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GAIT CYCLE ANALYSIS IN RHEUMATOID ARTHRITIS

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Abstract Rheumatoid arthritis is a chronic systemic inflammatory disease that affects synovial joints. The Joint pain, swelling, and reduced mobility lead to decreased quality of life. This disease is caused by autoimmune processes that result in inflammation. We understand that the accurate diagnosis is essential for effective treatment. Our present study evaluates the use of motion laboratory methods for early detection of rheumatoid arthritis and the assessment of a personalized movement therapy. We perform gait analysis under assisted and non assisted conditions to obtain objective biomechanical data. Our results indicate that non assisted walks lead to a longer and more natural gait cycle. Furthermore, the stability of the body center of gravity improves and the joint motion becomes more balanced with reduced asymmetry. These changes indicate better coordination and functional mobility. In addition, our motion laboratory analysis provides objective data to monitor disease progression and treatment outcomes. Our findings support the role of independent movement in rehabilitation and contribute to improved treatment strategies and quality of life.

Key words: Rheumatoid arthritis, joint angles, staff gait cycles, Centre of Gravity, biomechanics, kinematics, motion laboratory, early diagnosis, disease monitoring, movement therapy, rehabilitation, joint function, medical informatics.

AMS Mathematics Subject Classification: 92C10, 92C50, 65D10.

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1 Introduction

Rheumatoid arthritis is defined as a chronic inflammatory disease that affects synovial joints. This disease had been intoruced 1800 by Augustin Jacob Landre-Beauvais and later the term was coined and documented by Alfred Baring Garrod [1, 11]. This disease is considered as an autoimmune condition in which the immune system attacks joint structures which causes inflammation and cartilage damage. The disease generaly is chronic and often causes pain with reduced mobility. These symptoms lead to functional limitations and lowers the quality of life [2]. Gait analysis provides objective assessment of human movement. With gait analysis we can measure the patients' walk patterns, their joint motion, and overall functions [3]. In rheumatoid arthritis, patients show reduced speed, cadence, and stride length compared to healthy individuals [4]. The increased double support time and reduced single support time indicate compensatory strategies for instability and pain [5]. Daily variation in gait is reported, with improvement later in the day as stiffness decreases [6]. Joint motion at the hip, knee, and ankle is reduced, and joint moments are lower, reflecting impaired mechanical function [7]. Foot involvement alters plantar pressure distribution, particularly in the forefoot, and disease progression can lead to inefficient gait patterns [6]. Advanced tools such as three dimensional motion analysis systems and smartphone applications allow detailed measurement of spatiotemporal and kinematic parameters [7]. The Gait Deviation Index quantifies overall gait abnormalities [8]. Cluster analysis methods classify gait patterns according to disease severity [9]. These tools provide objective data for clinical evaluation and treatment monitoring [10]. Despite these advances, limitations remain. Many assessments rely on subjective observation or simple functional tests. Comprehensive analysis of the full gait cycle in controlled motion capture environments is limited. Daily variability in gait further complicates standardised assessment [4, 11]. Integrated evaluation of foot involvement within the complete gait cycle is insufficient which limits accurate monitoring of disease progression and therapeutic effects. Advanced computational approaches are not yet widely applied in clinical practice. Motion laboratory technologies allow precise and objective measurement of movement, joint angles, and forces in the gait cycle. These systems provide quantitative data that support early detection of abnormalities of disease progression [12]. They improve evaluation of treatments, through medications, orthotic devices, and sometimes the rehabilitation programs. In addition the cognitive infocommunication methods add the ability to process motion data and visualise movement patterns. Digital representations, such as avatars, allow detailed analysis of patient specific gait [13, 14]. Similar approaches show benefits in coordination training and rehabilitation. Consequently, we analyse gait cycle parameters in patients with rheumatoid arthritis through motion laboratory methods. The full gait cycle is assessed, with emphasis on joint and foot impairments. The study addresses gaps in motion capture based analysis and supports early detection and targeted rehabilitation. The results improve our knowledge of gait changes and aid the development of effective clinical and therapeutic strategies.

2 Materials and Methods

A. Hypothesis

In this study we aim to examine rheumatoid arthritis from a medical and biomechanical perspective. The disease causes chronic inflammation, joint damage, altered load distribution, and impaired movement. These effects reduce gait stability, coordination, and functional mobility. In our study the main hypothesis is that the structured movement therapy and assistive devices improve gait parameters. A secondary hypothesis is that a walking stick reduces joint load and improves gait symmetry and stability. The quantitative gait analysis is performed under controlled conditions. We aimed at measurements that are taken with and without a walk stick. The study also evaluates the effects of a structured therapeutic program on gait and posture over time. Objective biomechanical parameters are used to assess treatment related changes.

B. Eurythmy Therapy

Eurythmy Therapy, or Therapeutic Eurythmy, is a movement based intervention from anthroposophic medicine. It is based on the connection between physical movement, emotional state, and cognitive processes. The therapy aims to support the interaction of body, mental state, and physiological regulation [15]. It consists of structured exercises often derived from speech and sound patterns. Movements are performed in a controlled and conscious manner to improve posture, coordination, balance, and internal regulation. The therapy is a mind body intervention that integrates physical activity with attention and perception processes [16]. It is used as an adjunct treatment to enhance general health, quality of life, and stress adaptation. Applications include pre surgical preparation and chronic conditions such as fatigue related disorders and attention deficit disorders, where improvements in concentration, motor control, and emotional regulation are reported [17]. Physiological studies indicate potential effects on autonomic regulation, including increased heart rate variability, which suggests improved sympathetic and parasympathetic balance. Structured exercises also enhance body awareness and controlled movement. Current evidence is limited and heterogeneous. Studies vary in design, sample size, and quality, and many rely on subjective outcomes. Further controlled and quantitative research is needed to clarify mechanisms and clinical effectiveness. In this study, Eurythmy Therapy is applied as a standardised intervention to improve gait and posture in patients with rheumatoid arthritis.

