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Importance of the assessment of knee joint function after a stroke

Agnieszka Wareńczak-Pawlicka[1]*, Ewa Lucka[1], Mateusz Lucki[1], Przemysław Lisiński[1]

[1]Department of Rehabilitation and Physiotherapy, Poznań University of Medical Sciences, Poznań, Poland

*Corresponding author: Agnieszka Wareńczak-Pawlicka, Department of Rehabilitation and Physiotherapy, Poznań University of Medical Sciences, Poznań, Poland, e-mail address: a.warenczakpawlicka@gmail.com

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Abstract

Purpose: **This study aimed to assess** knee joint function in post-stroke patients using wireless motion sensors and functional tests. This type of evaluation may be important for improving gait quality. *Methods:* The study included 25 post-stroke patients **(age 53.5 ± 8.4 years)** and 25 healthy controls **(age 51.1 ± 7.7 years)**. **Knee function was assessed using** passive range of motion (PROM), active range of motion (AROM) at any speed, maximum speed AROM (FROM), and joint position sense (JPS). Orthyo® motion sensors and a mobile app **were** used for measurements. The following functional tests have been used: Five Times Sit-to-Stand Test (FTSST) and Timed Up and Go Test (TUG). *Results:* Before rehabilitation, the average values of PROM **(p=0.006)**, AROM **(p=0.005)**, FROM average **(p<0.001)** and maximal velocity **(p<0.001)**, JPS **30º (p=0.002), JPS 60º (p=0.002) and JPS 80º (p<0.001)** were significantly worse in the paretic limb than in healthy people. The applied rehabilitation contributed to improving the PROM and AROM and the average and maximum speed of rapid movement in the knee joint. **Proprioception (JPS)** also improved. Only the average **(p<0.001)** and maximum speed **(p<0.001)** in the FROM test in the knee joint of the paretic limb after rehabilitation significantly differed from the values in healthy people. The patients' performance (functional tests) improved after rehabilitation (TUG (<0.001) and FTSST (<0.001)), but it did not reach the level of healthy people. *Conclusions:* The function of the knee joint in the paretic limb is significantly impaired and requires inclusion in the therapy plan in the early period after stroke.

Key words: function of knee joint, hemiparesis, physiotherapy, stroke, wireless sensors, gait.

1. Introduction

According to the Helsingborg Declaration, every stroke patient should have access to early rehabilitation and a continuum of care, from stroke units in the acute phase to appropriate rehabilitation later [29], [38]. The main goal of therapy is to restore the ability to walk independently and safely; therefore, it is important to correctly assess the movement kinematics and functions of the lower limb to target and evaluate therapy [13]. While much attention in the literature has been devoted to assessing the impact of ankle joint dysfunction and foot dysfunction of the paretic limb [16], [33], [39], on the kinetics of gait in stroke patients, weaker pressure was paid to dysfunction of the knee joint [18], [23] in these clinical situations so more scientific attention should be directed to this problem.

During the gait cycle in healthy people, the knee joint alternates between flexion and extension through a range of approximately 53 to 75 degrees [46]. After a stroke, patients show considerable variations in gait patterns, depending on the residual function and the severity of sensorimotor impairment [5]. Many post-stroke hemiparesis patients experience hyperextension of the knee in the paretic limb during the stance phase (characterized by full knee extension (0°) or more) [17]. Another problem of the knee joint's kinematics of the paretic limb during walking is a condition defined as a stiff knee characterized by reduced knee joint flexion in the swing phase [8], [34]. From a functional point of view, limited knee flexion may affect gait stability and cause abnormal compensatory movements, thus increasing the risk of falls and energy costs [9], [45]. Furthermore, abnormal coactivation patterns of agonist and antagonist muscles at the knee and ankle joints during gait have been reported in patients with hemiparesis due to loss of central muscle control.

Since the smoothness of gait is determined by the alternating contraction of the extensor and flexor muscles of the knee joint, the abnormalities mentioned above disturb the gait cycle [43]. As the above data indicate, any anatomical or functional knee joint disorders result in an abnormal gait cycle. It should also be mentioned that in people after a stroke, the moment of initiating walking is essential, usually associated with getting up from a sitting position, and here, the role of knee mobility increases even more. Therefore, tests assessing knee joint function are necessary to assess gait disorders in patients after stroke. With the patient's safety in mind, we believe that implementing gait re-education procedures requires, at the beginning, a separate assessment of the degree of dysfunction for all joints of the paretic limb. Therefore, it should be carried out first in conditions that are safe for the patient (sitting or lying position), and as the general functionality of the patient improves, especially the ability to balance, it can and should be performed while standing or walking. However, then the assessment is comprehensive in relation to all joints of the paretic limb, taking into account the influence of co-movements of the trunk and other limbs.

