FACULTY OF ENGINEERING AND ARCHITECTURE
DEPARTMENT OF BIOMEDICAL ENGINEERING

GAIT ANALYSIS OF LUMBAR DISC HERNIATION AND LUMBAR SPINAL STENOSIS USING WEARABLE MOTION CAPTURE TECHNOLOGIES

GRADUATION/DESIGN PROJECT

in partial fulfillment of the requirements for the degree of
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by

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submitted to the DEPARTMENT OF BIOMEDICAL ENGINEERING of
İZMİR KÂTİP ÇELEBİ UNIVERSITY

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ABSTRACT

Motion capture systems are systems where movements can be monitored and recorded in real time. These systems are optoelectronic, inertial measurement unit (IMU), electromagnetic, acoustic, mechanical motion capture systems. Optoelectronic systems use cameras to take measurements, inertial measuring systems use sensors, magnetic systems use electromagnetic waves, acoustic systems use ultrasonic sound waves, and mechanical systems use an exoskeleton containing angle measuring devices such as potentiometers or goniometers. Optoelectronic motion capture systems are the most sensitive and accurate among motion capture systems. However, the use of this system is limited because it is very expensive. IMU motion capture systems have recently come to the fore as an alternative system. This system has started to become wearable in order to be more useful. Rokoko Smartsuit Pro is one of the wearable affordable IMU sensor-based motion capture systems used in the film industry, animations. This technology, which has the advantages of IMU sensors, is thought to be suitable for determining the effects of lumbar spinal stenosis and lumbar disc herniation diseases on gait.

These diseases are the most common diseases in spine surgery. There is no quantitative method for the diagnosis of these diseases. In order to determine the effects on walking with a quantitative method, walking data were obtained from 5 healthy and 5 patient subjects. Then analysis was done and single support I, double support I, single support II, double support II, stance phase, swing phase and step time were determined for each subject. With the data obtained, it has been determined that the patients move more slowly and take smaller steps. It has been found that healthy subjects can lift their feet higher and take smoother steps. From these results it can be concluded that the Rokoko Smartsuit Pro wearable motion capture technology is suitable for the diagnosis of Lumbar Disc Herniation / Lumbar Spinal Stenosis disease. With this affordable technology, more accurate diagnoses can be made and better treatment procedures can be determined thanks to quantitative data.

Keywords: Motion capture technologies, Inertial measurement unit, IMU sensor, Rokoko Smartsuit Pro, Lumbar Spinal Stenosis, Lumbar Disc Herniation, Gait Analysis

ÖZET

Hareket yakalama sistemleri hareketlerin gerçek zamanlı olarak izlenebildiği ve kaydedilebildiği sistemlerdir. Bu sistemler optoelektronik, atalet ölçüm birimi (IMU), elektromanyetik, akustik, mekanik hareket yakalama sistemleridir. Optoelekronik sistemler ölçüm almak için kameraları, atalet ölçüm sistemleri sensörleri, manyetik sistemler elektromanyetik dalgaları, akustik sistemler ultrasonik ses dalgalarını ve mekanik sistemler potansiyometre ve gonyometre gibi açı ölçen cihazları içeren bir dış iskelet kullanır. Optoelektronik hareket yakalama sistemleri hareket yakalama sistemleri arasında en hassas ve en doğru sonucu veren sistemdir. Fakat bu sistemin çok pahalı olması nedeniyle kullanımı sınırlıdır. IMU hareket yakalama sistemleri alternatif sistem olarak son zamanlar öne çıkmaktadır. Bu sistem daha kullanışlı olması için giyilebilir hale gelmeye başlamıştır. Rokoko Smartsuit Pro, film endüstrisinde, animasyonlarda kullanılan giyilebilir uygun fiyatlı IMU sensör tabanlı hareket yakalama sistemlerinden biridir. IMU sensörlerinin avantajlarına sahip bu teknolojinin Lomber spinal stenoz ve lomber disk hernisi hastalıklarının yürüyüşe olan etkisinin belirlenmesi için uygun olacağı düşünülmüştür.

Bu hastalıklar omurga cerrahisinde en sık görülen hastalıklardır. Bu hastalıkların teşhisi için nicel bir yöntem bulunmamaktadır. Yürüyüşe olan etkilerinin nicel bir yöntemle belirlenebilmesi için 5 sağlıklı ve 5 hasta denekten yürüme verileri alınmıştır. Daha sonra analiz yapıldı ve her denek için tek destek I , çift destek I , tek destek II , çift destek II , duruş fazı , salınım fazı ve adım süresi belirlenmiştir. Elde edilen veriler ile hastaların daha yavaş hareket ettikleri ve daha küçük adımlar attıkları tespit edilmiştir. Sağlıklı deneklerin ise ayaklarını daha yukarı kaldırabildiği ve daha düzgün adımlar attıkları tespit edilmiştir. Bu sonuçlardan Rokoko Smartsuit Pro giyilebilir hareket yakalama teknolojisinin Lomber Disk Hernisi / Lomber spinal stenoz hastalığının teşhisi için uygun olduğu sonucuna varılabilir. Uygun fiyatlı bu teknoloji ile nicel veriler sayesinde daha doğru teşhisler yapılabilir ve daha iyi tedavi prosedürleri belirlenebilir.

Anahtar Kelimeler: Hareket yakalama teknolojileri, Ataletsel ölçüm birimi, IMU sensör, Rokoko Smartsuit Pro, Lomber Spinal Stenoz, Lomber Disk Fıtıklaşması, Yürüyüş Analizi

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ACRONYMS

IMU: Inertial Measurement Unit

MOCAP: Motion Capture

3D: Three Dimensional

2D: Two Dimensional

LSS: Lumbar Spinal Stenosis

LDH: Lumbar Disc Herniation

GPi: Gait Posture Index

ODI: Oswestry Disability Index

PSI: Patient Satisfaction Index

DOF: Degrees of Freedom

I. INTRODUCTION

MOCAP (Motion Capture) technology is a technology where movements can be monitored, recorded and processed in real time with different developed systems [1]. Generally, when motion capture technology is mentioned, applications in the film industry and video games come to mind [2]. However, motion capture technology is used not only in these areas but also in many different areas due to its versatility [1]. It was first used for military purposes in the mid-1970s. Helmet movements were magnetically displayed in order to enable military pilots to reach their targets. Later, in the 1980s, the gait of children was monitored by doctors and used for diagnostic purposes. Today, motion capture technology is used in many different areas. While it is mostly used in the entertainment and gaming industries, it is also used in the construction, robotics, automotive, sports, security, advertising and health sectors [2].

1.1. Motion Capture Systems

The use and development of motion capture technology in different industries over the years has led to the emergence of different techniques and systems. These techniques are optoelectronic, inertial measurement unit (IMU), electromagnetic, acoustic, mechanical motion capture systems.

1.1.1. Optoelectronic Motion Capture System

Optoelectronic motion capture systems are based on a camera system. The number of cameras varies according to the purpose and application. Motion capture in these systems is based on the optical capture of interconnected and synchronized cameras, usually between 2 and 32. With these cameras, x, y and z coordinates of the same object are created by taking the x and y coordinates of an object from different angles and information such as position, angle, velocity and acceleration are obtained [3]. In other words, 2-dimensional images are combined with the coordinate information obtained from the cameras and 3-dimensional images are obtained. A minimum of 2 cameras is sufficient to obtain a 3 dimensions image, but it is recommended to use at least 3 cameras to obtain more reliable results [4].

