**	**Power (W)A2-3**
N		177	177	177	177	177	177	177	177
Normal Parameters,[b]	Mean	164.99	5.46	-1.78	-449.43	141.47	-0.59	-2.67	-4.68
	Std. Deviation	119.23	12.22	88.83	1966.47	112.49	9.50	84.20	688.22
Most Extreme Differences	Absolute	0.24	0.19	0.17	0.31	0.26	0.11	0.11	0.17
	Positive	0.24	0.19	0.17	0.27	0.26	0.07	0.11	0.16
	Negative	-0.08	-0.11	-0.14	-0.31	-0.10	-0.11	-0.11	-0.17
Test Statistic		0.24	0.19	0.17	0.31	0.26	0.11	0.11	0.17
Asymp. Sig. (2-tailed)		.00[c]	.00[c]	.00[c]	.00[c]	.00[c]	.00[c]	.00[c]	.00[c]

a. Test distribution is Normal.
b. Calculated from data.
c. Lilliefors Significance Correction.
A1 & A2 . Plane.
B. Subject.

Table 4. Kinetics and kinematics information of amputated knee joint

Subject	**plane**	**A1**				**A2**			
	levels	**1**				**3**			
	biomedical	**Angular velocity (deg/s)**	**Force (N)**	**Torque (Nm)**	**Power (W)**	**Angular velocity (deg/s)**	**Force (N)**	**Torque (Nm)**	**Power (W)**
A	**Mean**	-0.39	74.55	2.60	-420.33	5.62	78.63	1.50	-54.95
	Standard Error	6.98	7.055	0.49	92.57	8.26	2.94	0.39	56.14
	Median	7.03	17.15	0.27	-6.03	4.87	78.40	0.11	-9.71
	Standard Deviation	92.91	93.87	6.55	1231.68	110	80.55	5.19	746.96
	Sample Variance	8632.62	8811.73	42.98	1517037.52	12101.96	39.12	27.02	557958.22
	Kurtosis	1.03	-0.35	5.72	8.90	0.73	1530.80	-0.49	3.44
	Skewness	-0.53	1.01	2.43	-3.07	0.07	4.06	0.42	-0.56
	Range	478.75	301.25	34.28	6506.43	545.65	1.60	23.69	4978.96
B	**Mean**	-1.78	164.99	5.46	-449.43	-2.67	141.47	-0.59	-4.68
	Standard Error	6.67	8.96	0.91	147.80	6.32	8.45	0.71	51.73
	Median	4.54	148.47	1.86	-15.23	1.51	107.11	-0.33	3.52
	Standard Deviation	88.83	119.23	12.22	1966.47	84.20	112.49	9.50	688.22

	Sample Variance	7891.16	14215.99	149.46	3867015.12	7090.27	12654.83	90.33	473651.72
	Kurtosis	2.33	0.75	3.24	9.93	0.28	0.80	-0.30	1.42
	Skewness	0.35	1.21	1.83	-2.59	-0.13	1.28	-0.19	0.04
	Range	550.21	477.84	59.04	15456.62	405.87	474.02	40.74	3839.36

A1 & A2. Plane.

Table 5. Paired Samples Correlations

Subject	Plane _levels	N	Correlation	Sig.
A	**Force (N) A1-1&A2-3**	175	0.07	0.35
	Torque (Nm)A1-1&A2-3	175	0.49	0.00
	Angular velocity(deg/s) A1-1&A2-3	175	-0.34	0.00
	Power (W) A1-1&A2-3	175	-0.25	0.00
B	**Force (N) A1-1&A2-3**	175	0.09	0.22
	Torque (Nm)A1-1&A2-3	175	0.56	0.00
	Angular velocity (deg/s)A1-1&A2-3	175	0.37	0.00
	Power (W)A1-1&A2-3	175	0.25	0.00

A1 & A2 . Plane.

