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Muscle torque production and kinematic properties in post-stroke patients: a pilot cross-sectional study

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Purpose: Stroke-related hemiplegia is an important factor influencing parameters of gait. So far, limited papers have assessed temporo-spatial capabilities and their correlations with gait parameters in the early post-stroke stage. This pilot study evaluated the temporo-spatial parameters of gait and assessed the maximal isometric and isokinetic torque production of the plantar flexor and dorsiflexor muscles. *Methods*: 15 patients with lower limb spasticity and 15 healthy controls were included. Stroke severity was assessed using the Modified Ashworth Scale and the Barthel Index. Gait cadence, gait speed, and gait cycle were assessed using inertial sensors during a Timed Up and Go test. Maximal isometric and isokinetic torque production of the ankle plantar flexor and dorsiflexor muscles were assessed using an isokinetic dynamometer device. *Results*: Post-stroke patients had statistically significantly lower gait cadence than healthy participants (17%, $p < 0.05$). Statistically significantly lower values of vertical acceleration were also noted during a sit-to-stand movement task (42%, $p < 0.05$). Plantar flexion torque of the affected limb was significantly different during isometric (63%, $p \leq 0.01$) and isokinetic work for 30°/s (49%, $p = 0.04$), 60°/s (58%, $p = 0.01$) and 20 °/s (53%, $p = 0.01$). Dorsiflexor muscles' torque production was significantly different in isometric activity (38%, $p = 0.04$). A statistically significant positive correlation occurred between the absolute peak torque of the dorsiflexor muscles in both static and speed phases of gait ($Rs = 0.65$, $p = 0.04$). *Conclusions*: Despite the low intensity of spasticity and early phase after stroke, differences in the muscle torque production and temporo-spatial parameters, as well as the correlations between them, were noticeable.

Key words: *biomechanics, gait parameters, isokinetic assessment, neurorehabilitation, post-stroke hemiplegia, torque production*

1. Introduction

Hemiplegia is a common, long-term impairment reducing gait performance after a stroke [1]. Hemiplegia leads to a lack of independent motor control of the muscle groups and incorrect co-activation of muscles acting on the joints of the lower limbs [2]. These disorders can be caused by changes in the number and method of recruitment of motor units. Such adverse conditions result in impaired motor control during the gait cycle [3].

The ankle plantar flexor muscles generate the forces needed to initiate gait [8] while the ankle dorsiflexor muscles allow for alternate walking [4]. Asymmetrical torque production for muscles acting on the ankle joints may cause gait asymmetry. Kinematic properties of gait in persons after a stroke means change in the ranges of motion and this is reflected in gait phases, gait cadence, and gait speed, as well as limb load times during the stance and swing phases (temporo-spatial parameters) [5].

Kim et al. [6] reported that muscle torque may account for 66 to 72% of the variation in the temporo-spatial parameters of gait after a stroke. In post-stroke recovery, apart from asymmetrical gait cycles, people also exhibit asymmetrical muscle torque acting on the lower limb joints, which causes difficulties when

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changing position from sitting to standing [7]. This activity requires increased muscle torque production and a greater range of motion in the joints than walking [8]. In people at an early stage after a stroke, the first attempts to change positions from sitting to standing are a key barrier to be overcome in order to reeducate gait in the future. Lomaglio et al. [9] showed statistically significant correlations in post-stroke patients between the torque of the plantar flexor muscles on the affected side and the movement task in a Timed Up and Go test (TUG) ($r = -0.466$).

Moon et al. [10] concluded that greater emphasis should be placed on generating ankle muscle torque to improve gait functions, while Freire et al. [11] reported that morphological changes in the Achilles tendon in hemiparetic stroke survivors were not statistically significant, they also noted differences in the plantar flexor muscles' torque between the affected and the healthy limb. Rabelo et al. [12] showed that the correlation between the torque of muscles acting on ankle joints and the gait parameters of people after a stroke can be useful for monitoring differences in the torque of muscles acting on the ankle joint and can be helpful in programming rehabilitation to improve muscle strength in chronic, post-stroke hemiparesis.

In the daily clinical practice of the therapeutic team, there are a limited number of measurement tools that allow for objectively monitoring the improvement progress of individuals after a stroke. In the early stages of rehabilitation of people with low motor deficits, future compensations are difficult to predict, especially as their consequences last for many years. This study evaluated gait disorders following an early post-stroke period based on differences in the temporo-spatial parameters of gait components, TUG test and the torque of the ankle joint [13].