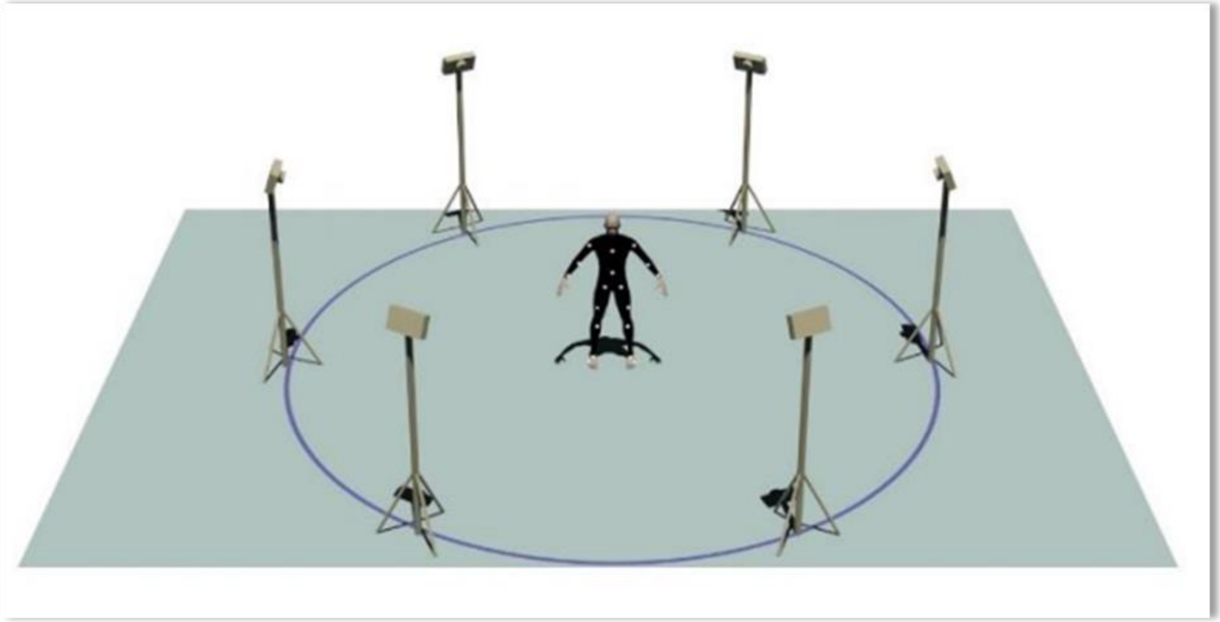


Figure I- 1 Example of optoelectronic motion capture system with 6 cameras [5]

Optoelectronic motion capture systems are divided into two: Marker systems and markerless systems. In systems with markers, markers are placed on body points that are key in describing the subject's movements [2]. Detection is similar to radar. Cameras often produce infrared light. These are reflected back to the cameras by the markers. Then, image formation takes place when the cameras detect the reflected light [3]. In these systems, 2 different markers are used. The first are passive markers that reflect light. The second are active markers that produce light. More accurate measurements can be made with systems containing active markers. The disadvantage of active markers is the limitations of the power source they have in order to produce light [5]. In markerless systems, motion is captured by computer algorithms [6]. In these systems, 3D position information is created as a result of the cameras comparing the patterns created by the infrared light with the reference pattern. While the accuracy rate of the systems with markers is higher, the mobility ability is higher in the systems without markers [5].

Optoelectronic systems are seen as the best technique among motion capture systems because they give the most accurate, clear and sensitive results [7]. However, there are many disadvantages that limit the use of these systems. To implement this system, laboratories with complex camera systems are required and the installation of the camera system is quite expensive. Since financial resources are limited in developing countries such as Turkey, the use of these systems is limited [8]. In addition, the slightest mistake in the locations, resolution and calibration of the cameras can cause false results. For the accuracy of the calibration, the locations of the cameras must be fixed. Therefore, the field of study in optoelectronic systems is limited. Another problem is the need for personnel with sufficient expertise and experience to implement this system (calibration, use, maintenance, etc.). The number and correct placement of markers affect the accuracy of the system [9]. The working mechanism of the optoelectronic system is based on the detection of the light emitted by the active and passive markers by the cameras [10]. If experiments are carried out in an open environment, there is a possibility that daylight may cause the cameras to misunderstand the light. Therefore, it is a disadvantage that measurements must be made indoors [9].

1.1.2. Inertial Measurement Unit (IMU) Motion Capture Systems

The inertial measurement system (IMU) is a system based on microelectro-mechanical systems technology [11]. Inertial measurement systems involve the use of IMU sensors. There are two main IMU sensors: Accelerometer and gyroscope [5]. Some systems have an additional magnetometer [12]. Generally, sensors with 3, 6, 9, and 10 degrees of freedom are used. As the degrees of freedom of the sensors increase, the sensitivity of the system also increases. Sensors are placed in specific anatomical regions of the moving subject. With the information obtained from the sensors, a solid model of the moving subject is created in computer programs. Movements can be tracked and analyzed [5]. With these systems, 3-dimensional position information, force and angular velocity can be measured [13]. The inertial measurement system is a lightweight, portable, low-cost and easy-to-implement system consisting of very small components [11]. There is no need for external cameras, a fixed infrastructure. Therefore, there are no lighting restrictions, no space restrictions. Total installation time is very short. This system is widely used for motion capture as it has many advantages. As the use of inertial sensors has increased over the years, the system has evolved into a wearable technology such as the Rokoko Smartsuit Pro for fast and convenient use of sensors and cables [12]. The disadvantage of these systems is the cumulative error generation. Integrating acceleration or angular velocity for position estimation can cause cumulative errors [14].

Figure I—2 Inertial Measurement Unit (IMU) Motion Capture System Sensor Layouts [12]

1.1.3. Electromagnetic Motion Capture Systems

Magnetic systems are based on magnetic field generation, electromagnetic waves [15]. Electromagnetic waves are produced by transmitting antennas with sensitive current pulses [14]. The position and orientation are determined by measuring the transfer time of electromagnetic waves between the receiver and the transmitter using receivers placed at certain points of the moving subject [5]. Magnetic systems are affordable. The precision and speed of the data is sufficient to capture simple movements [16]. There is no need for a specific field of view like optoelectronic systems [5]. The biggest disadvantage of these systems is that they are sensitive to magnetic fields such as mobile phones and metal parts [15]. Such objects may affect the signal, causing erroneous results [5]. The second major disadvantage is that the system contains a large number of cables. Cables greatly restrict freedom of movement during movement [16]. Other disadvantages include the increase in the amount of noise with increasing distance, the measurement area is not large, and the sampling frequency is low [5].