C. Subjects and Intervention Protocol

Participants with rheumatoid arthritis are enrolled in the study. All follow a structured Eurythmy Therapy program. Therapy sessions occur three times per week for four weeks. Each session consists of predefined exercises to targete posture, coordination, balance, and movement control. Participants are instructed to perform exercises at home between sessions. Compliance is monitored through self reports and therapist observations. Emphasis is placed on correct posture, controlled movement, and regular practice. Movement assessments are performed at baseline and after the intervention. Gait and posture are selected as primary outcomes. In the gait test, participants walk ten metres under standardised conditions. In the posture test, participants stand upright with feet together for two minutes. These assessments evaluate balance, stability, and motor control. Each participant completes twelve sessions. Data are collected in repeated measurement cycles, with three sets of ninety measurements recorded. To improve statistical robustness and address class imbalance, a synthetic dataset of six hundred cases is generated using the Synthetic Minority Over Sample Technique. This approach ensures more reliable statistical analysis and stable results.

D. Gait Analysis Protocol

Gait analysis is conducted under controlled laboratory conditions. Each participant completes trials with and without a walking stick. This allows direct comparison of the effect of the assistive device on gait. Full body motion is recorded during each trial. Analysis is based on time series of displacement functions. The gait cycle is divided into stance and swing phases. Each phase is analysed separately to identify phase specific changes. Temporal parameters include step duration, cadence, and support time. Spatial parameters include step length and stride length. Kinematic analysis is performed for the hip, knee, and ankle joints. Joint angles are measured in the sagittal, frontal, and transverse planes. Range of motion is calculated for each joint. This provides quantitative information on movement coordination, joint function, and symmetry. The method allows comparison of baseline and post intervention data. It also evaluates the biomechanical impact of when to use a walking stick.

E. Motion Analysis System and Data Processing

The motion analysis system includes a high performance computer and four digital video cameras. Each camera records at sixty hertz and captures front, back, and side views of the participant. The sampling frequency is fifty frames per second, and the shutter speed is one over two hundred fifty seconds. This setup provides a temporal resolution of 0.02 seconds for precise detection of movement phases. Video data are processed using the Goethe Gait Lab system. This system allows synchronised analysis from multiple views and extraction of kinematic variables. Movement trajectories, joint angles, and displacement functions are derived from the recordings. Statistical analysis is performed on a dedicated computer. Parametric and non parametric tests are applied according to data distribution. These include Student t test, paired t test, Mann Whitney test, and one way analysis of variance. Statistical significance is used to evaluate the effects of therapy and assistive device use on gait parameters.

3 Results

A. The normal gait

Human gait is the most common form of locomotion. It involves a change in the entire body's orientation. Gait is a movement, a cyclical behaviour, influenced by habits (body size, life functions), learning (in childhood and later), feelings, emotions (nervous system state), and other factors. Gait requires the coordinated work of many muscles, practically the whole body. The execution of these complex movements requires the appropriate development of the musculoskeletal system and the proper control of actions. Human gait is based on the authority and integrated functioning of the central nervous system and the complex work of the musculoskeletal system. The normal gait cycle consists of two main phases. The stance phase accounts for about 60% of the cycle and begins with heel contact and ends with toe off. Heel contact initiates the cycle, followed by full foot contact with the ground. Mid stance occurs when the opposite foot passes the supporting limb. This is followed by heel rise, when the heel lifts from the ground, and ends with toe off, when the foot leaves the surface. The swing phase accounts for about 40% of the cycle and begins after toe off. It starts with initial forward movement of the limb, continues with mid swing when the foot passes under the body, and ends with terminal swing, during which the muscles slow the limb in preparation for the next heel contact.

Considering the biomechanical efficiency of human walking, Human walking is considered a practical and efficient form of locomotion in which the centre of mass (CoM) of the body typically reaches a

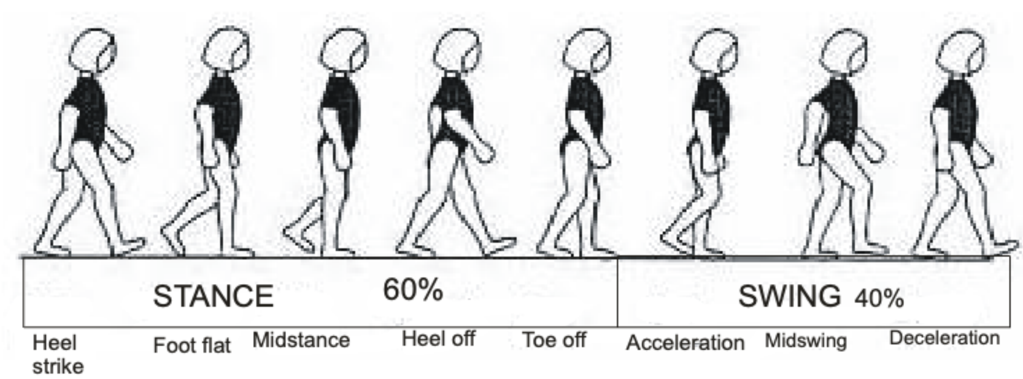

Figure 1: Normal gait cycle.

forward velocity in the sagittal plane of between 90 and 120 steps/minute, corresponding to a velocity of approximately 1.20–1.30 m/s. Minimising the spatial displacement of the centre of gravity is a fundamental requirement for biomechanical efficiency. Biomechanical stability and energy efficiency during movement are ensured by a healthy central nervous system, which continuously regulates the body's position and movement. As a result, the horizontal and vertical displacements of the centre of gravity are typically kept between 0 and 5 cm, while rotation about the transverse axis is minimised. This control mechanism is essential for maintaining balance, coordination of movement, and efficient progression.

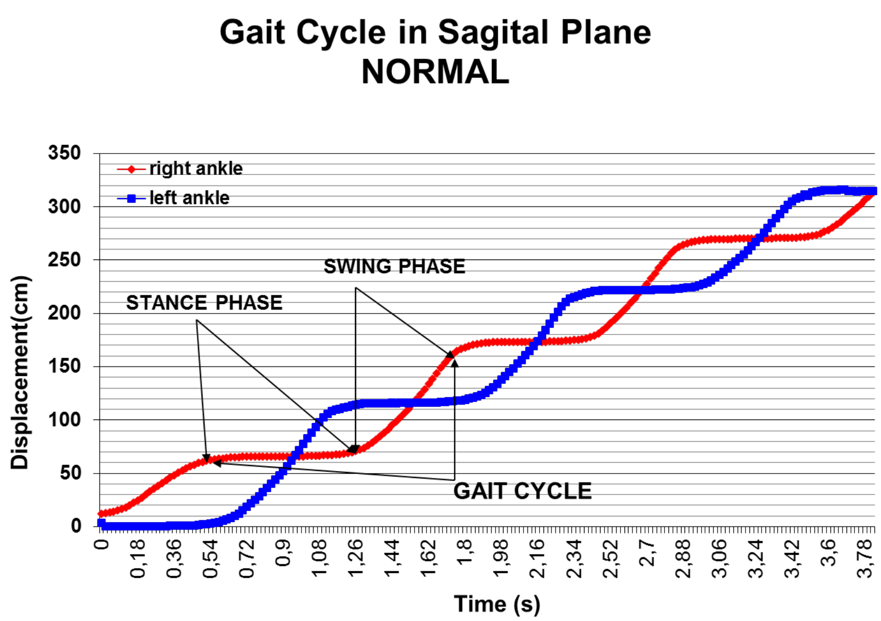

Figure 2: Data display: normal gait in the sagittal plane.