According to Mohan et al. [37], conventional qualitative gait analysis, usually used in clinics, is based mainly on gait observation and is, therefore, subjective and highly dependent on the observer's experience. However, there are many standard quantitative clinical measures assessing lower limb functions needed when getting up, sitting down, climbing stairs, or gait. They are for example: Five Times Sit-to-Stand Test (FTSST), step test (ST), Fugl-Meyer Assessment (FMA), Dynamic Gait Index (DGI), 6-minute Walking Test (6MWT), 10-meter Walking Test (10MWT), Timed Up and Go (TUG) [3], [14], [19], [36]. These tests provide results at an overall level of accuracy. They allow, for example, to determine the number of repetitions of a task (e.g., ST, FTSST) or to assess the ability to complete a motor task in a specific time, but without a detailed qualitative analysis and without taking into account incorrect compensations (e.g., TUG, 6MWT, 10MWT). Because they cannot "catch" subtle changes while performing a given task, they require repeatability of measurements to obtain acceptable measurement reliability, which extends the total test time. It seems that the described methods should be supplemented with more sensitive and precise tests. Recently published studies indicate the possibility of using sensor-based technologies to objectively quantify the presence and severity of motor impairments in stroke patients [6], [15], [24], [41]. Although these methods are not yet fully utilized in clinical settings, these tools provide the means to acquire, store, and analyze multivariate, complex gait data while capturing its non-linear dynamic variability and offering the invaluable benefits of predictive analytics [37]. **Global knee joint functions in stroke survivors, such as walking or climbing stairs, have already been assessed using wearable sensors in some studies [7]. However, there is a lack of studies in the literature that assess knee joint ranges of motion in stroke survivors using wireless motion sensors and different speeds of active movements in clinical settings. Furthermore, in the case of knee joint proprioception studies, most studies have focused only on comparative assessment of the paretic and non-paretic limbs without assessing the effect of rehabilitation on improving outcomes [25], [27].**

Hence, our study aimed to assess the functionality of the knee joint in hemiparetics, considering especially such parameters as range of motion, speed of movement, proprioception (joint position sense), rising from a chair, and gait in patients with hemiparesis, both using functional tests and wireless sensors. We used the described methods to compare the results of paretic and non-paretic limbs with the control group and assess the rehabilitation's effects.

In **the present** study, we wanted to obtain answers to the following questions:

1. In the case of hemiparesis after a stroke, is there a limitation of the passive and active range of motion in the knee joint of the paretic limb?
2. In the case of active exercise, is there a difference in the speed of this movement compared to healthy people?
3. Is there a disturbance in the sense of joint position in patients after stroke, and to what extent?
4. Does hemiparesis determine the way in which tasks are performed in functional tests?

2. Materials and Methods

2.1. Participants

The study was conducted at the Neurological Rehabilitation Department of Wiktor Dega Orthopedic-Rehabilitation Clinical Hospital, Poznań University of Medical Sciences. The study was conducted according to the Declaration of Helsinki and with the approval of the Bioethics Committee of the Poznań University of Medical Sciences (reference number 822/21). Written informed consent was obtained from all study participants after an explanation of the aim and methodology of the study.

The study groups consisted of the subject after stroke (SG) and the control group (CG) without a history of stroke. The experimental group (SG) consisted of twenty-five patients presenting with hemiparesis following confirmed stroke, as corroborated by computed tomography (CT) head scans, who met other inclusion criteria and who expressed written consent to participate in the study. There were 7 women and 18 men examined, with an average age of 53.5 (range 39–64, SD: 8.4). Thirteen patients had right-sided hemiparesis, and the remaining twelve patients—had left-sided hemiparesis. Subjects' diagnosis, age, gender, incident date, and the information necessary to classify the patients were obtained through medical record review and interviews. The control group consisted of 25 healthy volunteers with no prior history of trauma or neurological disease affecting the structure and function of the knee joint. This group included 11 women and 14 men with an average age of 51.1 years (range 37–65, SD: 7.7). The groups did not differ significantly in age (p=0.322), height (p=0.887), weight (p=0.528), BMI (p=0.538), or gender distribution (p=0.239). Table 1 shows patient characteristics for both the study and the control group.

Table 1. Demographic data of the study group and the control group.

Variables		Groups		p
		Stroke (SG)	Control (CG)	
Age	mean±SD	53.5±8.4	51.1±7.7	0.322
	median	54.0	51.0	
	min-max	39.0-64.0	37.0-65.0	
Body mass	mean±SD	86.1±17.5	82.2±15.3	0.528
	median	86.0	82.0	
	min-max	48.0-125.0	60.0-120.0	
Height	mean±SD	174.1±9.6	175.0±9.9	0.887
	median	176.0	176.0	
	min-max	160.0-202.0	159.0-195.0	
BMI	mean±SD	28.1±4.8	26.8±4.2	0.538

	median	28.7	26.5	
	min-max	18.3-40.0	19.2-36.0	

BMI-Body Mass Index, CG- control group, SD- Standard deviation, SG- stroke group

Due to the technical capabilities of the wireless sensors used in the study and the specificity of the functional texts, we decided to introduce rigid criteria for including patients in the presented project. The inclusion criteria consisted of: time from stroke: less than a year, age: between 35 and 65 years old, ability to stand independently for at least 5 minutes without an assistive device, ability to walk 5 m independently, ability to communicate and understand the tasks required in the study, a modified Ashworth scale spasticity score of 1+ or less in the affected knee (0: no resistance, 5: affected parts stiff in flexion or extension), muscle strength on the Manual Muscle Test (MMT) of 3/4 or more in the affected knee (0: no signs of contraction or movement; 5: full range of motion against gravity, full resistance), Barthel Index score 80 or more.

To increase the homogeneity of the study group, the following exclusion criteria will be used: age below 35 or over 65, sensorimotor aphasia, cognitive disorders that make it impossible to understand and obey commands, lack of active movement in the knee joint, MMT strength of the quadriceps muscles below 3, no ability to walk 5 meters, lack of informed consent to participate in the study, other neurological diseases (such as MS, Parkinson's disease, neuropathies), fractures in the lower limbs which could affected the structure and function of the knee joint, previous operations on the lower limbs (including ACL reconstruction, knee arthroplasty or hip, osteotomy of the knee joint), vision disorders, unilateral spatial neglect syndrome. The listed exclusion criteria exclude from the research people, whose dysfunctions observed during the assessment could have a source other than a stroke.