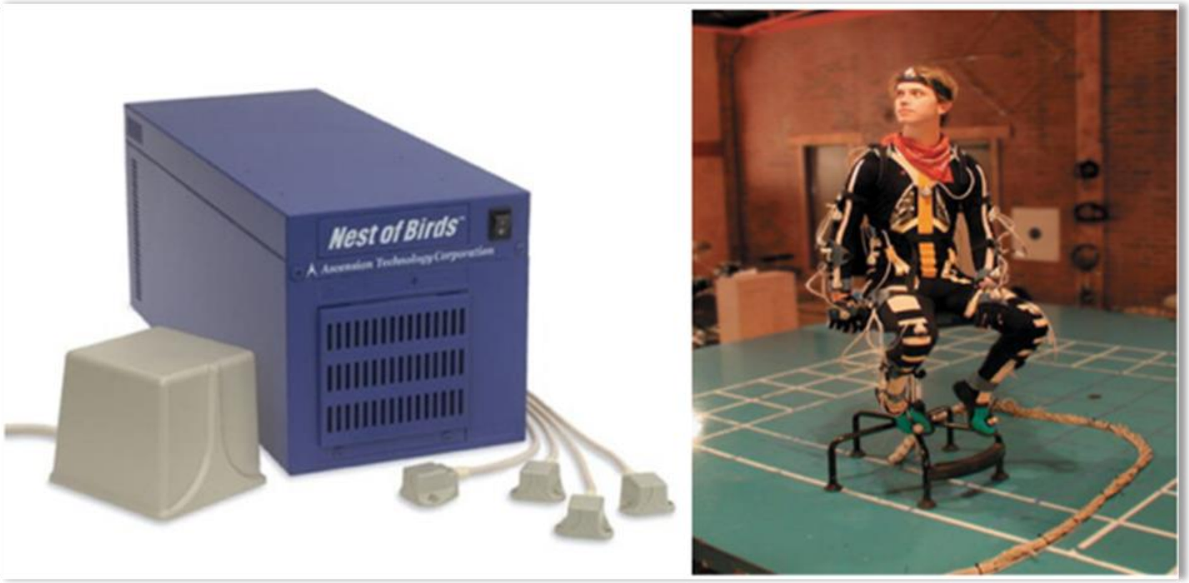


Figure I—3 Electromagnetic Motion Capture Systems [17]

1. 1. 4. Acoustic Motion Capture Systems

Ultrasonic sound waves are used to make measurements with acoustic systems [5]. Sound transmitters are placed at specific points on the moving subject. Sound receivers are placed in the capture zone. The working principle is based on the sequential activation of the transmitters and the receivers determining the positions of the transmitters using the intensity of the acoustic pulses [16]. The advantage of this system over other systems is that it is not affected by metallic and occlusive objects [5]. The most important disadvantage of this system is the sequential activation of transmitters and the difficulty of receiving data at a given moment due to non-fluid motion [16]. Secondly, it is sensitive to temperature, humidity, wind, sound reflections and external noise due to the use of frequency [14]. The accuracy of the system may be affected. The third disadvantage is the decrease in the mobility created by the cables [5]. The fourth disadvantage is that the quality is limited due to the limited quantity of transmitters [16].

1.1.5. Mechanical Motion Capture Systems

In mechanical systems, potentiometers or angle measuring goniometers are used [5]. The motion is measured by dressing the moving subject with an exoskeleton made of materials such as metal and plastic, which consists of parts that connect goniometers and potentiometers. The movements are converted into electrical signals and transferred to the computer [4]. Mechanical systems are underdeveloped systems. However, they are very advantageous because they are not affected by factors such as magnetic field, reflection, obstruction, and external forces [16]. Their cost is quite low [4]. The measurement is fast and it is a portable system. In addition to its advantages, there are also disadvantages such as limited freedom of movement due to the rigidity of the exoskeleton [14].

Figure I—4 Mechanical Motion Capture Systems [17]

When comparing all systems, optoelectronic systems are seen as the best technique because they give more accurate, clear and sensitive results [7]. Electromagnetic motion capture systems using electromagnetic sensors have lower sensitivity than optoelectronic systems. Another disadvantage of this system is that it is affected by magnetic materials. Magnetic materials can cause erroneous results. Therefore, the error rate of electromagnetic systems is higher than optoelectronic systems [14]. Ultrasonic sound waves are used in motion capture systems based on acoustic measurement [16]. Therefore, this system may not be able to measure accurately due to any sound reflection or noise [14]. Another system is mechanical motion capture systems [4]. The inability to perform natural movements in this system is a disadvantage [15]. Table I.1. shows a general comparison of motion capture systems.

Table I.1 Comparison of Different Motion Capture Systems

Systems	Accuracy	Compactness	Data Processing	Cost	Limitations
Optoelectronic - Marker based	Very high	Low	Inefficient	Very high	Camera obstructions
Optoelectronic - Markerless	Low	High	Inefficient	High	Camera obstructions, difficulties tracking bright or dark objects
IMU Systems	High	High	Efficient	Low	Drifts, battery life
Magnetic	Medium	High	Efficient	Low	Magnetic materials
Acoustic	Medium	Low	Efficient	Low	Occlusion
Mechanical	High	Low	Inefficient	High	Limited motion

Although optoelectronic systems are considered to be the best systems when comparing all systems, optoelectronic systems still have many disadvantages. In recent years, alternative methods to optoelectronic systems have been researched in order to overcome problems such as the optoelectronic system being too expensive, difficult to calibrate, space limitations, camera-related errors, and the need for expert personnel. Among these alternative methods, IMU motion capture systems are frequently encountered. It is known that most of the systems used in the industry today are IMU systems.

Smartsuit Pro, from Danish company Rokoko, is an example of affordable wearable IMU sensor based motion capture technology that doesn't need a marker. Smartsuit Pro is a system often used in the film industry, animations, art [8]. Since it has the advantages of inertial measurement systems, it is predicted that it will be beneficial to be used in health area apart from these sectors.Motion capture systems have many applications in the medical field such as diagnosis and treatment applications. For example, gait analysis [18] to diagnose movement disorders, gait analysis for clinical diagnosis of neurodegenerative diseases [11], monitoring of patient exercises for rehabilitation success and evaluation of accuracy of techniques [19], personalized internal body implants such as hip, knee, shoulder, wrist, etc. It is used in many applications such as biomechanical design [8], correction of body postures of disabled people [20], determining appropriate treatment methods before surgery [3], contributing to medical education [2], reducing health expenditures. Although motion capture systems are highly needed for medical applications, their use is limited. The high cost of optoelectronic systems, which is a very successful system and the best among other systems, and other reasons limit the use of this system. In the literature, there are applications of inertial measurement systems as an alternative to this system. Saba Bakhshi et al. developed a system with IMU sensors to measure the knee joint angle and compared with the “Vicon Motion System”, one of the optoelectronic motion capture systems. As a result of the comparison, it has been proven that the knee joint angle obtained from two separate systems is close to each other and that the IMU measurement system can be used [5]. Antonio I Cuesta-Vargas et al. compared inertial measurement systems with other systems and emphasized that inertial sensors are a reliable method to study human movement [6].

One of the areas where motion capture systems are used is spine surgery, which requires a large amount of cost and resources. Lumbar spinal stenosis and lumbar disc herniation are the most common spinal diseases [21].

1.2. Lumbar Spinal Stenosis and Lumbar Disc Herniation

The spinal cord contains a canal made up of vertebrae. This canal is called the spinal canal. With aging, changes occur in the human body such as water loss in the discs between the vertebrae, wear and tear of the cartilage tissue. As a result of these changes, narrowing of the spinal canal occurs. As a result of this narrowing, pressure occurs on the nerves and pain begins to occur. This condition, which is caused by the narrowing of the spinal canal, is called lumbar spinal stenosis. LSS is a spine disease mostly seen in people over 50 years of age [22, 23]. Symptoms such as back pain, leg pain, pain in the hip and anterior thigh region, loss of strength, limping, and decreased bladder control are generally seen in LSS patients [22, 23, 24, 25]. LSS causes serious losses in daily movement functions such as walking. Patients diagnosed with LSS can relax by bending their hips and legs slightly and leaning forward [24].