Previous studies have examined this significant research and clinical problem [14]. These differences in muscle torque production in early post-stroke period can serve as criteria to differentiate correct movement patterns from pathological ones, as well as tools to evaluate the rehabilitation process. After an early stage, a stroke becomes chronic. Therefore, there are a large number of potential outcomes of a stroke that require detailed examination. It has been hypothesized that incensement in the strength of muscles acting on the ankle joint may improve gait patterns. This improvement can be obtained by introducing resistance exercises to the rehabilitation process of post-stroke patients. Although the dynamometric device used to assess muscle strength is not a standard in clinical practice, the results of the study should encourage practitioners to use objective methods of assessing muscle strength even in people with small neurological deficits.

It should be pointed out that, to the best of our knowledge, the current body of literature lacks studies determining the correlations between ankle joint muscles in static and dynamic conditions at different angular velocities for plantar flexors and dorsiflexors, as well as gait speed in people during an early post-stroke period after a stroke. So far, only a correlation between gait asymmetry and muscle torque in patients with chronic stroke has been shown [6]. In our study, we expected to observe the same relation among patients being in an early post-stroke period.

Therefore, this research has aimed to find out the power-velocity capabilities of muscles acting on the ankle joint at low, medium, and high-speed angular velocities for ankle plantar flexor and dorsiflexor muscles, on both the affected and unaffected sides, in people in early post-stroke period. We also aimed at evaluation of the motor task of TUG, temporo-spatial variables of gait and correlation between the torque of muscles acting on ankle joints and gait speed.

2. Materials and methods

2.1. Study design and ethics

This study was carried out as a cross-sectional study. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines for observational studies have been followed [15]. The research project was approved by the Bioethics Committee of Wroclaw Medical University, Poland (approval no. KB–232/2016). All patients in the study were informed of its purpose and course and of their right to withdraw at any stage. All patients provided signed, informed consent at the beginning of the study.

2.2. Study participants

The study was conducted from March 2018 to November 2018 at the Department of Neurological Rehabilitation of the Provincial Specialist Hospital in Wrocław, Poland. In the present study, 30 participants were enrolled (14 male and 16 female). The post-stroke group consisted of 15 patients (7 male and 8 female, mean age of 57 ± 11 years old), and the time since stroke was 1.6 ± 0.6 months. The study group had a low level of disability. The Modified Ashworth Scale (MAS) was used to assess one of the symptoms of damage to the central nervous system, which is spastic muscular tension. The level of functional disability is assessed according to Barthel Index (BI). The control group consisted of 15 healthy people (7 male and 8 female, mean age of 32 ± 4 years old). For the participants in the control group, gait analysis and a torque measurement of muscles acting on ankle joints were collected, and available literature data indicating the reference values for healthy people were used respectively [16]. The detailed demographic and clinical characteristics of the study participants are shown in Tables 1 and 2.

Table 1. Demographic characteristics of study participants (M ± SD)

Characteristics	Post-stroke (*N* = 15)	Healthy (*M* = 15)
Age [years]	57.2 ± 11	32.3 ± 4
Male/female	7/8	7/8
Body mass [kg]	81.3 ± 21	80.1 ± 9
Height [cm]	164.3 ± 11	167.4 ± 10

Abbreviations: *M* – mean, SD – standard deviation, *N* – number of participants.

2.3. Qualification procedures

Patients were selected for the study via medical documentation and a medical examination performed by an experienced neurologist. The inclusion criteria were: the normal range of motion values for both ankle joints, no decreased strength of the muscles acting on ankle joints in a physical examination, and no cognitive or mental disorders. The exclusion criteria were: a level of spasticity higher than grade one on the MAS, severe limb pain, sensory impairment, visual impairment, cognitive impairment, balance disturbances, the presence of other neuromuscular or musculoskeletal disorders, and the inability to independently walk a distance of at least ten meters.

2.4. Gait analysis

To assess the temporo-spatial variables, an inertial sensor, the BTS G-Sensor (BTS Bioengineering Corp., Quincy, MA, USA), was used. The sensor was equipped with a triaxial 16-bit accelerometer with multiple sensitivity (±2, ±4, ±8, ±16 g), a triaxial 16-bit gyroscope

Table 2. Clinical characteristics in post-stroke patients

No.	Time since stroke [month]	Sex	Stroke etiology	Affected limb	MAS	Limb domination	BI
1	1	M	IS	R	1	R	80
2	2	F	IS	L	1	R	80
3	3	M	IS	L	1	R	85
4	2	F	IS	L	1	R	80
5	1	M	IS	L	0	R	80
6	2	M	IS	R	1	R	80
7	1	F	IS	R	1	R	80
8	2	F	HS	R	1	R	80
9	1	M	IS	L	0	R	80
10	2	M	IS	R	1	R	85
11	1	M	IS	R	1	R	80
12	1	F	IS	L	1	R	80
13	1	M	IS	R	0	R	80
14	2	F	HS	R	1	R	85
15	1	F	IS	L	1	R	80
M/N SD Me Min Max	1.53 0.64 1.00 1.00 3.00	F = 7 / M = 8	IS = 13 / HS = 2	R = 8 / L = 7	0.80 0.41 1.00 0.00 1.00	R = 15 / L = 0	81.00 2.07 80.00 80.00 85.00