B. The Centre of Gravity (COG)

In the physical sciences, the centre of gravity of a system of many parts is the single point where the mass of the system is concentrated. The location of the COG depends on the group and the

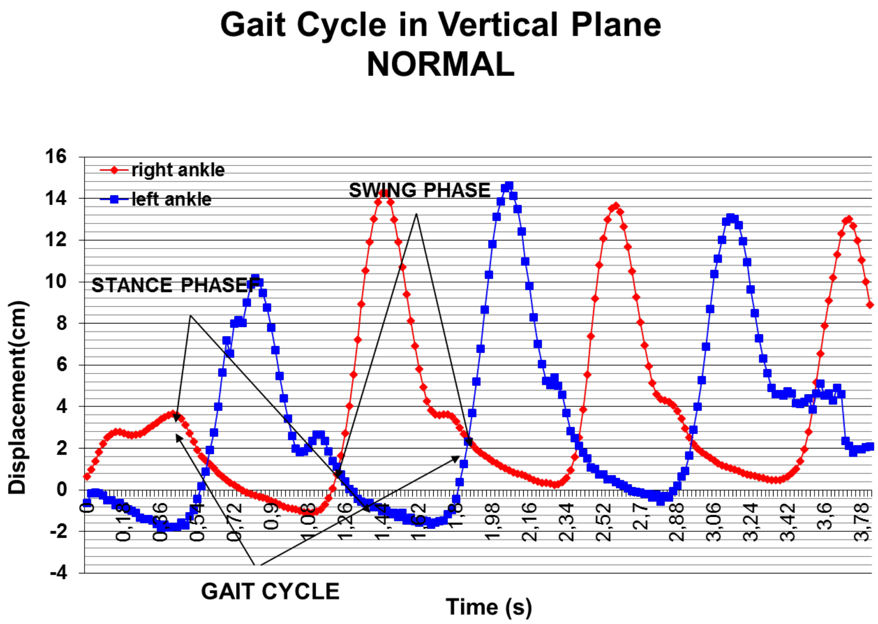

Figure 3: Data display: normal gait in the vertical plane.

displacement of the parts of the whole system. The COG of the parameters of the human body is calculated on the number of points at the local centre of gravity of each body segment. For my measurements, the calculation was performed automatically by software; however, these data were correlated with individual anthropometric data, as per Dempster (1955) and Vaughan (1992). The COG studies were necessary for two reasons. First, the displacement of the COG provides a wealth of information about the location and movement of the entire body, as these data were measured from the local COGs of the segments. However, it is essential to note that the COG properties (displacement, velocity, and acceleration) do not provide us with sufficient information. In the mechanical sciences, when studying the motion of an inert object, this data (e.g., the coordinates of the centre of mass) is sufficient. Yet, if the "object" is a living organism, this is not enough, because in this case, many control systems and mechanisms are involved. Consider that the amplitude of the COG in the vertical plane is 0–5 cm. When examining an inert object, a larger amplitude indicates more significant motion. It is also true when measuring the activity of a human body, but only in some instances. However, we choose to analyse the COG because it provides accurate information about the displacement of the whole body and the body's movement in open space (orientation). Exposure is a cardinal issue in the visually impaired group, and this is what therapists in Hungary use the COG for.

C. Rheumatoid Arthritis

Sagittal plane

The sagittal gait pattern of a person with rheumatoid arthritis shows significant deviations from the physiological norm. The patient in this study was unable to use the right lower limb properly biomechanically during the gait cycle. As a consequence, the movement pattern employed strong compensatory strategies, supported by the assistive personnel actively involved in executing the gait. From a gait mechanics point of view, this type of compensatory action cannot be considered as an accurate cyclical movement. Instead, the patient's movement followed a "pull and carry" pattern in which the right limb did not perform the typical phases of the gait cycle. Due to joint stiffness and a lack of coordination between the musculoskeletal system and the nervous system, the limb and trunk movements showed a disharmonious, biomechanically inefficient pattern. The gait cycle length was statistically significantly reduced ($p < 0.000$) compared to healthy controls, especially for the right

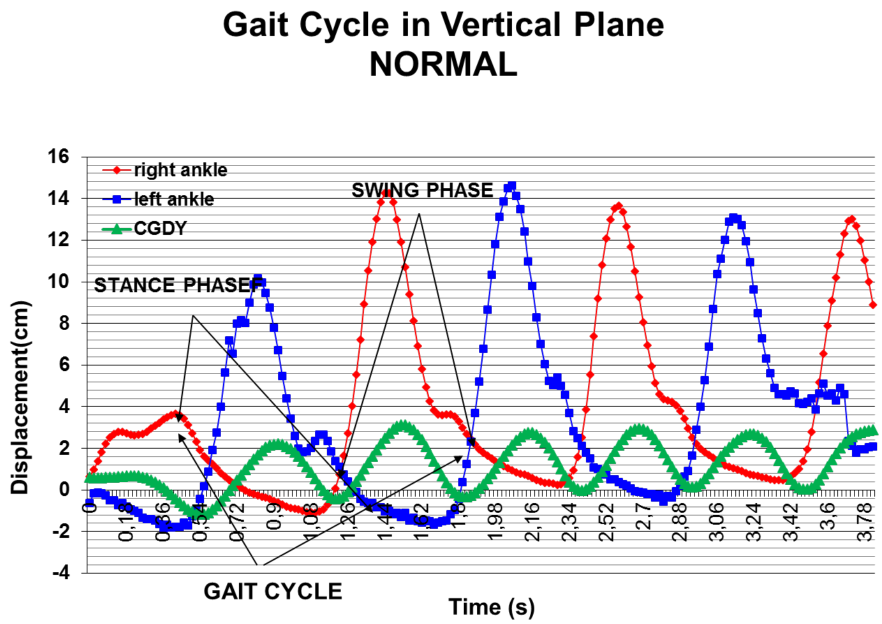

Figure 4: Data display: normal gait (centre of gravity) in the vertical plane.