2.2. Experimental Procedures and Instruments

All patients from SG were examined twice at the beginning and the end of this trial (after about 15±1 days of rehabilitation) by a physical therapist. The evaluation began with an interview questionnaire and finally finished with functional tests. Physical functional tests such as the Five Times Sit-to-Stand Test (FTSST), Timed Up&Go (TUG), and evaluation of the knee joints with the use of wireless motion sensors during activities such as Passive Range of Motion, Active Range of Motion (arbitrary speed), Fast Active Range of Motion (maximum speed) and Proprioception (joint position test) were performed **[14],[20],[28],[35].** Between measurements, patients participated in the same rehabilitation program, including general fitness exercises, balance and coordination exercises, gait training, strengthening exercises, exercises using the PNF method, and exercises using the biofeedback method **[10],[22],[32],[44].** On average, each patient exercised for two hours daily.

Sensors and Application The Orthyo® system

The study used wireless motion sensors connected to a mobile application (Aisens sp. z o. o. Poznań, Poland). The Orthyo® system uses three basic types of sensory data: velocity, acceleration, and magnetic field. The measurement system is approved by the Central Office of Measures in Poland. **The sensors have a declaration of measurement conformity. For angles measured in the X axis, in which the measurement range is <-180; +180>, the indication error is 1.4º, and the measurement uncertainty is ±0.8.** The sensor collects raw sensory data is filtered, calibrated, and computed in an estimation process by the sensor's microchip. As a result, the sensor generates orientation and relative position. The location of the sensors is established in a referential system whose axes are positioned following the East North Up (ENU) principle, (where X points eastwards, Y northwards, and Z upwards). Estimation and calibration are based on such estimators as the Kalman filter, complementary filters, and supporting artificial intelligence algorithms. After preliminary analysis, all computed data are sent to the Orthyo app by initiating the second data processing stage. At this stage, the parameters representing the movement of a knee joint are computed (for example, linear velocity, acceleration, and movement in space). All data is stored in the cloud, so web-based results tracking is possible. The detailed specification of the Orthyo® system is described in detail in the previous article by Lisiński et al. [35].

Orthyo® consists of motion sensors, a mobile application, and an online panel. Before the diagnostic examination, each patient was registered in the Orthyo online panel. Next, two Orthyo® system sensors were attached to the patient's lower limb using elastic Velcro tapes. The first sensor was attached to the lateral surface of the thigh, halfway between the greater trochanter and the aperture of the knee joint (15 cm distally to the greater trochanter), and the second sensor was attached to the anterior surface of the shin, 5 cm distally from the tibial tuberosity (Fig. 1 A). The sensors were used in conjunction with a mobile application installed on a smartphone fitted with the Android operating system (the application is compatible with Android 5.0 and newer versions). At the same time, four sensors (2 per limb) and two smartphones were used [20].

Testing Procedures using wireless sensors

The knee joint test consisted of four activities: Passive Range of Motion, Active Range of Motion (arbitrary speed), Active Range of Motion (maximum speed), and Proprioception (joint position sense).

Depending on the test, some parameters were recorded from the indicated:

- a range of motion (º; degrees),
- average angular velocity (AVG) in the knee joint during the diagnostic test [°/s],
- maximum angular speed during the test [°/s],
- the mean square error (MSE) - is the mean squared error from the knee joint trajectory in the sagittal plane expressed in (°)2 and calculated using the following formula: $MSE = \frac{1}{n}\sum_{i=1}^{n} r_i^2$ where "r" is the deviation angle from the initial sagittal plane to the actual sagittal plane.

The examiner started recording the results in the application by simultaneously giving the "start" command and stopping it after the patient had completed the task. For the single-arm tests, results were recorded separately for each limb.

Passive Range of Motion (PROM)

The subject was lying prone with the lower limbs extended, head in a neutral position, and feet off the couch. The examiner stabilized the pelvis with one hand and, with the other hand, performed passive flexion movement in the knee joint until resistance appeared or the patient reported pain. Before making a move, the examiner started the registration, and after the move was finished, he stopped the registration in the application. Sensors recorded the difference between the initial and maximum angles at the knee joint. The test was performed for both lower extremities. **The PROM measurement methodology was based on the technical capabilities of the sensors and applications and has not been described in this form before.**

Active Range of Motion - arbitrary speed (AROM)

The subject was lying prone with the lower limbs extended, head in a neutral position, and feet off the couch. The examiner stabilized the subject by placing a hand on the pelvis. The subject was requested to perform maximum knee flexion at any preferred speed following the start command initiating registration by the examiner. Sensors recorded the difference between the initial and maximum angles at the knee joint. The test was performed for both lower extremities **[35]**.

Fast Active Range of Motion - maximum speed (FROM)

The subject was lying prone with the lower limbs extended, head in a neutral position, and feet off the couch. The examiner stabilized the subject by placing a hand on the pelvis. The subject was asked to perform knee flexion as speed as possible [35]. The average (AVG) and maximum (MAX) angular velocity and the mean square error (MSE) were recorded during this test. The test was performed for both lower extremities.

Proprioception - joint position sense (JPS)

The subject was lying prone with the lower limbs extended, head in a neutral position, and feet off the couch. The test assessed the ability to recreate a given position without visual modality. The examiner passively flexed the subject's knee joint to the selected position, held it for 5 seconds, asked the subject to remember it (without looking), and then extended the knee joint. Then, the subject was asked to actively recreate the previously indicated position and command "stop" or "ok." The application measured the angle reached and calculated the difference between this angle and the set angle [20]. The ability to restore knee flexion was assessed in 3 ranges: 30°, 60°, and 80°. The subjects did not know the value of the given angles before testing. The test was performed for both lower extremities.

