Journal of Rehabilitation Sciences and Research

Journal Home Page: jrsr.sums.ac.ir

Original Article

Kinetic and Kinematic Gait Changes in Patients Suffering from Foot Drop Disorder

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ARTICLE INFO

Article History:
Received: 10/04/2023
Revised: 11/06/2023
Accepted: 03/07/2023

Keywords:
Foot drop
Gait analysis
Kinematic
Kinetic

Please cite this article as: Karimi MT, Ashraf AR, Vafaei MA, Barati K, Shamsi F. Kinetic and Kinematic Gait Changes in Patients Suffering from Foot Drop Disorder. JRSR. 2024;11(3):161-167. doi: 10.30476/JRSR.2023.98568.1366.

ABSTRACT

Background: Patients with foot drop may need compensatory mechanisms to improve their gait. Although several gait analysis parameters have been studied in these individuals, no prior research has examined their joint contact force. Thus, this study investigated multiple gait analysis parameters and the joint contact force in patients with foot drop.
Methods: This experimental study recruited twenty individuals aged 15 to 60 (mean value 56.4±3.68) with foot drop disorders. A control group was also matched with the first group based on age, height, and gender. The participants were instructed to walk along a 12-meter path. A motion analysis system with eight high-speed cameras and a Kistler force plate was used. During gait analysis, various parameters were measured, such as spatiotemporal, peak forces applied on the leg, range of motions, moments applied on the lower limbs, and joint contact forces.
Results: The mean values of stride length and speed for normal subjects were 1.32±0.2 m and 1.24±0.177 m/s, respectively, compared to 0.961±0.24 m and 0.686±0.25 m/s for foot drop subjects (P=0.00). The joint contact force components of the ankle joint increased significantly in foot drop subjects compared to normal subjects.
Conclusion: The joint contact forces of the ankle joint increased significantly in foot drop patients, which should be considered in the rehabilitation treatment of these patients.

Introduction

Foot drop is a common condition that refers to a patient's inability to dorsiflex the ankle joint during the swing phase. It can be temporary or permanent, and it can affect one (unilateral) or both (bilateral) sides [1]. A common cause of unexpected foot drop is peroneal neuropathy, often due to pressure at the fibula neck around the knee area [2]. This disorder can also result from upper and lower motor neuron disorders, including neurodegenerative disorders of the brain such as stroke and multiple sclerosis; injuries to the nerve roots such as L5 radiculopathy and spinal stenosis; and peripheral nerve disorders, such as diabetes, lumbosacral plexopathy, partial sciatic nerve injury, and common peroneal nerve injury [2-6]. However, data on the incidence and prevalence of foot drop are scarce in the literature [7].

Complications associated with foot drop include contracture, muscle atrophy, an inability to load the lateral side of the foot, and difficulty standing and walking on the heel [4]. Patients with foot drop tend to flex their knees more than usual to prevent their toes

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from dragging, resulting in increased joint loading and potentially osteoarthritis over time. During the swing phase of walking, foot drop forces the patient to flex the hip joint more than normal to prevent falls. However, the toes are the first part that makes contact with the ground in the initial contact phase [3]. Patients with foot drop experience difficulty walking due to their abnormal gait pattern, known as steppage gait. This results in increased energy consumption while walking, decreased walking speed and distance, and a longer period in the double support phase to maintain balance and prevent falls [1, 8]. Patients with foot drop compensate by using mechanisms such as anterior pelvic tilt and trunk tilt in the direction of movement. This pelvis position can lead to excessive tension in the two joint muscles of the ischiocrural group. When this group is activated simultaneously with the gastrocnemius muscle, it can lead to limited flexion during loading in the standing phase at the hip joint [9].