limb. Gait was markedly asymmetric: the left limb compensated for the loss of function of the right limb, which showed significantly poorer function during both the stance and swing phases. These results suggest that biomechanical analysis of gait in RA, particularly in the sagittal plane, provides valuable insights into the extent of functional impairment and the compensatory strategies employed. Therefore, the use of detailed movement analysis is essential for rehabilitation planning.

In the second phase of the study, the patient's gait pattern was also analysed without a cane to assess the ability of the lower limbs to bear weight and coordinate independently in the absence of assistance. The results showed a significant improvement in gait parameters, particularly the length of the gait cycle, compared to walking with the assistive device ($p < 0.000$). It was observed that the right lower limb was able to cooperate with the left limb during the gait cycle, although asymmetry between the two sides persisted. Dynamic and kinetic parameters (e.g., centre of gravity acceleration, reaction forces, joint moments) showed an improving trend: these indicators were significantly close to the typical values of normal gait ($p < 0.05$). It suggests that unaided gait enhances lower limb cooperation and improves motor coordination, which may serve as a favourable baseline for rehabilitation. It is therefore helpful for the design of clinical interventions to assess gait in different conditions (e.g. with and without assistive devices).

At a later measurement time, the gait analysis was repeated after a specific movement therapy intervention had been administered. The results showed a significant improvement in balance control, especially in support phase stability and weight transfer dynamics. Gait cycle parameters, again without an assistive device, further converged to standard gait patterns, both kinematically and temporally. The symmetry of the cycle, joint range of motion and postural characteristics became more harmonious, indicating the positive effect of movement therapy on neuromuscular integration. The improved biomechanical coordination supports the role of individual physiotherapy in the functional rehabilitation of patients with rheumatoid arthritis, particularly when therapy is complemented by targeted exercises that do not require the use of assistive devices.

Vertical component of the gait cycle

As observed in the analysis plots, the parameters in the vertical plane of the gait are significantly weaker during the assisted gait than in the unaided, independent gait cycles ($p < 0.000$). No typical phases of the normal gait cycle are detected in the right lower limb: neither heel strike nor toe-off is

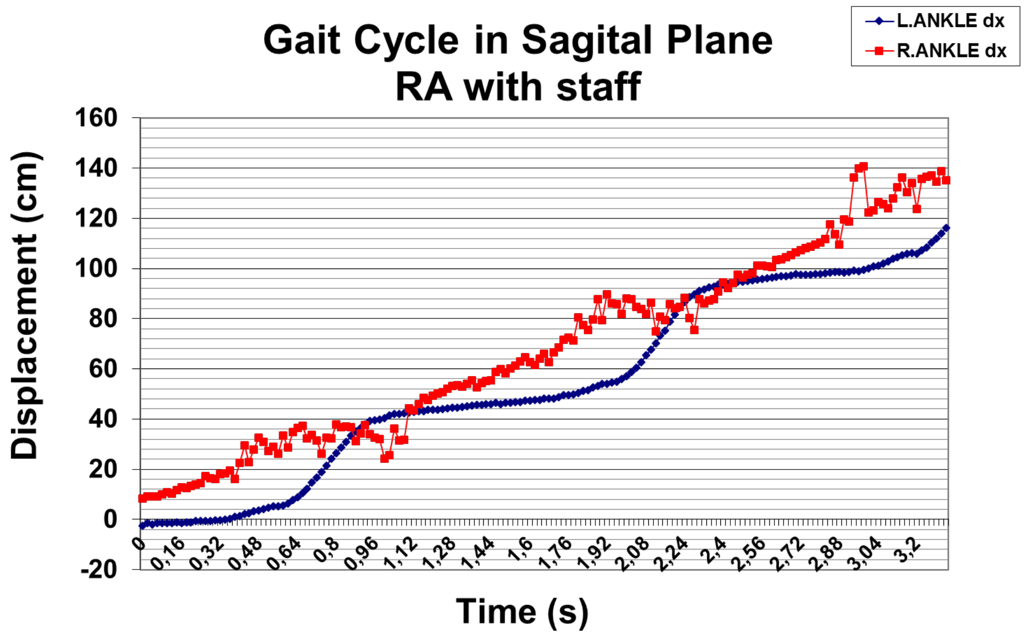

Figure 5: Gait cycle in the sagittal plane in RA with staff.

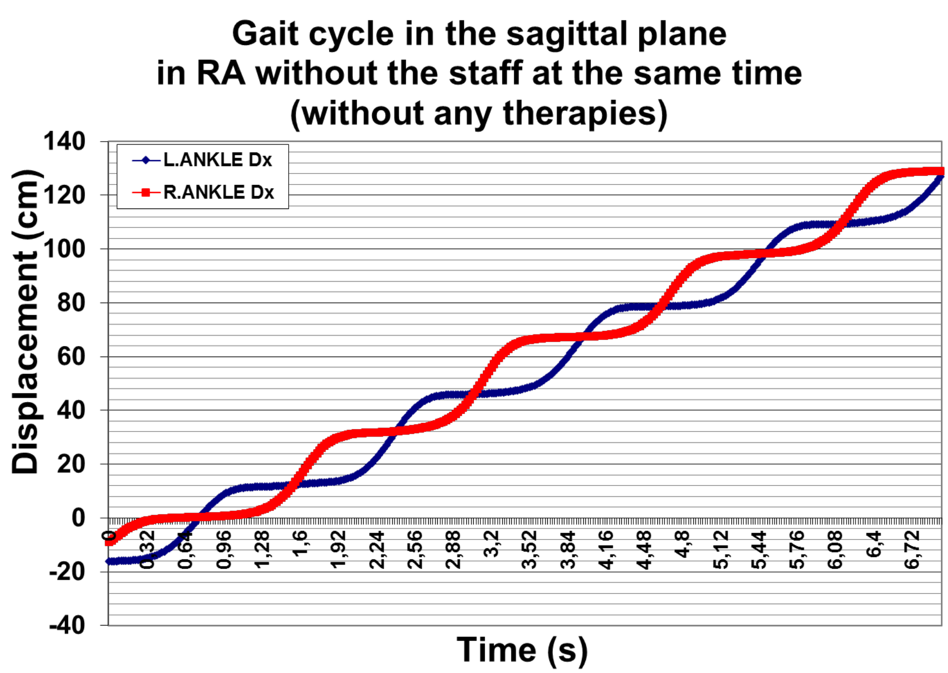

Figure 6: Gait cycle in the sagittal plane in RA without the staff at the same time without any therapies.