Abbreviations: IS – ischemic stroke, HS – hemorrhagic stroke, MAS – Modified Ashworth Scale, BI – Barthel Index, R – right, L – left, *N* – number of participants, SD – standard deviation, Me – median, Min – minimum; Max – maximum.

with multiple sensitivity (±250, ±500, ±1000, ±2000 °/s), and a triaxial 13-bit magnetometer (±1200 μT). An accelerometer recorded acceleration in three axes (vertical, antero/posterior and medio/lateral). The G-Sensor has been found valid for assessing physical activity in healthy adults, with an inter-instrument correlation coefficient between 0.90 and 0.99 and an intra-instrument coefficient of variation of ≤2.5% [17]. The output data were converted into numeric units on one axis or as a composite vector (i.e., the result of the sizes of all three axes). This study used the data of composite vectors recording selected temporo-spatial variables characterizing gait.

Measurements were always performed by the same researcher. The research procedure began by measuring the weight and height of patients, as well as the absolute length of their lower limbs (i.e., the greater trochanter of the femur to the lateral malleolus of the lower leg). The data were collected during two movement tasks – namely, gait with self-selected speed and the TUG test. An inertial sensor was placed on the patient's body according to the manufacturer's instructions (i.e., at the level of the sacral bone (S_1) for gait analysis and the level of the lumbar spine (L_2) for TUG). Measurements were undertaken in footwear without the use of any additional orthopedic equipment. Gait assessments were performed during a movement task in which the subject walked a distance of seven meters. This distance ensured free and full communication between the sensor and the control unit and enabled us to register about two to four full gait cycles, depending on the patient's gait speed. Repetitions of this movement task were recorded for further analysis of the mean course and to extract the pattern of representative data. The selected temporo-spatial parameters analyzed were: gait cadence (GCAD) [steps/min], gait speed (GSP) [m/s], and gait cycle (GC) for the single stance phase [%]. A single stance/support time ratio measured as a ratio of a single stance time to gait cycle time and expressed in percent.

The TUG test was measured by vertical acceleration (VTA) [m/s²] during sit-to-stand and stand-to-sit activities. The stabilization period, identified by Schenkman et al. [18], was not included in the time to complete the TUG. Individuals were seated on an armless chair with the lower limbs flexed at the hip and knee joints at approximately 90°. The distance from the feet to the chair was not defined. The subject's task was to stand up from the chair (without any upper limb assistance), walk a distance of about three meters, and then return to the seat (Fig. 1).

Fig. 1. The assessment of temporo-spatial variables during gait using an inertial sensors

2.5. Torque analysis

The professional Biodex System 4 Pro™ (Biodex Medical Systems Inc., Shirley, NY, USA) was used to assess power-velocity capabilities. People from the study group were asked to sit in the dynamometer chair, which is an integrative part of the Biodex System [19]. The subject's position, with stabilized trunk, pelvis, and thighs, was assured by belts, according to the manufacturer's recommendations, in such way that the knee joint stayed in extension.

A dynamometer construction ensured a precise adjustment of the motion axis (the dynamometer arm) to the tested joint's axis of movement (in this case, the ankle joint). The measurement was conducted at three angular velocities in the sagittal plane and under isometric conditions at the neutral position of the ankle joint. The torque measurement in the static condition (isometry) was also carried out in the ankle joint's neutral position (0° = perpendicular angle between the shank and the foot), with the foot strapped to the dynamometer platform [20]. Due to differences in the transverse muscle mass of the ankle plantar flexors and dorsiflexors, different angular velocities were assumed for plantar flexion (30, 60, and 120 °/s) and dorsiflexion (60, 120, and 180 °/s) in isokinetic testing.

For each angular velocity, participants were instructed to perform plantarflexor or dorsiflexor maximal voluntary contractions (MVC). Five movement repetitions were done for both isometric and isokinetic measurements. Group testing after a stroke started with an affected limb. For the control group, the first measurement was taken for the lower right and then for the left lower limb. The measurements contained one trial at each angular velocity and isometry. The interval between isokinetic measurements was at least one minute between each trial and 30 seconds between isometric repetitions. Before the measurements began, each person was informed, in detail, about his or her course. The patient was also allowed to perform trial tests. Muscle torque was assessed over the entire range of motion in the isokinetic measurements. The torque measurement was first performed for the affected limb. There were no side differences between the torque values of muscles acting on the ankle joints in the control group. The comparative parameters were the relative and absolute peak torques of the healthy limb and the affected limb. One person from the post-stroke group (No. 9) did not agree to the torque measurements.