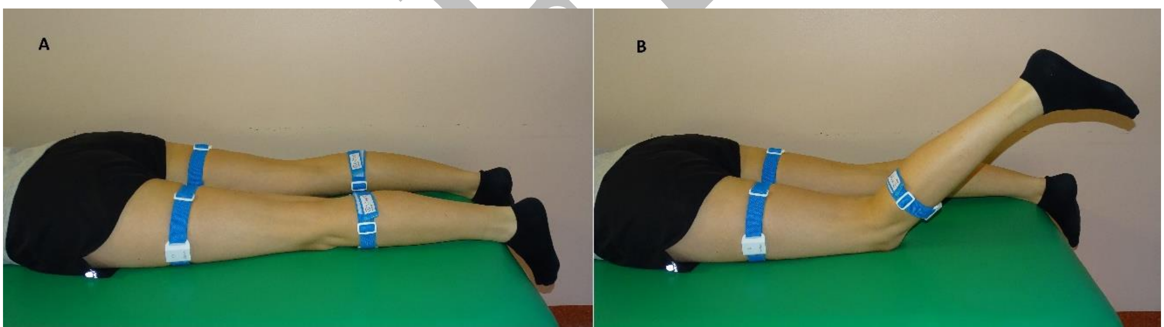

Fig. 1. Measurement of JPS. (A) Starting position. (B) Final position.

For clarity, we used the following terms to describe the results obtained in the wireless sensor study:

- the limb directly affected was called the paretic limb,
- the asymptomatic side in stroke patients was called the non-paretic limb,
- the average result of the left and right limbs of the healthy group was called the control limb.

Functional tests

Functional tests were performed in the same order on all study participants.

The Five Times Sit-to-Stand Test (FTSST)

The subject was asked to perform five repetitions of standing up and sitting on the chair with their back against the backrest of the chair as rapidly as possible. During the test, the arms were crossed over the chest [14]. The task completion time was measured, and only one attempt was made.

Timed Up&Go Test (TUG)

During the test, the participant was asked to rise from a chair, walk a distance of 3 meters, make a turn of 180° having crossed a designated line, and return to the chair. The timing in seconds starts from a "go" command and ends when a patient returns to a correct starting position. One trial was performed for each patient [28].

Statistical analysis

Data were analyzed with the Statistica™ version 13.1. Demographic data and clinical characteristics are presented as means, standard deviations (SD), median, and range. The Shapiro-Wilk test was used to assess the normality of distributions in the test scores. The independent t-student tests or Mann-Whitney tests were conducted to compare the differences between the study and the control group. A repeated-measures ANOVA and Fisher's LSD post hoc tests were used to assess significant differences between the paretic and non-paretic limb measurements performed by wireless sensors before and after therapy. The dependent t-student test or Wilcoxon signed ranked test was performed to compare outcomes before and after rehabilitation in functional tests in the study group. Pearson correlation was used to determine the association between functional test results and PROM, AROM, and AVG speed. **The PQStat v.1.8.6 was used to determine the required sample size using results for the first ten subjects from functional tests and PROM, AVG (FROM), and JPS obtained in the paretic limb before and after treatment with a power of 80% and a significance level of 0.05 (two-tailed).** The p-values of less than 0.05 were considered statistically significant.

3. Results

Functional tests

The results obtained in functional tests differ significantly before and after rehabilitation in the study group. The TUG test time improved by an average of 2.1s, and the FTSST test time improved by an average of 2.9s. Unfortunately, regardless of the significant improvement, the results differed significantly from those of healthy people (Table **2**).

Table 2. The results of functional tests.

Variable		Stroke group		p^1	Control group	SG vs CG before	SG vs CG after
		Before	After			p^2	p^3
TUG	mean±SD	12.6±8.8	10.5±7.9	**<0.001***	6.3±0.7	**<0.001***	**<0.001***
	median	9.5	8.1		6.5		
	min-max	6.2-48.5	5.1-45.5		4.7-7.3		
FTSST	mean±SD	14.3±5.6	11.4±4.4	**<0.001**	8.3±1.0	**<0.001***	**0.001***
	median	13.3	11.2		8.2		
	min-max	7.9-32.3	6.7-24.2		6.1-10.8		

p^1—the comparison of intragroup pre- and post-treatment (dependent t-student test or Wilcoxon* signed ranked test); p^2 -the comparison between the study group and the control group before treatment (Mann-Whitney test*), p^3-the comparison between the study group and the control group after treatment (Mann-Whitney test*)

Passive Range of Motion (PROM)

Before rehabilitation, the passive range of motion in both knee joints in the stroke group was significantly lower than in the control limb (p=0.006, p=0.008). After rehabilitation, statistically significant improvement was observed in both knee joints in the stroke group. In the paretic limb, there was an increase in flexion by approximately 5.6º (p=0.001), and in the non-paretic limb, by an average of 5.4º (p=0.001). After rehabilitation, the ranges of flexion motion did not differ significantly from those obtained in the control limb (Table 3).

Active Range of Motion - arbitrary speed (AROM)

Before rehabilitation, the active flexion range of motion in the paretic limb was, on average, 14.1º lower than that of the control group (p=0.005), and the range of motion of the non-paretic limb was 6.8º lower than that of the control group (p=0.019). After therapy, the active ranges of motion in people after stroke did not differ significantly from those in the control group (Table 3).