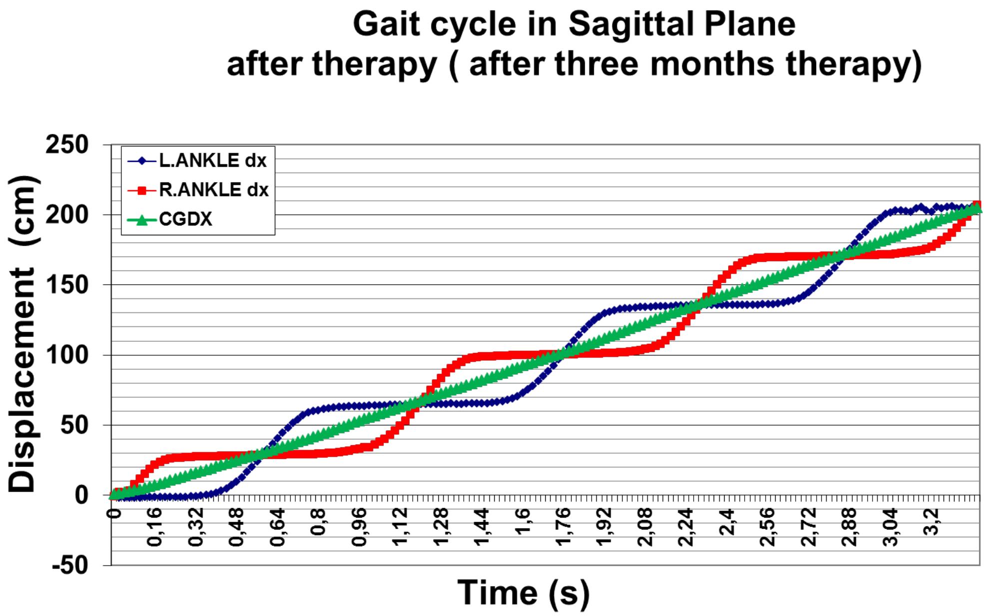

Figure 7: Gait cycle in sagittal plane after therapy after three months.

observed. The data should not be considered noisy or random; the different amplitudes are due to inappropriate muscle tone or inappropriate compensatory biomechanical use of the lower limb. These phenomena suggest that the patient's gait pattern is not only asymmetric but also that the cyclic structure is significantly impaired, especially on the right side, indicating a functional deficit and a movement coordination disorder.

Improving the quality of the gait cycle without assistive devices

During walking without a cane, the study's results showed that the gait cycle was reorganised and approached the physiological pattern. From the graphs, it is clearly observed that the phases of the cycle, including heel strike and foot strike, have been significantly reorganised. The amplitude of displacement of the lower limbs has stabilised at around 5 cm on both sides, indicating a reduction in the asymmetry previously observed. The positive changes documented are exclusively due to differences in "personal factors". The results open a new perspective on therapeutic approaches to rheumatoid arthritis in Hungary and the role of staff. The cases suggest that a patient in this functional state does not necessarily need the use of staff.

Examination of the displacement of the center of gravity in the sagittal and vertical planes

The analysis in the sagittal plane shows that the use of the stick did not significantly affect the displacement of the centre of gravity (COG) of the body. As a consequence, the global stability rate remained essentially unchanged between the two different test conditions. In contrast, without a stick, the COG displacement in the vertical plane was significantly reduced. This reduction in displacement indicates biomechanically enhanced balance and stability. The lower vertical COG position, analogous to the behaviour of flexible structures, increases the static and dynamic stability of the body, as the lower centre of gravity relative to the gravitational force makes the body less prone to buckling.

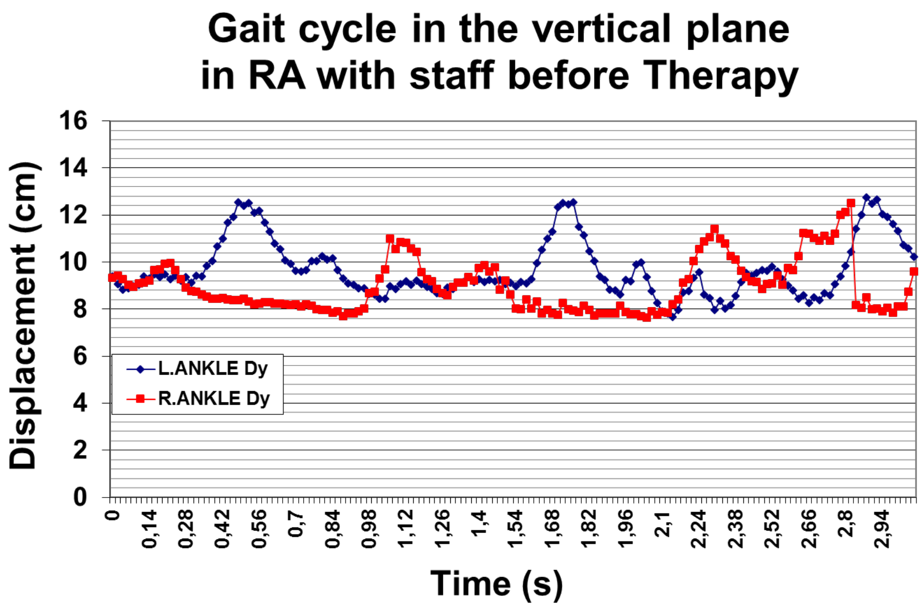

Figure 8: Gait cycle in the vertical plane in RA with staff.