One research study indicated that decreasing the moment of plantar flexion in the ankle joint led to an increase in the extensor moment in the knee joint while maintaining the same walking speed [10]. However, in another study, paradoxically, this did not occur in patients with foot drop [3]. Although augmenting knee flexion may increase the external moment of the arm concerning the knee joint, thereby boosting the extensor moment of the knee joint, it remains uncertain why individuals with foot drop opt for this approach. Despite this, it is crucial to note that this strategy should not be encouraged as an increase in the extensor moment at the knee joint results in heightened bone-on-bone forces [11, 12]. Interestingly, the compensation mechanism is more significant in the knee joint than the hip joint, as observed in patients with foot drop [4].

Foot drop can significantly disrupt the normal gait pattern, with the primary treatment goal being restoring a normal gait cycle. In addition to redistributing net joint torque to lower limb joints such as the ankle, knee, and hip, it is hypothesized that foot drop can also affect other joints [3]. Over time, this could potentially lead to joint overload, destruction, and chronic pain. This wider impact on joints may help explain the increased energy consumption and fatigue experienced by patients with foot drop [9]. Previous studies have investigated some kinetic and kinematic parameters in patients suffering from foot drop. However, to date, no studies have examined the effect of joint contact force on the various joints of these patients and have compared them with healthy individuals [3, 4]. Consequently, this study seeks a more comprehensive insight into the compensation mechanisms in individuals with foot drop by investigating joint contact forces and contrasting them with those in healthy individuals. These insights are vital for rehabilitating patients with foot drop and could help prevent secondary effects such as osteoarthritis in the affected joints. Thus, this study will revisit other kinetic and kinematic parameters of patients with foot drop and explore the impacts of joint contact force on their various joints. This methodology will augment our comprehension of the influence of foot drop on multiple joints and inform the treatment of this condition.

Methods

Participants and Settings

This research was conducted as an experimental study at the Shiraz University of Medical Sciences. The study protocol received approval from the same university's research ethics committee, with the Approval Code IR.SUMS.MED.REC.1400.061. All participants were required to sign a consent form before data collection. Only individuals who voluntarily provided written informed consent were included in the study.

This study enrolled twenty individuals with foot drop disorders. A control group was also established and matched based on age, height, and gender with the foot drop group. The study incorporated both male and female participants. The inclusion criteria encompassed all patients aged 15 to 60 with foot drop resulting from trauma, injection, discopathy, or other lower motor neuron disorders. Eligible subjects were those who could walk independently without assistive devices, without any progressive neurological disease, limitations in joint movement in the lower limbs, history of stroke, orthopedic surgery on the lower limbs, rheumatic diseases, or orthopedic problems affecting gait. Subjects should have been capable of walking 10 meters unaided, and no more than two years should have elapsed since the onset of foot drop. The exclusion criteria encompassed patients who experienced a lower limb fracture during the study or those diagnosed with myelopathy, myopathy, polyneuropathy, and motor neuron diseases.

Data were collected from each affected side. In cases where both sides were involved, the mean was calculated. Participants completed walking trials at a comfortable speed, traversing a 12-meter pathway, regardless of the force plate's position. The trial in which the foot was entirely on the force plate was selected for variable assessment. A familiarization process was completed at the start of all sessions to mitigate the influence of learning and familiarize participants with the biomechanics lab.

The subjects' movements were captured using a Qualysis motion analysis system (Switzerland). Eight high-speed cameras, along with a Kistler force plate (50*60 cm, Kistler Company USA), were utilized to measure the force exerted on the foot. Reflective markers were affixed to precise anatomical points on the body, such as the first and fifth metatarsal heads, medial and lateral malleoli, heels, greater trochanters, medial and lateral femoral epicondyles, posterior superior iliac spines, anterior superior iliac spines, and acromioclavicular joints on both the right and left sides, for motion tracking purposes. Figure 1 depicts the locations of these markers.

To determine the range of motion of joints, moments applied on the joints, muscle forces, and joint contact forces, we used the OpenSIM model 2392 software, validated in previous studies [13, 14]. The analysis of muscle force was conducted using computer muscle control in the OpenSIM software. In this study, we used model 2392 and analyzed 76 muscles. Given the extensive information in this study, we decided not to report the details of muscle forces. The full description of the procedure is detailed in the authors' previous publications [13-15].