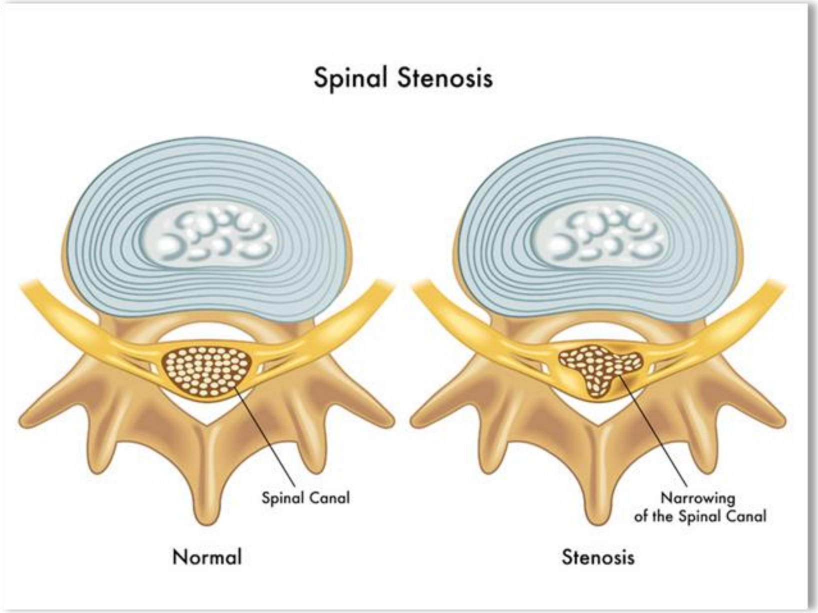


Figure I—5 Narrowing of the spinal canal in lumbar spinal stenosis [26]

While lumbar spinal stenosis is a disease mostly seen in elderly people, lumbar disc herniation is a disease mostly seen between 30-50 years of age [21, 25]. Lumbar disc herniation occurs at the L4-S1 level in 95% of cases [27]. LDH cases are usually seen in occupational groups that involve heavy lifting and heavy physical work. Excess weight, rotational strains on the spine are other factors that cause lumbar disc herniation [28]. LDH is usually manifested by back pain [27]. Leg pain, gait and posture disorders, and loss of activities of daily living are other symptoms [27, 29].

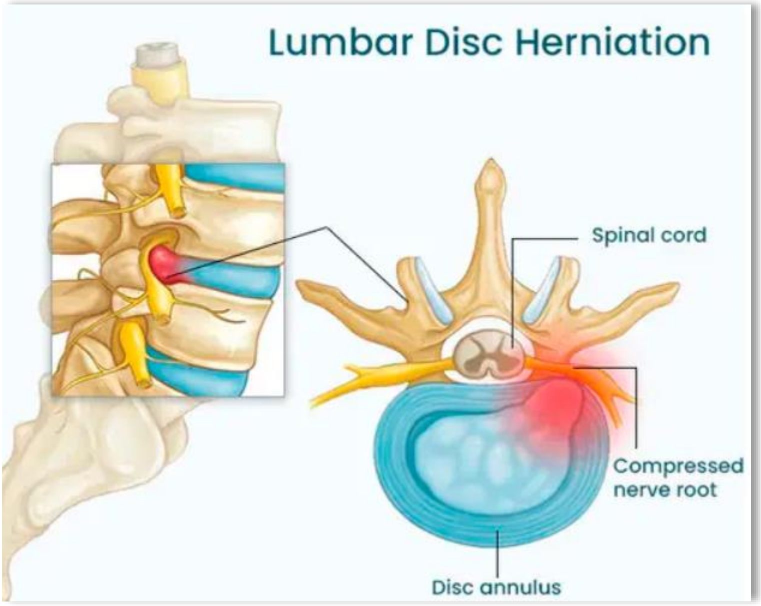


Figure I—6 Nerve compression in lumbar disc herniation [30]

There is not yet a universal, quantitative diagnostic method for the diagnosis of spinal diseases such as lumbar spinal stenosis and lumbar disc herniation. Disease assessment is made using qualitative methods such as the Oswestry Disability Index, the Roland Morris Disability Questionnaire, the 12-item Short Form Questionnaire, and the visual analog pain scale [21, 24]. In this way, qualitative methods may prevent accurate assessments due to psychological reasons and misidentifications [27]. Along with these methods, physical examination and methods such as magnetic resonance imaging are used [24]. However, there are often differences between the results obtained by qualitative methods and magnetic resonance imaging [25]. These difficulties in the diagnosis of the disease encourage the development of quantitative and objective methods. Specific, patient-specific, standardization methods are being investigated. A study using wearable accelerometers for quantitative evaluation in lumbar spinal surgery was published for the first time in 2016. The number of practices is increasing day by day [22]. In Table I.2, the systems, the characteristics of the subjects, the evaluated parameters, the experiments and the results are shown by giving examples from the articles in the literature.

Walking is a part of our daily life and the deterioration of the way we walk is related to diseases. People with different diseases have different gait characteristics [25]. Therefore, gait analysis has an important role in the evaluation of diseases. Quantitative gait analyzes are performed to detect gait deviations and gait difficulties with different gait parameters, to follow the progression of the disease and to determine treatment methods [31]. In this study, it is aimed to understand the effects of these diseases on gait functions by performing gait analysis in patients with lumbar disc herniation/lumbar spinal stenosis and healthy people. By using the wearable motion capture system Rokoko Smartsuit Pro, which is both an affordable and portable system, the research can be done easily and the evaluation of diseases is accelerated.

Table I.2 Literature review of studies with wearable motion capture systems on lumbar disc herniation disease

Study	System	Subjects	Features	Activities	Result
Ghent et al., 2020 [21]	Wearable wrist and chest-based accelerometer (smart watch) and observational recordings	24 patient subjects	Number of steps per day (with accelerometer), Walking speed (with accelerometer), Average stride length (with accelerometer), Walking posture (observational)	Preoperative (at least 1 week) and postoperative data (3 months) were obtained. The traditional Oswestry Disability Index was compared with the objective Gait Posture Index.	There is improvement in all parameters after the operation. There was a correlation between GPi and ODI with r=0.56, p=0.005.
AMIR RASHEDI BONAB et al., 2020 [31]	WIN-TRACK Gait Analysis Platform Visual Analog Scale to measure pain intensity	20 healthy subjects and 25 patients with Lumbar disc herniation and 25 patients with chronic mechanical low back pain, totally 50 patients	Pause time, swing time, double support time, long stride length, stride length, gait speed and cadence, stride time, gait cycle time, double stance time, gait cycle length.	Walking data from healthy and patient subjects correlated with pain intensity. The mean pain scores for the two diseases were compared.	Gait parameters were significantly decreased especially in LDH groups, LDH and CMLBP groups compared to the healthy control group ($p \geq 0.001$). Pain intensity was found to be negatively correlated with stride and stride length, cadence and speed ($p < 0.001$).