Fast Active Range of Motion - maximum speed (FROM)

The results obtained during fast active knee flexion movement show significant differences between groups in average and maximum speed. The average speed of flexion movement increased after therapy by an average of 34.0°/s in the paretic limb (p<0.001) and the non-paretic limb by 32.6°/s (p<0.001). Regardless of the improvement, a significant difference was observed in the results of the study group both before and after therapy compared to the control group. Both before and after rehabilitation, the average and maximum movement speed of the non-paretic limb was significantly higher than that of the paretic limb but, at the same time, significantly lower than in the control limb.

Table 3. The results of the passive, active and fast range of motion tests.

Variable		Control limb	Paretic limb			Non-paretic limb			Paretic vs non-paretic		
			Before	After	p^2	Before	After	p^3	Main effect p^4	Before	After
Passive ROM	mean±SD	128.2±10.0	119.0±12.4	124.6±13.6	**0.001**	119.1±13.0	124.5±13.6	**0.001**	**<0.001**	0.958	0.958
	median	127.8	119.5#	121.7		119.8	126.5#				
	min-max	112.4-143.9	96.0-146.2	101.1-152.5		95.7-147.4	93.2-153.3				
	p^1		**0.006**	0.301		**0.008**	0.289				
Active ROM	mean±SD	115.0±7.6	100.9±24.8	106.8±24.3	0.126	108.2±11.6	113.3±12.0	0.179	**0.016**	0.058	0.086
	median	117.5	105.3#	110.6		107.7	114.9#				
	min-max	103.2-126.4	18.0-138.9	19.7-141.1		88.2-133.5	85.9-137.6				
	p^1		**0.005***	0.290*		**0.019**	0.571				
Fast ROM	mean±SD	111.7±8.3	102.3±22.9	104.5±22.1	0.540	111.2±12.5	111.9±12.0	0.830	**0.018**	**0.016**	**0.043**
	median	111.7	103.9#	110.1		111.9	113.1#				
	min-max	97.9-128.3	14.8-130.8	25.8-129.9		79.2-132.9	90.0-141.2				
	p^1		0.103*	0.567*		0.858	0.935				
Fast AVG speed	mean±SD	199.1±41.5	102.8±40.8	136.8±52.8	**<0.001**	126.9±37.6	159.5±37.4	**<0.001**	**<0.001**	**0.005**	**0.007**
	median	184.7	100.4#	134.4		117.2	166.2#				
	min-max	136.1-282.1	15.5-181.3	54.7-268.8		62.5-214.8	98.6-222.1				
	p^1		**<0.001**	**<0.001**		**<0.001**	**0.001**				
Fast MAX speed	mean±SD	498.5±83.5	307.7±131.3	358.2±116.1	**0.012**	361.0±91.3	398.0±98.7	0.064	**0.022**	**0.009**	**0.047**
	median	487.7	293.4	343.8		346.3	379.7				
	min-max	382.1-701.0	49.9-540.1	180.0-614.5		224.0-588.0	177.6-538.8				
	p^1		**<0.001***	**<0.001***		**<0.001***	**0.001***				
Fast MSE	mean±SD	12.7±8.4	18.2±14.4	20.1±17.8	0.945	12.8±13.2	12.2±9.8	0.998	0.058	0.400	0.108
	median	10.1	12.4	14.7		10.0	8.0				
	min-max	3.3-37.5	0.9-58.6	4.3-58.8		0.8-51.1	0.9-35.8				
	p^1		0.260*	0.383*		0.337*	0.467				

p1-comparison between the control group and paretic or non-paretic limb, t-student or *Mann Whitney test; p^2-the comparison of pre-and post-treatment results for the paretic limb (post hoc); p^3-the comparison of pre-and post-treatment results for the non-paretic limb (post hoc); p^4 -a repeated-measures ANOVA-main effect.

Proprioception - joint position sense (JPS)

The results obtained in the JPS test show a significant improvement in proprioception after rehabilitation in patients after stroke in the paretic limb in all tested ranges. Before therapy, the results of the paretic limb were significantly worse than those of healthy people, but after rehabilitation, the results improved and did not differ significantly. Interestingly, before rehabilitation, significantly worse results were observed in the non-paretic limb in the case of the JPS 60º and JPS 80º tests than in the control limb. Detailed data are presented in Table **4**.

Table 4. The results of proprioception evaluation (end angle for JPS test).

Variable		Control limb	Paretic limb			Non-paretic limb			Paretic vs non-paretic		
			Before	After	p^2	Before	After	p^3	Main effect p^4	Before	After
JPS 30	mean±SD	34.7±2.9	40.1±7.8	35.7±5.2		37.6±8.3	36.6±5.2				
	median	33.9	39.0#	35.6	**0.004**	35.0	35.0#	0.508	**0.026**	0.096	0.546
	min-max	28.8-41.8	29.1-59.0	27.0-44.9		26.4-59.9	26.0-46.9				
	p^1		**0.002**	0.434		0.111	0.127				
PS 60	mean±SD	64.8±3.2	71.2±8.9	65.6±8.3		72.7±8.3	67.4±5.5				
	median	64.5	71.4#	66.8	**0.004**	73.9	68.2#	**0.006**	**<0.001**	0.423	0.346
	min-max	59.0-72.6	51.0-88.7	51.4-86.9		55.3-86.5	55.7-76.5				
	p^1		**0.002**	0.661		**<0.001**	0.049				
8PS 80	mean±SD	84.8±3.3	93.0±9.1	85.1±6.7		94.2±6.5	86.7±7.6				
	median	85.2	90.7#	86.3	**<0.001**	93.9	87.8#	**<0.001**	**<0.001**	0.447	0.315
	min-max	78.0-89.8	70.7-109.5	71.4-99.3		84.5-106.4	64.3-102.8				
	p^1		**<0.001**	0.826		**<0.001**	0.252				

p1-comparison between control group and paretic or non-paretic limb, t-student test; p^2-the comparison of pre-and post-treatment results for the paretic limb (post hoc); p^3-the comparison of pre-and post-treatment results for the non-paretic limb (post hoc); p^4 -a repeated-measures ANOVA-main effect.