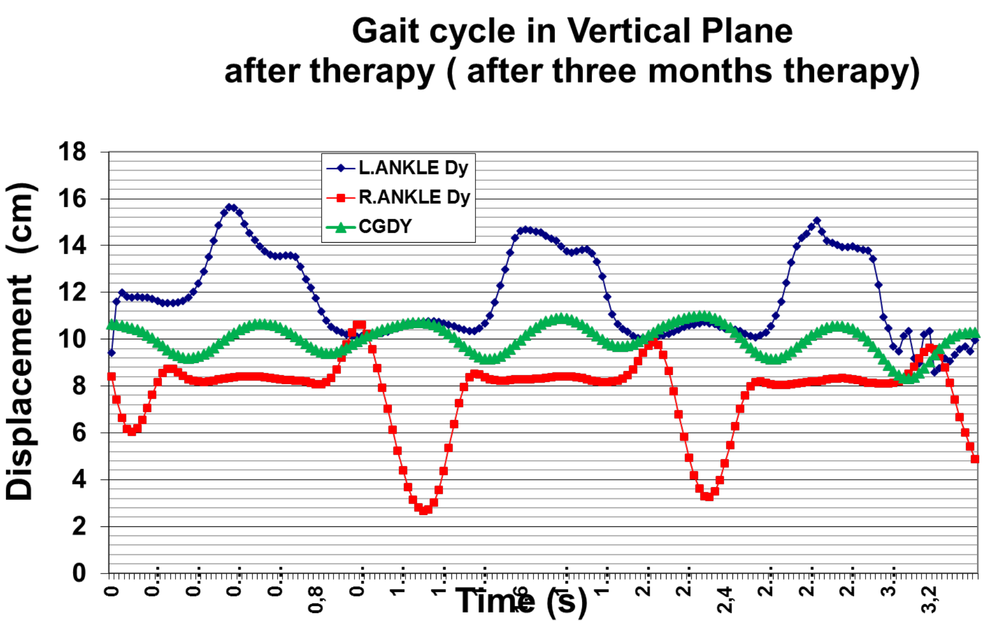

Figure 9: Gait cycle in the vertical plane in RA after therapy without staff.

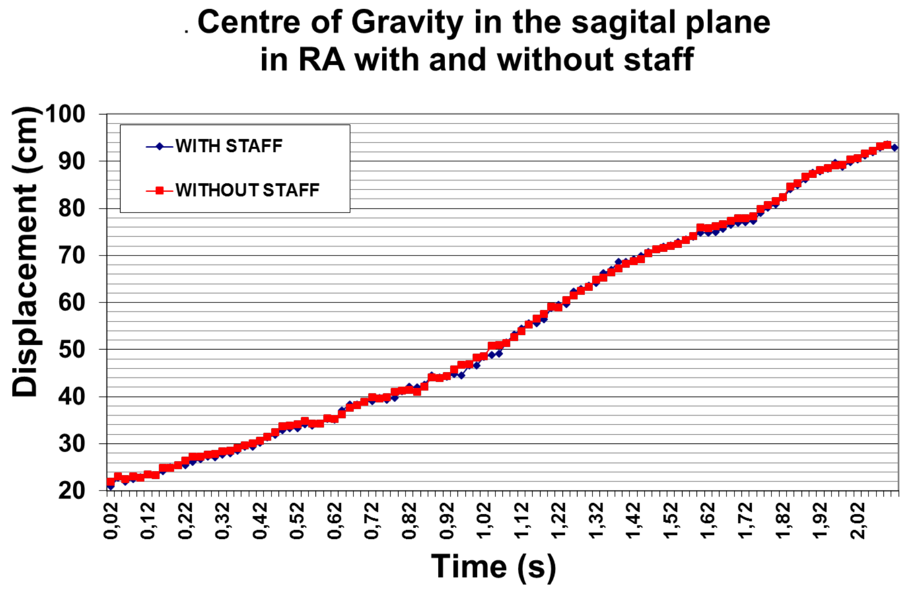

Figure 10: Centre of Gravity in the sagittal plane in RA with and without staff.

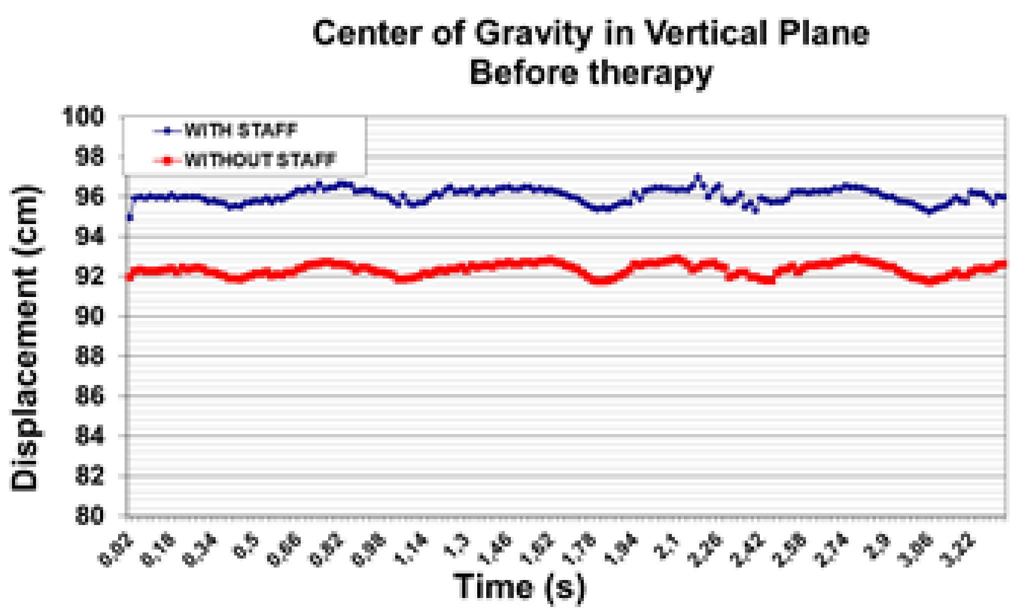

Figure 11: Centre of Gravity in the vertical plane in RA with and without staff.