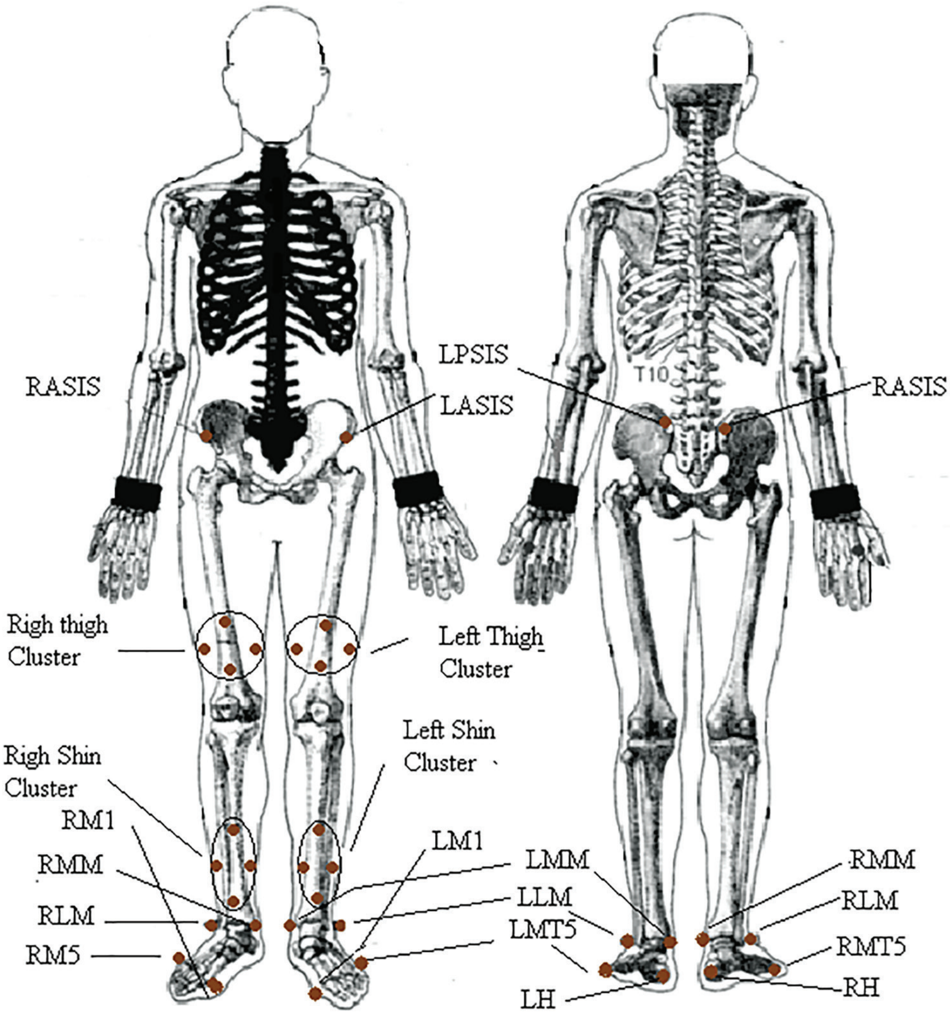

Figure 1: Location of reflective markers

We extracted the ground reaction force and kinematic parameters from the force plate and motion data. We used a combination of both to compute joint moments and joint contact forces.

Statistical Analysis

Statistical analysis was performed using the Statistical Package for Social Sciences (SPSS) software, version 19. The Shapiro-Wilk test was used to assess the data's normal distribution, which confirmed that the data were normally distributed. As a result, a two-sample t-test was utilized to determine the differences in the mean values of the parameters for both groups. Results with P values less than 0.05 were interpreted as statistically significant.