Correlation analysis

A correlation analysis of the results of functional tests obtained before rehabilitation was performed with the passive range of motion, active range of motion, and average speed of knee flexion movement in people after stroke. There were no significant relationships with the results of the PROM in the paretic and non-paretic limbs. However, significant correlations were demonstrated between the test results and the AROM of the paretic limb and the average speed obtained in the FROM test. It was observed that the greater the active range of movement and the greater the average speed of movement in the paretic limb occurred, the better outcomes the patients achieved in the functional tests, i.e. they performed the TUG and FTSST tests faster. **The results of the correlation analysis between AROM, AVG speed (FROM), and functional tests are presented in Figures 2 and 3.**

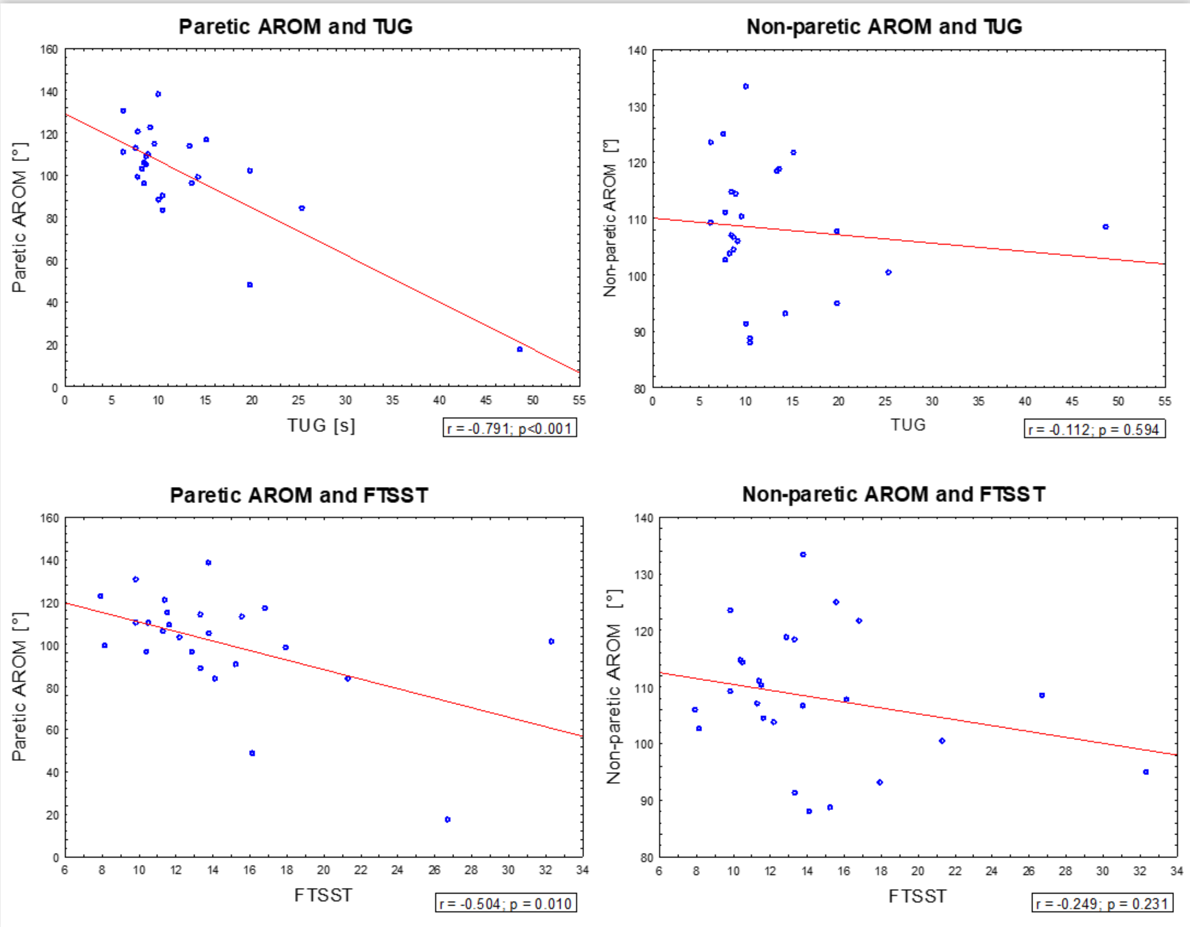

Fig. 2. Analysis of the correlation between the active range of motion (AROM) in the paretic and non-paretic limbs and functional test results (TUG and FTSST).