Analysis of joint angles in the gait cycle

One of the most important outputs of the motion data recorded during the gait cycle is the analysis of the change in joint angles over time. These data are usually presented in the form of time curves, which represent the angular parameters of each joint during different phases of gait. Several methods exist for the quantitative analysis of such curves, including the use of Fourier series, pattern recognition algorithms, and neural network classifiers. These methods allow a more accurate understanding and comparison of joint motion patterns between different test conditions. The calculation of joint angles in two dimensions is based on the scalar product of vectors, expressed as

$$\vartheta = \arccos \frac{\langle \mathbf{v}_1, \mathbf{v}_2 \rangle}{\|\mathbf{v}_1\| \, \|\mathbf{v}_2\|} \cdot \frac{180}{\pi} \tag{1}$$

Where $\langle \cdot, \cdot \rangle$ denotes the dot (scalar) product of vectors; if we want to use a signed indicated angle, we need to use the $\operatorname{atan2}(y, x)$ function:

$$\vartheta = \operatorname{atan2}(v_{2,y}, v_{2,x}) - \operatorname{atan2}(v_{1,y}, v_{1,x}) \tag{2}$$

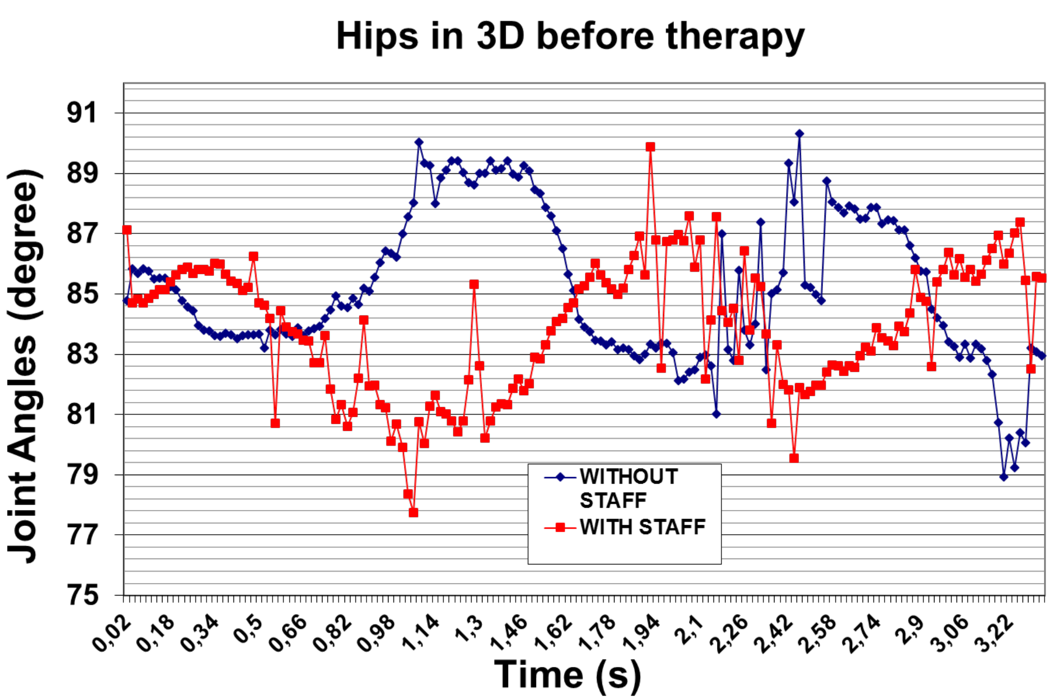

Figure 12: The joint angles of the hips (3D) in RA with and without staff.

$$F(x) = \begin{cases} f_1(x), & \text{if } x_1 \le x < x_2, \\ f_2(x), & \text{if } x_2 \le x < x_3, \\ \vdots & \\ f_{n-1}(x), & \text{if } x_{n-1} \le x < x_n \end{cases} \tag{3}$$

Where $f_i(x)$ is a third-degree polynomial defined by

$$f_i(x) = a_i(x - x_i)^3 + b_i(x - x_i)^2 + c_i(x - x_i) + d_i \tag{4}$$

for

$$i = 1, 2, \ldots, n - 1$$

The properties of cubic splines:

$$F(x)$$

interpolates all data points,

$$f(x),\ \dot{f}(x),\ \ddot{f}(x)$$

continuous on every interval.

They are the vectors involved in a given movement. If you want to determine a sign-directed angle, you need to use a special function that takes into account the direction of the vectors and the sign: In three dimensions (3D), the determination of the sign depends on the conventions of the axis and the coordinate system chosen, so a uniform treatment of the direction of rotation about the axis is crucial for consistency of results. In real measurements, missing or inaccurate data are often encountered, and correction is essential for reliable analysis. To this end, interpolation techniques are used to pre-process the signals. Especially useful are polynomial interpolations, which are easy to handle and can be analytically integrated and differentiated. However, higher-order polynomials can lead to overfitting and significant errors. Therefore, the use of piecewise polynomial functions, particularly cubic spline interpolations, is recommended, as they ensure the accurate fitting of data points under continuity conditions. Cubic spline interpolation is defined as

$$S_i(x) = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3, \qquad x \in [x_i, x_{i+1}] \tag{5}$$

Where each segment is a polynomial of degree three, which ensures accurate interpolation of the data and continuity of the first and second derivatives between adjacent segments. The economy of hip joint motion contributes significantly to the efficiency of gait. Dynamic changes in joint stability and mobility occur during the gait cycle, as reflected in the movement of the body's centre of gravity. This movement enhances balance and spatial orientation, which are crucial for maintaining a stable and efficient gait, particularly in patients with limited mobility or rheumatoid arthritis. For example, the angular parameters of the hip joint show different patterns during assisted (e.g. walking stick) and unaided walking. Measurements show significant differences in amplitudes between the two conditions. In tests with walking sticks, joint angular time curves are noisier due to the presence of the team (or assistive personnel) - these external influences distort the natural movement pattern. As before, the data were pre-processed using spline and cubic interpolation algorithms to reduce noise. It is essential to emphasise that these noises are not measurement errors, but instead signs of biomechanical instability resulting from the patient's condition, particularly during hip movements. Hip instability, in the case of frequent RA, also contributes to asymmetry in movement patterns and irregular displacement of the body's centre of gravity. Based on these observations, accurate monitoring of joint angles is a key element in diagnosing movement and designing personalised rehabilitation therapy.