Table 6. Paired Samples Test (T-Test)

Subject	**Plane_ levels**	**Paired Differences**					**t**	**df**	**Sig. (2-tailed)**
		Mean	**Std. Deviation**	**Std. Error Mean**	**95% Confidence Interval of the Difference**				
					Lower	**Upper**			
A	**Force (N) A1-1&A2-3**	-3.79	96.87	7.32	-18.25	10.65	-0.51	174	0.60
	Torque (Nm)A1-1&A2-3	1.11	5.87	0.44	0.23	1.98	2.50	174	0.01
	Angular velocity (deg/s)A1-1&A2-3	-5.67	162.77	12.30	-29.95	18.61	-0.46	174	0.64
	Power (W)A1-1&A2-3	-354.83	1559.38	117.87	-587.48	-122.17	-3.01	174	0.00
B	**Force (N) A1-1&A2-3**	24.26	152.63	11.53	1.49	47.03	2.10	174	0.03
	Torque (Nm)A1-1&A2-3	6.10	10.21	0.77	4.57	7.62	7.90	174	0.00
	Angular velocity (deg/s)A1-1&A2-3	0.83	94.24	7.12	-13.22	14.89	0.11	174	0.90
	Power (W)A1-1&A2-3	-430.55	1869.96	141.35	-709.54	-151.55	-3.04	174	0.00

A1 & A2 . Plane.