J.Mobbs et al., 2019 [32]	Wrist accelerometer, TracPatch	13 patient subjects	Number of steps walking speed stride length Stance	Patients were asked to walk 120 m if they could complete it, or 30 m. An algorithm was created to calculate the objective Gait Posture Index (GPi) with the values of pre- and postoperative gait parameters. The GPi was compared with the Oswestry Disability Index and the Patient Satisfaction Index.	A positive correlation was found between GPi and ODI. r=0.682, n=13, P=0.01 A negative correlation was found with the Patient Satisfaction Index. r=-0.618, n=13, P=0.024 A significant correlation was observed between GPI changes, ODI changes and PSI.
Betteridge et al., 2021 [33]	They compared the MetaMotionC device, a chest-based wearable sensor, and the inertial measurement unit python script with videography, a reference standard. MetaMotionC data was transferred to the IMU Gait application developed for the study, which used a modified version of the GaitPY program.	25 patients and 25 healthy subjects	Walking speed, stride length, stride length, cadence, stride duration, stride duration, gait symmetry	They were asked to walk at a comfortable pace between 5-120 m. The aim is to create a disease-specific anterior gait profile.	Patients have shorter, less frequent steps and higher asymmetry. There is over 90% compatibility between the MMC/IMUPY system and the videography system.
Perring et al., 2020 [24]	Manual calculations were made over the video recording.	15 patients and 15 healthy subjects	Cadence walking speed stride length step time	The aim is the functional evaluation of the intervention with quantitative gait analysis. Subjects were asked to walk at their normal speed in an area of 30 m with no obstacles.	Significant differences were found between healthy subjects and patient data. Differences in mean cadence, stride length, walking speed, and stride duration were -14%, -24%, -37%, and +16% between patients with LSS and healthy subjects, respectively.
Li et al., 2021 [25]	A portable smart device consisting of a recorder and five acceleration sensors has been developed.	49 elderly patients and 49 healthy subjects. Average age is 80.	Single brace, double brace, single brace/double brace, swing time, stride time, cycle time, pull acceleration, swing power, ground impact, foot drop, foot lift, push, speed, cadence, stride length data collected.	Subjects were asked to walk approximately 120 meters in a 30-meter field.	All patients have minor intermittent claudication. The duration of the single support increased significantly ($p < 0.05$). Compared to the control group, double support, stride duration, and pull acceleration increased ($p < 0.05$) and thrust,

					velocity, stride length, and stride length decreased ($p < 0.05$) in the experimental group.
Kuligowski et al., 2021 [29]	G-Walk wearable device	The number of patient subjects is 19, the number of healthy subjects is 24. (between 18-35 years old)	Symmetry index (%), walking cadence (steps/min), walking speed (m/s); three-dimensional pelvic symmetry: pelvic tilt index (%), pelvic oblique index (%), pelvic rotation index (%) were evaluated.	6 m walking test was done. Dynamic lumbopelvic and gait measurements were made.	The LDH group showed higher velocity ($p = 0.02$), lower symmetry of pelvic tilt ($p = 0.01$), and lower pelvis rotation ($p = 0.04$) compared to healthy controls. Correlation calculations showed significance between pelvis obliqueness and pelvis rotation ($r = 0.53$), but only in healthy controls. Lumbopelvic biomechanics show differences in the index of pelvis tilt and symmetry rotation parameters between LDH and healthy controls.
Loske et al., 2018 [34]	RehaGait system consisting of 7 inertial sensors	35 subjects were used, but 20 patients could be evaluated for various reasons.	Step duration, stride length, gait speed, cadence, gait phases for each leg Gait asymmetry: stance phase, swing phase, double brace, single brace	The aim of the study was to evaluate the functional outcomes after surgery. Data were obtained one day before surgery and 10 weeks and 12 months after surgery. Spatial-temporal parameters were evaluated during the traditional ODI and the 6-Minute Walk Test.	The data is ODI compliant. Improvement was observed in the patients 10 weeks after the operation. ODI decreased by 17.9% and 23.9% at 10 weeks and 12 months, respectively, and 6MWT increased by 21 m and 26 m, respectively. Gait quality remained unchanged. Mean gait asymmetry did not change at follow-up.

II. MATERIAL AND METHODS

Smartsuit Pro, owned by Rokoko company in Denmark, is an example of an affordable IMU sensor-based wearable motion capture technology that does not need a marker [35]. IMU motion sensors are 9 DOF (Degrees of Freedom) [36]. DOF refers to the number of independent parameters that determine the configuration or state [37]. The fact that the IMU sensors are 9 DOF occurs when each of the 3 different sensors inside can detect 3 DOFs. The accelerometer, gyroscope, and magnetometer each detect 3 DOF [38]. The IMU sensors are placed in a zippered suit made of nylon-derived durable fabric with adjustable straps for body type [35]. There are 19 IMU sensors inside the suit. The sensors are connected by cables and all connected to a hub located on the back of the suit. The sensors are placed at the joints. In the center where the sensors are connected, all data is collected, fused, and the data generated by joint movement is transferred to the computer via USB, Bluetooth, or WiFi.In connection with WiFi, the range is up to 100 meters and there is a delay of 15 ms. The WiFi network has two different bands, 2.4 GHz and 5 GHz [36]. While 5 GHz WiFi is faster, 2.4 GHz provides connection at longer ranges [39]. The frame rate is 200 fps. It captures 200 frames per second. The suit needs external power. The suit is energized using a power bank. There are some advantages to the use of the suit. The dress design is unisex and is available in different sizes such as S, M, L, and XL. Since the electronic parts are easily removable, the suit can be machine washed and cleaned easily [36].

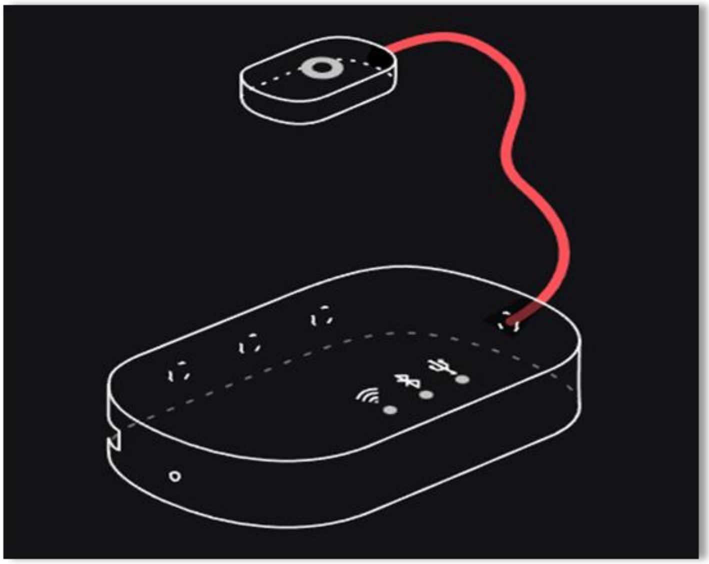


Figure II-1 The center at the back of the suit where the sensors are joined [36]

Figure II- 2 Rokoko Smartsuit Pro suit [40]

The data obtained with the sensors in the Smartsuit Pro are observed in the Rokoko Studio program. Rokoko Studio is a program exclusive to Smartsuit Pro. The motion is observed in real-time as a solid model [36]. With Rokoko Studio, motion can be monitored, recorded, and data can be exported for analysis. Data is exported in Microsoft Excel file format. Position information on the x, y, and z axes of the limbs and many data such as extension, flexion, adduction, and rotation can be accessed.

Figure II- 3 Rokoko Studio Interface [41]

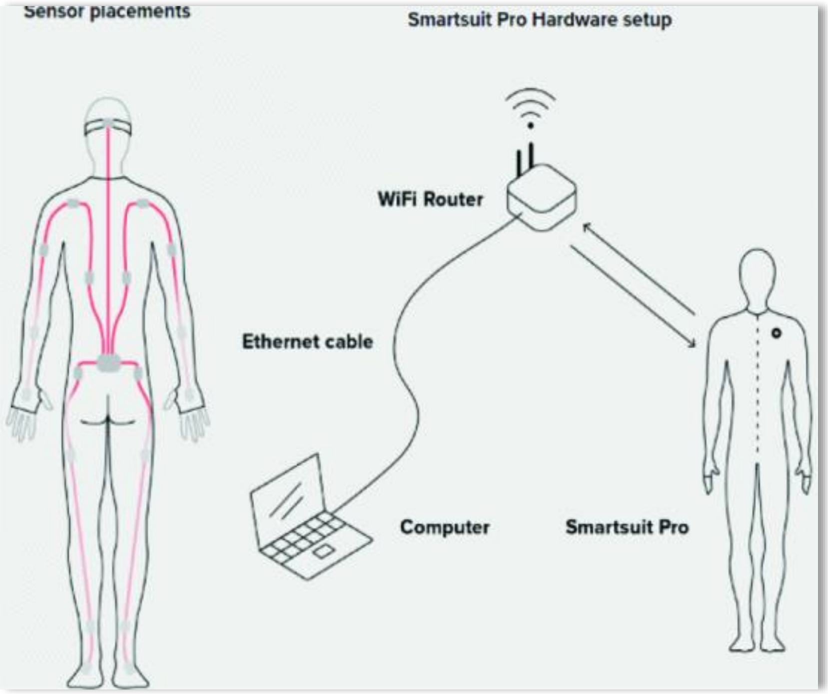


Figure II- 4 The layout of the sensors on the suit on the left and the system of the Smartsuit Pro on the right [8]

Smartsuit Pro is a system often used in the film industry, animations, and art [8]. Since it has the advantages of inertial measurement systems, it is predicted that it will be beneficial to use in medical area. One of these areas is gait analysis.