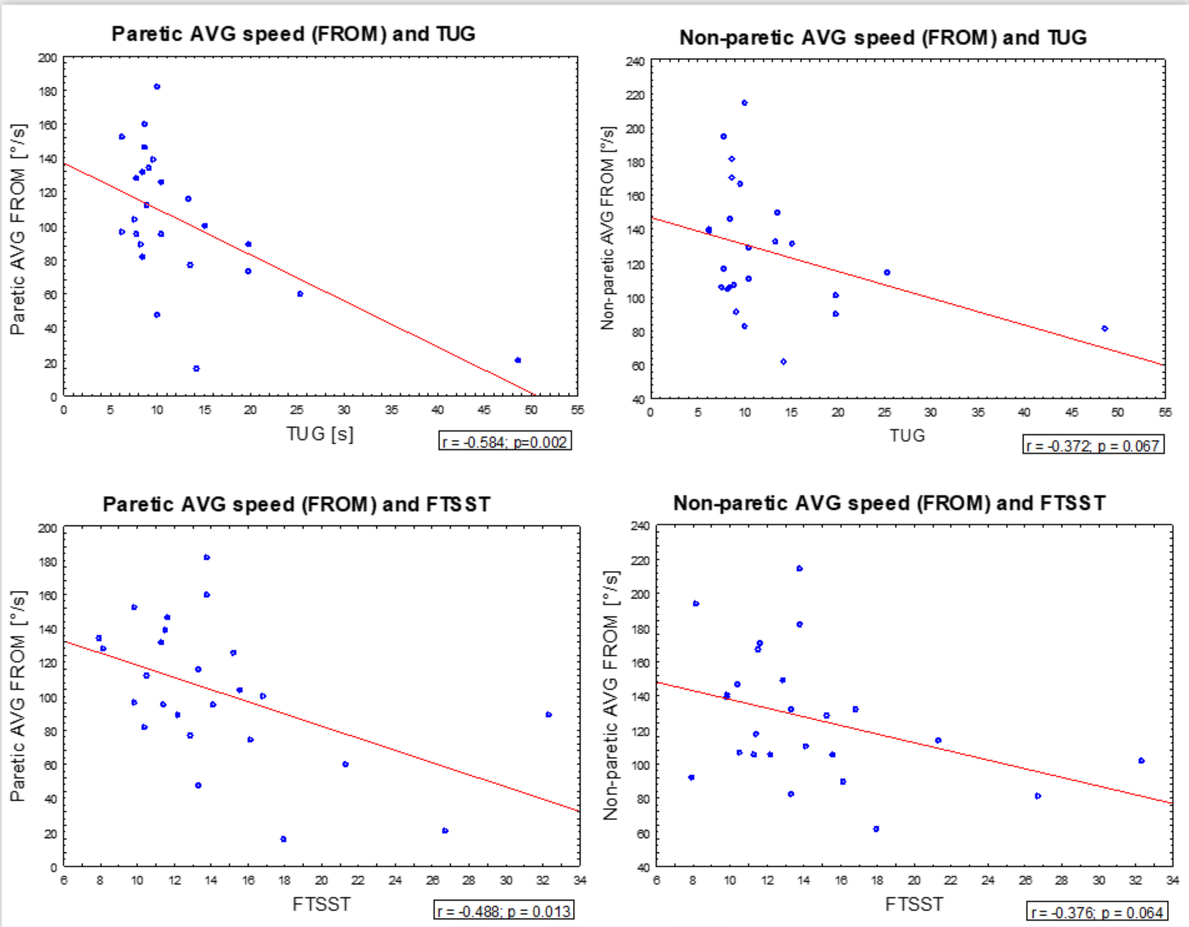

Fig. 3. Analysis of the correlation between the average angular speed (AVG FROM) in the paretic and non-paretic limbs and functional test results (TUG and FTSST).

4. Discussion

Rehabilitation is a crucial part of recovery after a stroke, and numerous studies have examined the impact of various methods on improving patients' health. The goal of stroke rehabilitation is to minimize patients' impairment and recover daily activities [2], [32]. In **the present research**, we wanted to precisely assess the severity of knee joint dysfunctions in people with hemiparesis early after a stroke and assess the possibility of eliminating them through targeted rehabilitation. It is difficult to objectively assess them only using functional tests, which often provide only a general idea of the importance of the problem. Therefore, we used both wireless motion sensors and simple, functional tests to assess the impact of rehabilitation on the kinematics of the knee joints.

Range of motion (ROM) measurement is one of the most commonly used procedures for evaluation in rehabilitation by physical therapists. It is widely used to quantify baseline joint function, target appropriate therapeutic interventions, and document their effectiveness. The universal goniometer remains a commonly used tool in clinical practice for measuring ROM.

However, measuring ROM using it can be cumbersome and time-consuming. Kumar et al. [30] suggested that the ROM measurements using the wireless sensor system are highly correlated with goniometer assessment. Additionally, the advantages of the sensor system are speed, convenience, ease of use, and the possibility of obtaining additional parameters such as maximum angular velocity or maximum angular acceleration.

In the literature, the analysis of the range of motion of the knee joints in people after stroke focuses mainly on assessing abnormalities in the range of motion during walking [8], [17], [23]. The results presented in the study provide valuable insights into the impact of rehabilitation on the ROM in individuals post-stroke, with particular emphasis on passive range of motion, active range of motion, and active knee flexion range at maximum speed using wireless sensors. **Our first question was: In the case of hemiparesis after a stroke, is there a limitation of the passive and active range of motion in the knee joint of the paretic limb?** Before rehabilitation, significantly lower passive and active ranges of motion were observed in both knee joints of stroke patients compared to the control group, indicating a statistically significant difference ($p=0.006$, $p=0.008$). However, after rehabilitation, a positive transformation emerged, manifesting a significant improvement in PROM. In the paretic limb, there was an increase in flexion by approximately 5.6° ($p=0.001$), and in the non-paretic limb, by an average of 5.4° ($p=0.001$). Importantly, the post-rehabilitation flexion motion ranges did not differ significantly from those obtained in the control group (Table 3), highlighting the effectiveness of the rehabilitation program.