Results

Table 1 presents the mean values of spatiotemporal gait parameters for individuals with a normal gait and those with foot drop. The average root mean square of the marker tracking error was less than 0.02. The stride length was significantly lower in subjects with foot drop compared to normal subjects (0.961±0.24 m vs. 1.32±0.2 m, P<0.05), and a significant difference was observed in the walking speed between the two groups (P<0.05). In terms of ground reaction force components, Table 2 indicates that the peaks of anteroposterior force (braking and progression components) were significantly lower in subjects with foot drop compared to normal subjects, while the peaks of vertical force applied on the leg were the same in both groups (P=0.756).

Table 3 presents the range of motion (ROM) of the pelvic, trunk, hip, knee, and ankle joints for normal and foot drop subjects. The ROM of sagittal plane pelvic motion increased in foot drop subjects, while the ROM of lateral tilt decreased in these subjects compared to normal subjects (p-value <0.05). There was no statistically significant difference in the range of motion (ROM) of the hip joint between the normal and foot drop groups (P>0.05). Although the ROM of the knee joint showed an increase in foot drop subjects compared to those with a normal gait, this difference did not reach statistical significance (P=0.32). The ROM of the ankle joint was 31.98±4.18 in normal subjects compared to 40.04±13.78 in foot drop subjects, which was not significantly different (P=0.07). However, there was a significant difference in the ROM of the lumbar in both bending and rotation motions between foot drop and normal subjects.

Table 4 presents the mean values of moments applied to the lower limb joints for normal and foot drop subjects. Although there was no significant difference in the hip joint flexion moment between the two groups, a significant decrease in the hip joint extension moment was observed in subjects with foot drop (P<0.05). The flexion moment of the knee joint increased significantly in foot drop subjects, while the knee extension moment

Table 1: The characteristics of the subjects involved in this study

Participants	Mass (kg)	Height (m)	Age (y)
Foot drop	55.9±7.09	1.7±0.12	56.4±3.68
Normal	57.1±6.1	1.71±0.11	58.2±3.7
P value	0.14	0.12	0.14

Table 2: The mean values of spatiotemporal gait parameters and the peak of forces applied on the leg in walking of normal and foot drop subjects

Parameter	Normal Group	Foot drop Group	P value
Stride length (m)	1.32±0.2	0.961±0.24	0.00*
Walking Speed (m/sec)	1.24±0.177	0.686±0.25	0.00*
Cadence (steps/min)	98.44±17.2	84.76±17.93	0.04*
First peak of vertical force (N/ BW)	106.9±7.37	112.1±23.8	0.47
Peak of vertical force in midstance	74.7±7.25	98.5±18.9	0.00*
Second peak of vertical force	113.4±6.1	111.4±21.2	0.75
First peak of anteroposterior force	13.3±6.72	7.65±5.36	0.00*
Second peak of anteroposterior force	21.1±3.7	13.5±6.29	0.00*

N/BW: Newton/Body weight

Table 3: Range of motions of lower limb joints, pelvis, and trunk of normal and foot drop subjects

Parameters	Normal Group	Foot drop Group	P value
Pelvic anteroposterior tilt (degree)	5.53±4.71	9.43±3.87	0.02*
Pelvic lateral tilt (degree)	10.25±3.27	6.87±3.19	0.01*
Pelvic rotation (degree)	15.47±6.68	14.34±7.04	0.66
Hip flexion/extension (degree)	46.66±7.4	48.91±12.55	0.58
Hip abduction/adduction (degree)	14.94±3.46	12.06±4.89	0.09*
Hip rotation (degree)	19.24±6.36	18±7.29	0.65
Knee flexion/extension (degree)	63.88±6.59	67.55±10.67	0.32
Ankle dorsi/plantar flexion (degree)	31.98±4.18	40.04±13.78	0.07*
Lumbar flexion/extension (degree)	9.18±6.12	9.4±4.1	0.9
Lumbar lateral bending (degree)	13±4.21	8.6±3.74	0.00*
Lumbar rotation (degree)	37.85±13.38	11.92±4.92	0.00*

Table 4: The mean values of the moments applied on lower limb joints in normal and foot drop subjects