Gait analyzes are applications to evaluate the effects on the walking ability of people with diseases that affect the walking ability and to produce solutions to these assessments [42]. In this study, a total of 10 subjects, 5 patients with lumbar spinal stenosis or lumbar disc herniation disease affecting walking ability, and 5 healthy subjects, were used. Subjects were older than 18 years and voluntarily participated in the study. Healthy subjects do not have any neurological or musculoskeletal disease that can disrupt their normal gait. It aimed to determine the effects of diseases on individuals by comparing the data obtained from the patient subjects with the data obtained from the healthy subjects.

Data were collected with the Rokoko Smartsuit Pro with IMU sensor-based wearable motion capture technology. Rokoko Smartsuit Pro and computer connection provided via WiFi. The body measurements of the subjects were accurately measured and the values were entered in Rokoko Studio and a solid model of the subjects was created. The body measurements of the subject were entered into the Rokoko Studio. Initial exposure and initial position between body parts and sensors are unknown [43]. The first calibration was taken to determine the body dimensions and to make the alignment. It is also very important to calibrate before each recording to create the correct solid model in Rokoko Studio. For this reason, calibration was performed before each recording. Subjects were asked to walk at normal walking speeds in a specific area with no obstructions. Three separate recordings were taken of the subjects' daily walks.

The gait cycle includes the movements of the foot from the moment a foot touches the ground to the moment it touches the ground again. In other words, we can express the walking cycle as “one step”. The right or left foot is referenced for the gait cycle. The movements of the reference foot are evaluated. For this study, analyzes were performed using both the right foot as a reference and the left foot as a reference. The stance phase, in which the reference foot touches the ground, constitutes 60% of the duration of the gait cycle. The swing phase constitutes 40% of the gait cycle. In the swing phase, the reference foot is not in contact with the ground [42].

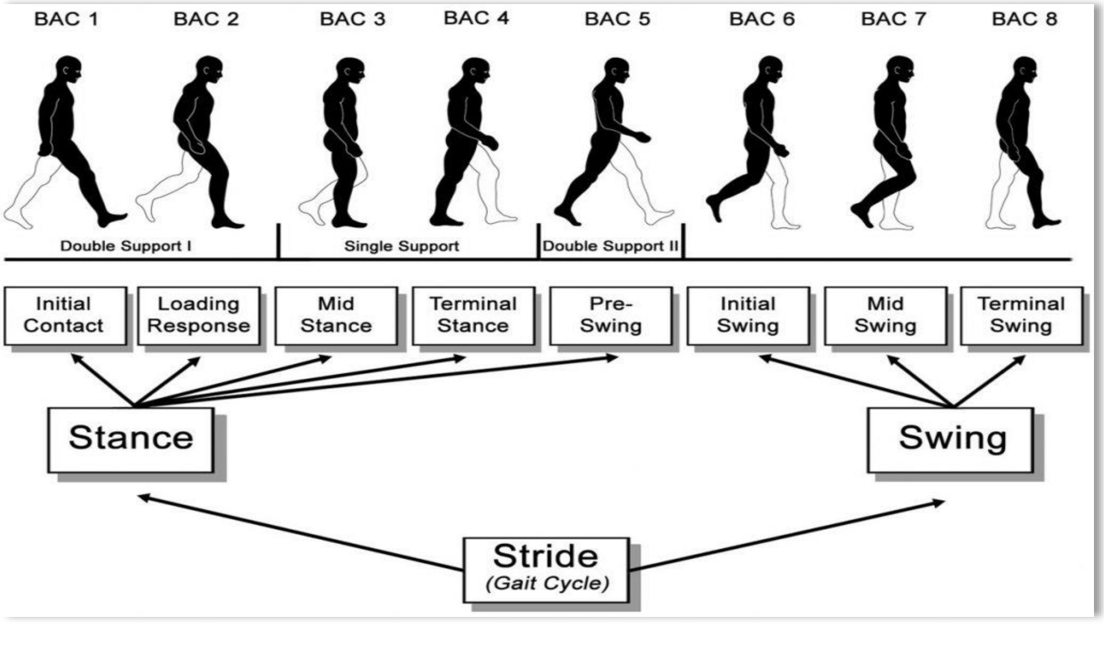


Figure II- 5 Phases of the Gait Cycle [44]

During the stance phase, the contact of the feet with the ground is evaluated in 2 ways: Single support and double support. Single support means that one foot is in contact with the ground. Double support means that both feet are in contact with the ground [42].

2.1. Statistical analysis

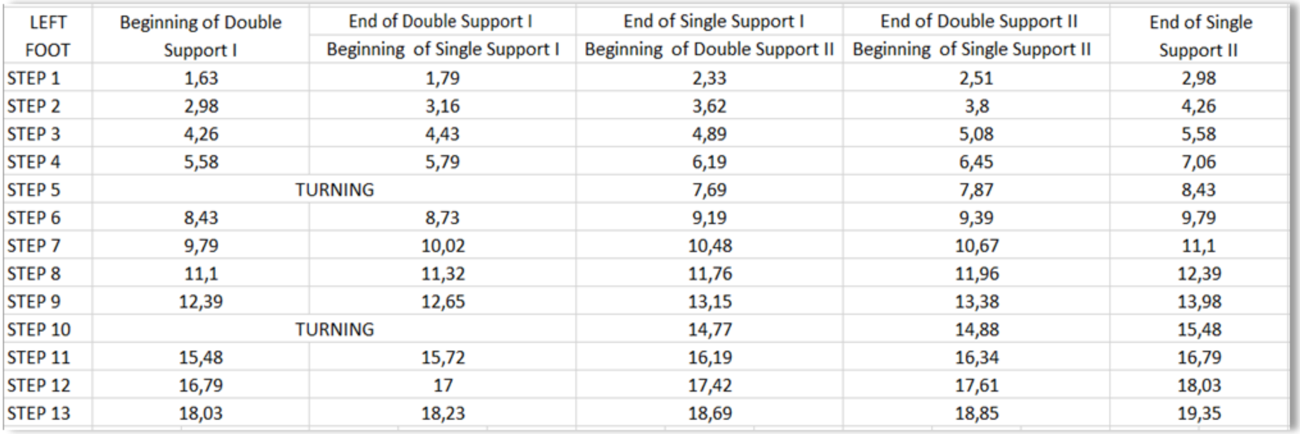
Data collected from subjects with Rokoko Smartsuit Pro were recorded in Rokoko Smartsuit Studio program. Then, these motion data were analyzed one by one. Gait cycle parameters of patient and healthy subjects were examined. Right and left foot data were analyzed separately. In the data examined with reference to the right foot, the step starts with the heel of the right foot touching the ground. The time between the heel of the right foot touching the ground and the contact of the left foot with the ground is the double support I period. The time from the moment the left foot stops contacting the ground until the left foot touches the ground is the single support I period. The period from the moment the left foot touches the ground to the moment when the right foot stops contacting the ground is the double support II period. The time elapsed from the moment the right foot stops contacting the ground until the right heel touches the ground again is the single support II period. The sum of these times is equivalent to one step time. In addition to these parameters, the duration of the stance phase, which is the sum of the times that the reference foot touches the ground, and the duration of the swing phase, which is the sum of the times that the reference foot does not contact the ground, were recorded. The same operations were performed with reference to the left foot.