In the present research, we wanted to obtain an answer to the next question: In the case of active exercise, is there a difference in the speed of this movement compared to healthy people? Therefore, we assessed the fast ROM (FROM) during active knee flexion **and extension. This type of selective assessment of the flexion and extension speed of the knee joint in the paretic and non-paretic limbs compared to healthy individuals has not yet been published. Typically, the analysis of movement speed in stroke patients involves the assessment of gait speed. Our results reveal** significant speed differences between post-stroke patients and controls. Despite therapy-induced improvements in both limbs, a persistent speed gap remained, with the non-paretic limb showing higher speeds than the paretic limb but lower than the control group, **Moreover, we also observed significantly worse results in functional tests assessment gait (TUG) and get up and sit down on a chair (FTSST), in which higher movement speed is associated with faster task completion. It is worth considering the cause of the decrease in movement speed in stroke patients. As Lattouf et al. [31] noted, patients with hemiparesis have muscle atrophy, specifically atrophy of type**

II (fast twitch) muscle fibers in favor of type I (slow twitch) fibers, which makes it difficult to initiate and produce rapid movements with high force. Interestingly, some studies have also shown the occurrence of muscle strength weakness in non-paretic limbs in stroke patients [12]. It is worth mentioning the study by Huniccutt et Gregory [26] research incorporated fifteen studies with 375 participants and demonstrated deficits in muscle size and strength in both paretic and non-paretic limbs compared to age-matched controls. Moreover, Gray et al.'s [21] study underscored structural alterations in post-stroke muscles, including reduced mass, fiber length, and pennation angle, emphasizing the importance of preventing such changes through targeted rehabilitation programs to mitigate weakness. Muscle weakness and spasticity lead to inefficient and abnormal gait patterns, resulting in difficulties performing everyday activities and reducing the quality of people's lives [18]. Even though our enrolled patients scored 0 or 1 on the Ashworth scale (0: no increase in muscle tone and 1: slight increase in muscle tone, with a catch and release or minimal resistance at the end of the range of motion when an affected part is moved in flexion or extension), we observed limited AROM and average speed of movement during FROM tests in both limbs and slower gait compared to healthy subjects before rehabilitation. After rehabilitation, many of the stroke survivors' outcomes improved. However, tasks requiring rapid movement were still performed more slowly by stroke survivors than healthy individuals, indicating the need for continued rehabilitation and greater emphasis on improving lower limb muscle strength, which is directly related to movement speed.

In stroke survivors, sensory deficits may contribute to walking disability, so we supplemented the ROM assessment using wireless sensors with joint position sense measurement. Our third research question was: Is there a disturbance in the sense of joint position in patients after stroke, and to what extent? Pre-therapy, significantly poorer JPS results were observed in all tested ranges (30º, 60º, 80º) for the paretic limb than the control limb (Table 4). Hwang et al. also observed significant proprioceptive deficits in the paretic knees in stroke patients [25]. Nevertheless, post-rehabilitation, no significant differences were noted between the outcomes of this limb and those of healthy individuals. The results of the JPS test are promising, suggesting a significant improvement in proprioception among post-stroke patients, particularly in the affected limb, following rehabilitation. It is noteworthy that such normalization of JPS results after therapy may indicate the effectiveness of rehabilitation efforts in enhancing joint position perception, which holds significant importance in the context of motor function. Apriliyasari et al. [4] indicated that proprioceptive training may improve balance performance, gait speed, trunk control, and basic functional mobility

among people with stroke. Consistent with Chia et al.'s [11] outcomes, further research is needed to **investigate** specific intervention mechanisms, long-term impact, and optimal protocol parameters **used to improve proprioception**.

The final question was: Does hemiparesis determine the way in which tasks are performed in functional tests? Stroke survivors achieved significantly worse on the functional tests than healthy controls. Before rehabilitation, the study group performed the TUG test 6.3 seconds slower, and the FTSST test 6 seconds slower than the healthy controls. We also observed interesting correlations between functional test results and the paretic limb outcomes. Greater active range **of motion** and higher **average** speed in the paretic limb were linked to faster completion times in the TUG and FTSST tests **(Fig. 2 and Fig. 3)**. Therefore, assessing knee ROM using sensors seems valuable, as it allows automatic recording of results and easy comparison of changes occurring during rehabilitation. Additionally, the study by Sijobert et al. [42] provides evidence of the promising technical and rehabilitative potential of a sensor-based system for controlling the knee joint during gait after a stroke. **As shown in Table 2, rehabilitation improved the performance of stroke survivors.** The TUG test showed a mean reduction in time by 2.1 seconds, and the FTSST test exhibited an average time improvement of 2.9 seconds **after rehabilitation**. Despite these significant advancements, it is noteworthy that the results still significantly differed from those of the healthy control group (Table **2**). **Agustín et. al [1] showed that the FTSTS is responsive to functional changes in patients with stroke and that their degree of severity and stage of recovery may influence the minimal clinically important difference (MCID), which is the smallest change that is meaningful to patients. The results of Persson et al. [40] indicate that TUG has the ability to detect changes in mobility over time in stroke patients. Therefore, we believe that these tests can be used to monitor the effects of therapy.**

5. Conclusions

Considering the characteristics of the study group and the functional deficits detected in the studies, we emphasize the importance of early rehabilitation with a suggestion for possible further research on the used rehabilitation protocols. Due to the precision and, at the same time, ease of performance of assessment using wireless motion sensors used in the conducted studies, we can recommend this form of measurement for monitoring the effectiveness of the rehabilitation program in the early period after stroke.

Limitation

The study included a relatively small number of patients. Although the study groups were not large, they were statistically representative based on the statistical analysis. Another limitation is the similar level of functional disability of the examined patients. In subsequent studies, people with more diverse levels of disability should be assessed, which will require the inclusion of much larger groups of patients. Assessment of knee joint function in patients with significant disability will require the use of other functional tests. Additionally, the weak point of the work is the use of only one improvement algorithm; however, the results obtained may contribute to the search for new improvement methods.

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