Parameters	Normal Group	Foot drop Group	P value
Hip flexion moment (N/BM)	0.536±0.186	0.72±0.392	0.15
Hip extension moment (N/BM)	1.044±0.31	0.521±0.265	0.00*
Hip abduction moment (N/BM)	0.5±0.15	0.51±0.22	0.15
Hip abduction moment (N/BM)	0.586±0.199	0.403±0.199	0.13
Hip rotation moment (N/BM)	0.081±0.035	0.085±0.036	0.77
Knee flexion moment (N/BM)	0.175±0.086	0.288±0.193	0.07
Knee extension moment (N/BM)	0.709±0.3	0.332±0.34	0.00*
Ankle dorsi flexion moment (N/BM)	0.311±0.088	0.0247±0.03	0.00*
Ankle plantar flexion moment (N/BM)	1.41±0.205	1.2±0.38	0.09

Table 5: The mean values of joint contact forces in normal and foot drop subjects

Parameters	Normal Group	Foot drop Group	P value
Hip anteroposterior shear force (N/BW)	3.17±0.91	1.84±1.11	0.00*
Hip mediolateral shear force (N/BW)	1.04±0.45	1.51±0.63	0.04*
Hip vertical force (N/BW)	3.76±1.13	3.75±1.13	0.85
Knee anteroposterior shear force (N/BW)	2.61±0.37	1.01±0.3	0.00*
Knee mediolateral shear force (N/BW)	0.365±0.13	0.32±0.14	0.38
Knee vertical force (N/BW)	4.04±1.08	3.64±0.88	0.28
Ankle anteroposterior shear force (N/BW)	0.87±0.216	2.75±0.95	0.00*
Ankle mediolateral shear force (N/BW)	0.36±0.26	0.72±0.38	0.00*
Ankle vertical force (N/BW)	4.89±0.66	7.21±1.73	0.00*

N/BW: Newton/body weigth

decreased significantly (P=0.005). The ankle joint's dorsiflexion and plantarflexion moments decreased in foot drop subjects, but the difference was only significant for the dorsiflexion moment (P<0.05).

The joint contact force was another parameter evaluated in this study, with the results shown in Table 5. The mean values of anterior and medial shear forces were 1.184±1.114 and 1.51±0.637 N/BW in foot drop subjects, respectively, compared to 3.17±0.913 and 1.04±0.456 N/BW in normal subjects (P<0.05).

There was no significant difference in the vertical component of joint contact forces of the hip and knee joints between normal and foot drop subjects. Although the shear force of the knee joint in the anteroposterior direction significantly decreased in foot drop subjects, there was no significant difference in the mediolateral and vertical force components of knee joint contact forces between the two groups (P<0.05). The ankle joint force exhibited a significant increase in all planes among subjects with foot drop compared to those with normal gait patterns.

Discussion

Disruptions to the kinematic chain can occur as a result of muscle dysfunctions, leading to the development of abnormal motor patterns. Pathological conditions in the foot region can impact the alignment of the pelvis and the hip and knee articulations. Even subtle malfunctions, such as the impairment of muscles regulating dorsiflexion, can disrupt the uniform distribution of forces across the body. In response to such issues, individuals may resort to compensatory strategies, leading to repeated use of alternative movements and perpetuating certain locomotive abnormalities [16]. However, the main questions here focus on which joint experiences more force due to compensatory mechanisms and which joint causes more complications in the future. Therefore, our study aimed to evaluate joint contact force parameters and other gait analysis parameters to answer these questions. The outcomes of this research unveiled notable distinctions between the two groups across various factors, encompassing spatiotemporal gait characteristics, joint movements, joint torque, and joint contact pressures.