Single support I time, double support I time, single support II time, double support II time, stance phase time, swing phase time and step time were determined for 10 subjects by taking the left foot as a reference and the right foot as a reference. A comparison was made between the obtained data and healthy subjects and patient subjects, and the effect of lumbar spinal stenosis or lumbar disc herniation on gait was evaluated.

III. RESULTS

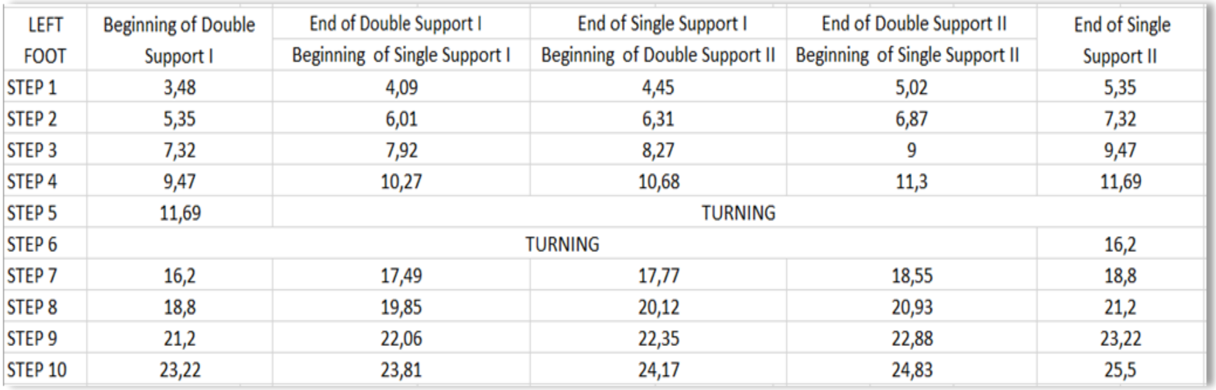
Separate analyzes were performed for each subject using data collected with the Rokoko Smartsuit Pro from 5 patients and 5 healthy subjects. Double support I start and end time, single support I start and end time, double support II start and end time, single support II start and end time were determined during the walks of the subjects. Table III.1 shows the start and end times of the gait cycle parameters with reference to the left foot of a healthy subject. Table III.2 shows the start and end times of the gait cycle parameters with reference to the left foot of a patient subject. Then, using these data, single support I time, double support I time, single support II time, double support II time, stance phase time, swing phase time and step time were calculated. Table III.3 shows analysis result with reference to the left foot of the same healthy subject. Table III.4 shows analysis result with reference to the left foot of the same patient subject.

Table III.1 The start and end times of the gait cycle parameters obtained with reference to the left foot of a healthy subject



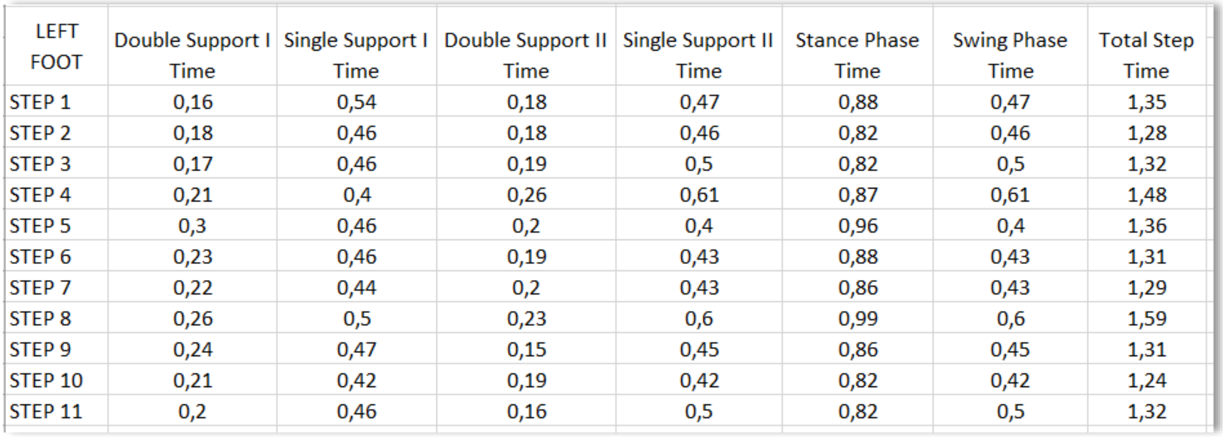
LEFT FOOT	Beginning of Double Support I	End of Double Support I	End of Single Support I	End of Double Support II	End of Single Support II
		Beginning of Single Support I	Beginning of Double Support II	Beginning of Single Support II	
STEP 1	1,63	1,79	2,33	2,51	2,98
STEP 2	2,98	3,16	3,62	3,8	4,26
STEP 3	4,26	4,43	4,89	5,08	5,58
STEP 4	5,58	5,79	6,19	6,45	7,06
STEP 5	TURNING		7,69	7,87	8,43
STEP 6	8,43	8,73	9,19	9,39	9,79
STEP 7	9,79	10,02	10,48	10,67	11,1
STEP 8	11,1	11,32	11,76	11,96	12,39
STEP 9	12,39	12,65	13,15	13,38	13,98
STEP 10	TURNING		14,77	14,88	15,48
STEP 11	15,48	15,72	16,19	16,34	16,79
STEP 12	16,79	17	17,42	17,61	18,03
STEP 13	18,03	18,23	18,69	18,85	19,35

Table III.2 The start and end times of the gait cycle parameters obtained with reference to the left foot of a patient subject



LEFT FOOT	Beginning of Double Support I	End of Double Support I Beginning of Single Support I	End of Single Support I Beginning of Double Support II	End of Double Support II Beginning of Single Support II	End of Single Support II
STEP 1	3,48	4,09	4,45	5,02	5,35
STEP 2	5,35	6,01	6,31	6,87	7,32
STEP 3	7,32	7,92	8,27	9	9,47
STEP 4	9,47	10,27	10,68	11,3	11,69
STEP 5	11,69	TURNING			
STEP 6	TURNING				16,2
STEP 7	16,2	17,49	17,77	18,55	18,8
STEP 8	18,8	19,85	20,12	20,93	21,2
STEP 9	21,2	22,06	22,35	22,88	23,22
STEP 10	23,22	23,81	24,17	24,83	25,5

Table III.3 Analysis result obtained with reference to the left foot of the healthy subject