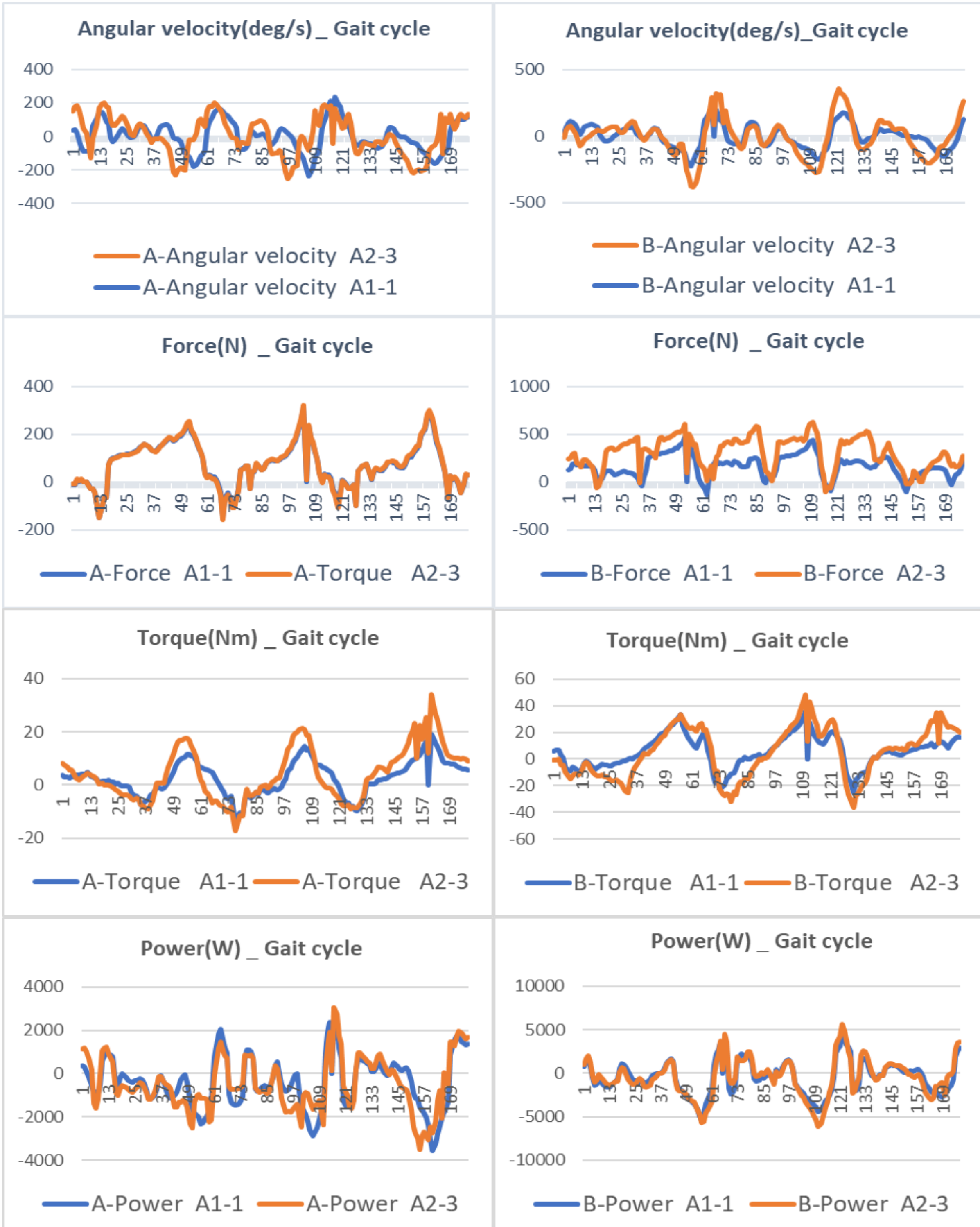

Figure 2. The range of changes in angular velocity, force, torque, and power in the knee joint of the amputee (data after data normalization for t-test comparison) related to the first experiment in the first stage (A1-1) and the third experiment in the second stage (A2-3).

4. DISCUSSION

The most critical daily human movement is walking. In this research, the main goal is to investigate the effect of walking on an uneven-sloping surface. This study assumes differences in the participants regarding physical parameters, foot type, and prosthesis structure, so the biomechanical parameters and kinematic and kinetic variables of walking are different.

This study is a case study of the kinetic and kinematic parameters of the amputated leg below the knee. As mentioned, statistically significant differences have been observed before and after walking on the uneven, sloping hybrid surface. The results show an improvement in the mechanical power of the knee joint.

According to the results of Table 4, the kinematic variable (angular velocity) and the kinetic variable (force) both had similar changes (in participant A (increase) and in participant B (decrease)). One of the causes of knee osteoarthritis is abnormal kinematics [32]. Also, it is one of the criteria that shows the severity of knee osteoarthritis is the knee joint's kinetic parameters (such as torque and force) [33].

In terms of kinetics, the average torque of the knee joint decreased after this exercise, which may be because the prostheses used by the participants are not a suitable and sufficient substitute for improving the biomechanical parameters of natural walking after amputation [27]. From a kinetic point of view, the average changes in knee joint torque have decreased after this exercise. According to studies [34, 35], published results show increased lower limb inertia and metabolic costs during walking in an amputated limb (unilateral amputation).

Mattes et al. reported no effect on the recovery of the metabolic cost of walking in the distal limb by adding 0.85 kg. Still, a 6% increase in metabolic cost during walking was obtained by adding 1.70 kg [34]. Kent et al. investigated the effect of rough surfaces on motion dynamics. A treadmill surface was used to make and check the uneven surface [36].

In this method, it was shown that walking on uneven ground can evolve after training. The kinematic characteristics of artificial legs under the influence of design and stiffness (carbon structure) have been identified as important factor for walking on a slope [37, 38].

Ernst et al. facilitated walking with an artificial leg with a microprocessor-based controller in uphill and downhill. To check the biomechanical characteristics of the knee joint, walking at a 10-degree slope was used. The results show a decrease in the torque of the knee joint for the amputee. Knee power is an important factor in the mobility of people with arthritis [2].

Maintaining and improving knee joint strength is an important factor. Enhancing the strength of the quadriceps muscles effectively increases the knee joint's power and reduces the pressure on the knee. Reducing the metabolic cost of walking depends on the relationship between the strength of the knee joint and the quadriceps muscle.

Measuring knee joint strength may be a more appropriate indicator of quadriceps weakness [39]. Our aim is to show the importance of future study. There are limitations to this study. This is a case report on the positive effect of momentary training on the uneven sloping surface in improving knee joint strength and power. On the other hand, more studies are needed to evaluate clinical parameters during walking.

5. CONCLUSION

Investigating the effect of momentary exercise on an uneven sloping surface on kinetic and kinematic parameters during a walking period has reflected useful information. If we consider the improvement of the strength of the knee joint in amputee patients as a turning point and a factor for improving movement, training on an uneven sloping surface is a positive factor in the rehabilitation of amputee patients. Increased recovery in rehabilitation will lead to reduced metabolic costs in walking on a smooth surface.

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