Two basic parameters were considered in the analysis of hip joint angles: the minimum and maximum values of the joint range of motion. For the evaluation, fixed three-dimensional angle values in the XZY coordinate system were used on both sides. The results show that both range of motion and lateral asymmetry were significantly reduced in the unaided gait test, especially for the hip joint.

4 Conclusions

The present study aims to provide a quantitative analysis of gait in patients with rheumatoid arthritis under different conditions, with and without the presence of a personal assistant. The objective is to obtain an accurate description of changes in gait dynamics and to assess the effectiveness of movement therapy. The results show significant changes in gait stability, coordination, and body centre of gravity behaviour. The gait cycle is longer in the unaided condition, which indicates more natural and less restricted movement. Yet, we note that the stability increases in the sagittal plane, while mobility improves in the horizontal and vertical planes. These changes support better balance and more efficient energy use. In addition we report that the joint motion improves especially in the hip and knee joints. Nonetheless, the range of motion becomes more balanced, and asymmetry decreases. In fact, these changes lead to the improved dynamic balance and functional mobility. Our results indicate that the hip mobility can support efficient mechanics of walk. The presence of a personal assistant increases

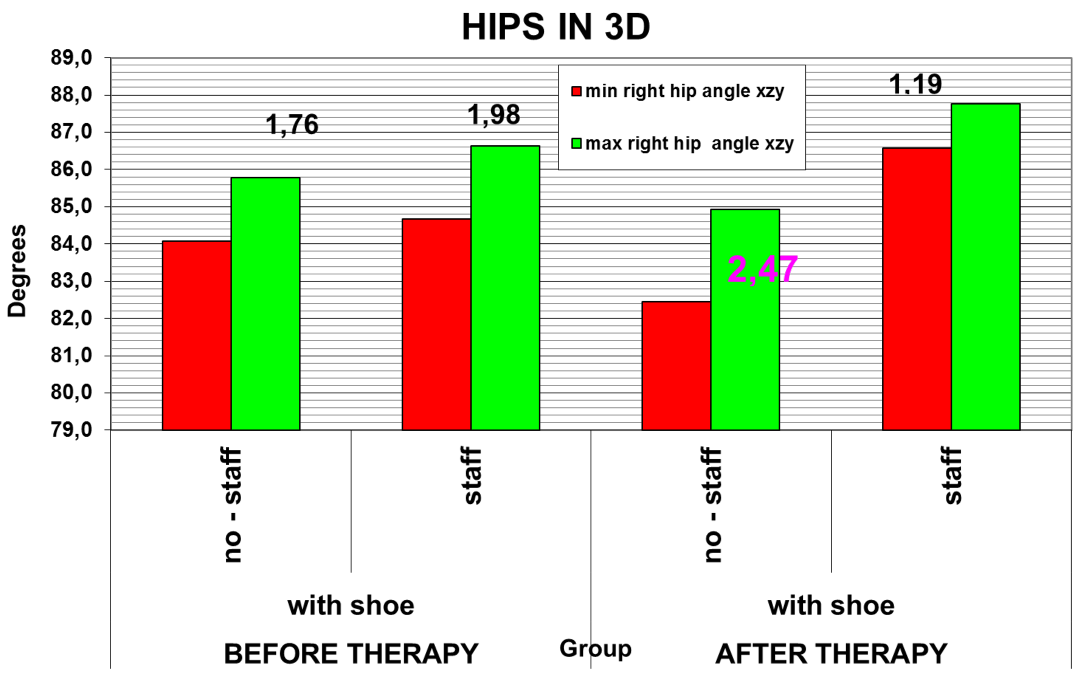

Figure 13: The standard curves of the hips (3D) in RA with and without staff.

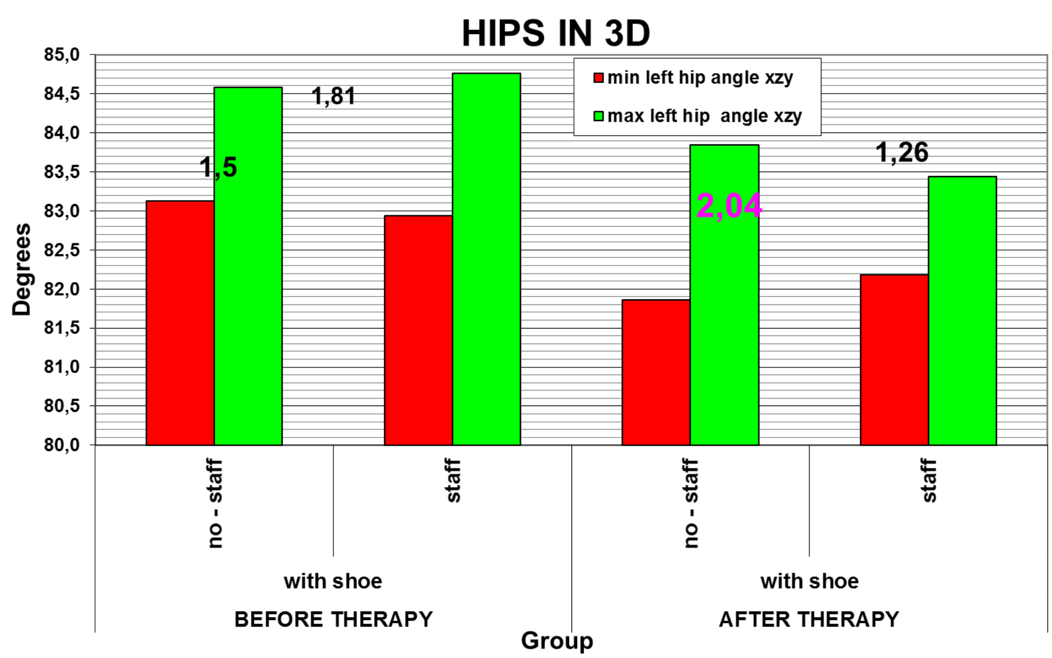

Figure 14: The standard curves of the hips (3D) in RA with and without staff.

safety but may limit natural movement patterns. The patients may adjust movement due to external presence. It is worth menting that the independent movement should be encouraged under safe and controlled conditions. Independent and device free gait trains improves the overall mobility, posture, and balance. We aslso conclude that it supports spatial orientation and reduces injury risk. Our findings support the value of natural gait in rehabilitation. Further research with larger samples and long term follow up is required.

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