LEFT FOOT	Double Support I Time	Single Support I Time	Double Support II Time	Single Support II Time	Stance Phase Time	Swing Phase Time	Total Step Time
STEP 1	0,16	0,54	0,18	0,47	0,88	0,47	1,35
STEP 2	0,18	0,46	0,18	0,46	0,82	0,46	1,28
STEP 3	0,17	0,46	0,19	0,5	0,82	0,5	1,32
STEP 4	0,21	0,4	0,26	0,61	0,87	0,61	1,48
STEP 5	0,3	0,46	0,2	0,4	0,96	0,4	1,36
STEP 6	0,23	0,46	0,19	0,43	0,88	0,43	1,31
STEP 7	0,22	0,44	0,2	0,43	0,86	0,43	1,29
STEP 8	0,26	0,5	0,23	0,6	0,99	0,6	1,59
STEP 9	0,24	0,47	0,15	0,45	0,86	0,45	1,31
STEP 10	0,21	0,42	0,19	0,42	0,82	0,42	1,24
STEP 11	0,2	0,46	0,16	0,5	0,82	0,5	1,32

Table III.4 Analysis result obtained with reference to the left foot of the patient subject

LEFT FOOT	Double Support I Time	Single Support I Time	Double Support II Time	Single Support II Time	Stance Phase Time	Swing Phase Time	Total Step Time
STEP 1	0,61	0,36	0,57	0,33	1,54	0,33	1,87
STEP 2	0,66	0,3	0,56	0,45	1,52	0,45	1,97
STEP 3	0,6	0,35	0,73	0,47	1,68	0,47	2,15
STEP 4	0,8	0,41	0,62	0,39	1,83	0,39	2,22
STEP 5	1,29	0,28	0,78	0,25	2,35	0,25	2,6
STEP 6	1,05	0,27	0,81	0,27	2,13	0,27	2,4
STEP 7	0,86	0,29	0,53	0,34	1,68	0,34	2,02
STEP 8	0,59	0,36	0,66	0,67	1,61	0,67	2,28

After finding the results for each subject separately, the mean values were found with the data of all healthy subjects and all patient subjects in order to be able to compare. Table III.5 shows the mean values. The differences between patient and healthy subjects are clearly visible. Double Support I, Double Support II, Stance Phase, Step Duration times of the patients are considerably longer than the healthy subjects. Patients move more slowly. Single Support I, Single Support II and Swing Phase times are longer in patients but close to the results obtained from healthy subjects. When patients move their feet forward, they can progress less slowly in distance. Healthy subjects were able to move faster and move their feet further. These values were close due to the fact that the patients moved more slowly and the healthy subjects could go further in terms of distance. When Table 1 and Table 2 are compared, it is seen that the return times of the patients are much longer than the healthy subjects. Again, when a comparison is made between Table 1 and Table 2, it is seen that the number of steps is less although the patient was recorded for a longer time than the subject. Patients take longer step times in less distance.

Table III.5 Comparison of gait parameters in healthy and patient subjects

Gait Parameters	Patient Subject	Healthy Subject
Double Support I, seconds	0,58	0,16
Single Support I, seconds	0,49	0,43
Double Support II, seconds	0,52	0,18
Single Support II, seconds	0,400964	0,40
Stance Phase, seconds	1,59	0,76
Swing Phase, seconds	0,400964	0,399286
Step Duration, seconds	1,99	1,16

During the analysis, the differences between healthy subjects and patient subjects were clearly seen. Figure II-1 shows the single support stance of a healthy subject and Figure II-2 shows the single support stance of the patient subject. While healthy subjects can lift their feet higher, sick subjects can lift their feet less. Some patients could not lift their feet at all and moved them by rubbing. Some patients were not able to perform all of the gait cycle parameters properly. They moved on to a new step before all parameters were completed. Some patients could not move straight because their legs were shaking, and they moved their legs to the side.

Figure III-1 The single support stance of the healthy subject

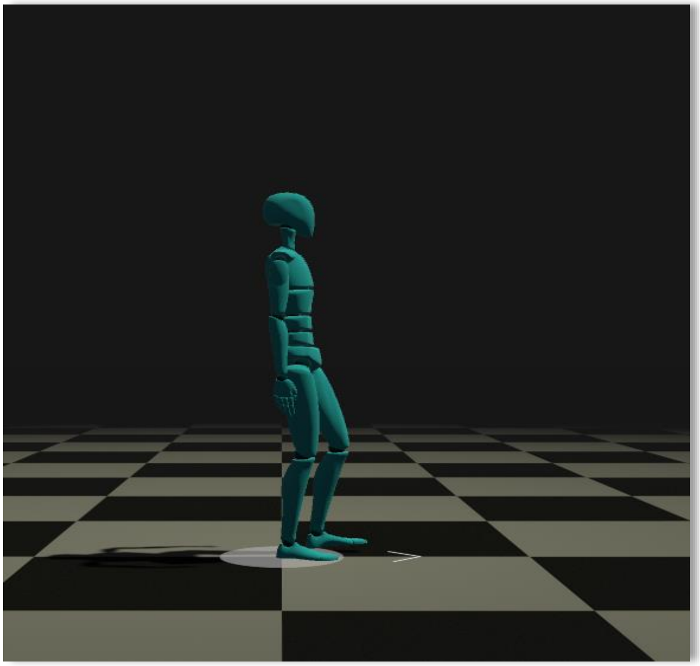


Figure III-2 The single support stance of the patient subject

IV. DISCUSSION

The aim of this study was to quantitatively demonstrate the effect of Lumbar Disc Herniation / Lumbar Spinal Stenosis disease on gait with Rokoko Smartsuit Pro, an affordable and convenient IMU sensor-based wearable motion capture system. There is a need to develop an affordable and practical quantitative method for diagnosing these diseases. For this purpose, in this study, differences in gait cycle parameters of patients with Lumbar Disc Herniation / Lumbar Spinal Stenosis and healthy subjects were demonstrated. The average duration of double support I of the patient subjects was 0.58, while the average duration of the healthy subjects was 0.16 seconds. While the average duration of single support I of the patient subjects is 0.49, the average duration of the healthy subjects is 0.43 seconds. While the average duration of double support II of the patient subjects was 0.52, the average duration of the healthy subjects was 0.18 seconds. While the average duration of single support II duration of patient subjects is 0.40964, the average duration of healthy subjects is 0.40 seconds. The mean durations of the stance phase, swing phase, and step of the patient subjects were 1.59, 0.40964, and 1.99, respectively, while the average durations of the healthy subjects were 0.76, 0.399286, and 1.16 seconds, respectively. These results show that patients are slower than healthy subjects. Patients take smaller steps and have longer turnaround times. During the analysis, it was determined that the healthy subjects lifted their feet higher and took more correct steps than the patient subjects. The results obtained are consistent with the results obtained in other studies in the literature. From these results it can be concluded that the Rokoko Smartsuit Pro wearable motion capture technology is suitable for the diagnosis of Lumbar Disc Herniation / Lumbar Spinal Stenosis disease.

The strength of this study is that an affordable quantitative system has been developed to show the effects of diseases on gait. This system can be useful for efficient planning of rehabilitation programs and optimization of treatment. The limitation of this study is the problems arising from ferromagnetic materials. Such materials should be avoided. Another limitation is that the subjects make their gait more consciously and the naturalness of the gait may be lost. In order to better understand the trends in gait cycle deterioration, this study needs to be done with more subjects. More parameters such as angle change, walking speed, cadence and acceleration should be examined.

V. CONCLUSION

This study shows that the effect of Lumbar Disc Herniation and Lumbar Spinal Stenosis diseases on gait can be quantitatively determined with the IMU sensor-based wearable motion capture technology Rokoko Smartsuit Pro. Significant changes in gait parameters were quantitatively demonstrated by comparison between patient and healthy subjects. The results of the study may be valuable for an objective approach in clinical evaluations in the future. It can be used to identify more accurate diagnoses and better treatment procedures.

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