As observed in the results of our study, the walking speed of foot drop subjects was nearly half that of normal subjects (P<0.05), as shown in Table 2. This is due to decreased stride length and cadence, consistent with previous studies [4, 8, 16]. This can be partially attributed to the foot drop subjects' inadequate plantar flexion strength and knee hyperextension posture during the stance phase, which impairs their gait pattern. However, the main problem for this group of subjects is the weakness in the anterior compartment of the leg muscles, which leads to a decrease in the progression force and swing phase clearance [17]. Interestingly, foot drop subjects exhibited a decrease in lumbar motion in the frontal and transverse planes, an increase in pelvis anteroposterior tilt, and a decrease in pelvic lateral tilt, as shown in Table 3. The results of the kinematic analysis showed that this group of subjects did not use any compensatory mechanisms to lift the foot off the ground in the swing phase, as there was no significant increase in the range of motion (ROM) of the hip and knee joints in the sagittal plane, as shown in Table 3.

Significantly, alterations in body kinematics were predominantly observed in the pelvis and trunk. This is noteworthy as therapeutic exercises for individuals with foot drop typically concentrate on the ankle, knee, and hip joints. Consequently, it is suggested that rehabilitation exercises for patients with foot drop should incorporate considerations for the pelvis and trunk. Targeting these areas during treatment can potentially enhance the overall gait mechanics of these patients, thereby improving functional outcomes.

The Ground Reaction Force (GRF) was assessed as part of this study. As per the data outlined in Table 2, there was no significant difference in the mean measurements of the initial and subsequent peaks of the vertical GRF between individuals with normal gait and those diagnosed with foot drop. However, a marked increase in the mid-stance peak of the vertical GRF component was observed among foot drop subjects. This could be attributed to the hyperextended knee joint posture of foot drop subjects during mid-stance [18, 19]. Intriguingly, both components of GRF in the anteroposterior direction exhibited a decrease in foot drop subjects, likely due to the reduced walking speed, as indicated in Table 2. This diminished walking speed can be ascribed to the weakened ankle joint muscles and decreased performance of ankle dorsiflexors and plantar flexors, which also impact the GRF in the anteroposterior direction. Therefore, it can be inferred that patients with foot drop experience a decrease in GRF primarily in the AP (anteroposterior) plane due to muscle weakness in the ankle joint and reduced walking velocity.

Joint moments were another parameter evaluated in this study, with results in Table 4. Few studies in the literature have evaluated this parameter. The mean values of most moments of the hip, knee, and ankle joints were significantly different from those of the normal subjects, similar to the findings of the study by Michalina et al. The dorsiflexion moment of the ankle joint significantly decreased due to weakness or paralysis of the ankle dorsiflexor muscles. There was also a weakness in the plantar flexor, but it was not significant. Previous studies have indicated that a reduction in the plantarflexion moment at the ankle joint may result in an elevation of the extensor moment at the knee joint, assuming a consistent walking speed [10].

However, surprising results were observed in the current study among individuals with foot drop. Contrary to expectations, this group did not exhibit the anticipated increase in the extensor moment around the knee despite the diminished plantarflexion moment at the ankle joint. The knee extension moment significantly decreased due to the hyperextended posture of the knee and weakness of the knee joint extensor muscles. In the study by Michalina et al. [16] The decreased knee moment in individuals with foot drop was attributed to the absence of heel strike at the beginning of the gait cycle. The lack of heel strike results in reduced plantar flexor activation during early stance, which subsequently leads to decreased knee extension moments. In both studies, the observed first knee extensor peak moment was approximately half of that observed for the control group (P<0.05). This underscores the significance of the plantar flexor muscles in providing initial dynamic stability during the initial stance phase of gait.

The hip extension moment also significantly decreased in subjects with foot drop. Based on the joint moment's results, it can be inferred that individuals with foot drop experienced a significant alteration in the performance of the flexor and extensor muscles that support and move the joint in sagittal planes. Consequently, it is recommended to enhance the strength and performance of the flexor and extensor muscles of the ankle, knee, and hip joints in rehabilitation treatment.

In contrast to the study by Kim et al., the mean values of hip joint extension, flexion, and rotation moments were 0.33, 0.32, 0.68, and 0.06 NM/BW, respectively [20]. These values were less than the moments found in the current study. Kim et al. also reported knee extension moment and ankle plantar flexion moment as 0.3 and 0.64 NM/BW, respectively. The differences between the moments of the current study and those found by Kim et al. may be attributed to variations in walking speed and the age of the participants. In the study conducted by Kim et al., the subjects with foot drop walked at a speed of 0.45 m/s, compared to 0.686 m/s in the current study. These findings underscore the importance of evaluating joint moments in patients with foot drop and formulating effective treatment strategies to strengthen the muscles involved in joint stabilization and movement. It is also crucial to consider factors such as walking speed and age when comparing joint moments across different studies.

Joint contact force was another parameter evaluated in this study. To our knowledge, no previous investigation has assessed this specific parameter in individuals with foot drop. It is known that patients with foot drop employ compensatory mechanisms to mitigate the effects of ankle joint muscle weakness during walking [17, 18]. It was hypothesized that these compensatory mechanisms might increase joint contact forces in other joints, such as the hip and knee. However, an intriguing finding was that the peak joint contact forces of the hip and knee joints were lower in foot drop subjects than in normal subjects. Only the hip joint exhibited increased shear force in the mediolateral direction, which might be attributed to the muscles stabilizing the hip joint and pelvis in the mediolateral plane (Table 5).

A key finding from the research was the significant increase in the peaks of joint contact forces at the ankle joint across all planes among foot drop patients. This increase could be attributed to the joint's instability and the need for muscular stabilization during ambulation. Therefore, based on the study's findings, it can be inferred that the ankle joint may be at a higher risk of osteoarthritis and pain due to an increase in joint contact forces [3] Stabilizing the ankle joint in this group of subjects might be necessary to decrease joint contact forces and prevent future complications. Clinicians treating patients with foot drop should consider evaluating joint contact forces as part of their assessment and planning targeted interventions to address forces causing excessive joint stress.

Some limitations to this study warrant consideration. The primary limitation is the lack of assessment of dynamic stability. Evaluating dynamic stability using innovative methods such as coordination could reveal the interrelation of joints, which would aid in predicting the risk of falls. Another limitation is that the study only analyzed one group of subjects with foot drop, classified based on walking speed. Lastly, the study was conducted in a controlled laboratory environment, which may not accurately reflect the real-world conditions and challenges encountered by individuals with foot drop. These factors should be taken into account when interpreting the study's findings.

Future research should strive to incorporate a larger and more diverse sample of subjects with foot drop. Subsequent studies are advised to measure dynamic stability in these patients. Including different foot drop patient groups, categorized by their walking speeds, could enable a more precise assessment. It is also suggested that future investigations be conducted in real-world settings to evaluate the impact of foot drop on daily activities and individuals' capacity to perform them. Researchers should also assess the influence of foot drop and its treatments on the overall quality of life, encompassing social and psychological aspects. Furthermore, this study's findings could prove beneficial in clinical trials aiming to compare the long-term effects of various therapeutic approaches on foot drop patients, particularly those that reduce the load on the ankle joint relative to other joints.

Conclusion

The study's findings indicate that individuals with foot drop show a significant reduction in walking speed. This reduction may be due to walking instability, muscle weakness, and an increased risk of falling. The study also revealed a significant decrease in moments of lower limb joints, predominantly in the sagittal plane. Moreover, the kinematics of the trunk and ankle joints differed in this group. It's important to note that the combined contact forces at the ankle joint significantly increased among these participants, indicating a key area to address during rehabilitation therapy. The results suggest that rehabilitation interventions focused on reducing the load on the ankle joint could play a vital role in restoring the functional mobility of individuals with foot drop.

Acknowledgment

This paper is derived from Mohammad Amin Vafaei's MD thesis (NO. 21390). It was approved and financially supported by the Vice-Chancellor of Research, Shiraz University of Medical Sciences, Shiraz, Iran. The ethics registration number is IR.SUMS.REC.1399.1202.

Source(s) of Support and Funding

This study received financial assistance from Shiraz University of Medical Sciences, reference number 21390.

Conflict of Interest: None declared.

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