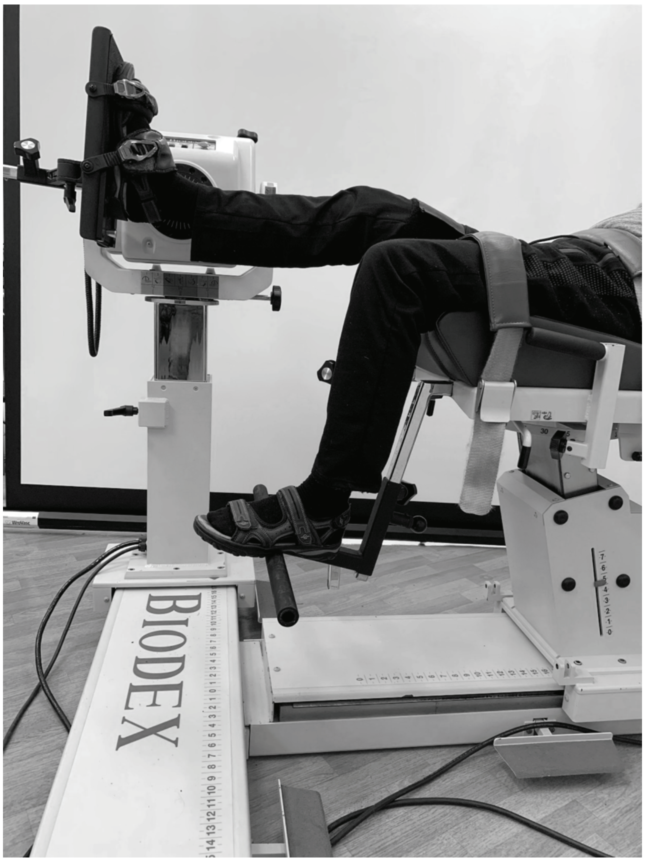

Fig. 2. The assessment of power-velocity capabilities of lower limb using a dynamometer

Muscle torque was analyzed using the Biodex software (Biodex Medical Systems Inc., Shirley, NY, USA). Peak torque was defined as the highest recorded torque value in all conditions assumed for this study. The relative torque was defined as the highest recorded torque value for each of the analyzed conditions in relation to the subject's body weight [Nm/kg]. The isokinetic torque (dynamic) was evaluated for a given constant angular velocity in the concentric activity. The isometric torque (static) was evaluated as a measurement in a constant angle. The influence of gravity was reduced by using a horizontal position. The G-Studio software, version 3.0.18.0 (BTS Bioengineering Corp., Quincy, MA, USA) was used to assess the temporo-spatial parameters (Fig. 2).

2.6. Statistical analysis

Statistical analysis was performed using Statistica software, version 12 (StatSoft, Inc., Tulsa OK, USA). Arithmetic means and standard deviations were calculated for continuous variables. None of the continuous variables had a distribution similar to a normal distribution (based on the Shapiro–Wilk test). Therefore, non-parametric tests were used. The Mann–Whitney *U*-test was used to compare the results of GCAD [steps/min], GSP [m/s], stand-to-sit VTA [m/s^2], and sit-to-stand VTA [m/s^2] between the post-stroke and control groups. The Kruskal–Wallis variance analysis and post-hoc tests were used to compare the results of GC [%] and torque parameters of the affected and contralateral limbs (post-stroke group) versus the healthy limb (control group). Spearman's test (*Rs*) analyzed the linear association between the results of GSP and torque parameters in both groups. For all analyses, a type 1 error probability of 5% ($\alpha = 0.05$) was considered, and the obtained *p*-values were rounded to three decimal places for this study.

3. Results

3.1. Gait parameters and the TUG

The results of the mean temporo-spatial parameters and the TUG in the post-stroke group are presented in Table 3. Post-stroke patients had a statistically significantly lower GCAD compared to healthy participants (17%, $p \leq 0.01$). There was also a difference in single stance phase times during the gait cycle between the affected (2%, $p < 0.93$) and contralateral (7%, $p < 0.99$) limbs. In post-stroke patients, a gait cycle for the single stance phase was longer for a healthy limb than for an affected limb. For the sit-to-stand task, statistically, significantly lower values of vertical acceleration were found (42%, $p < 0.03$) in stroke patients.

Table 3. Results of time-space parameters for gait and TUG (M ± SD)

Test	Parameter	Post-stroke group		Control group
		Affected limb	Contralateral limb	Healthy limb
Gait	GCAD [steps/min]	93.3 ± 17.4*		112.9 ± 6.1
	GSP [m/s]	0.9 ± 0.1		1.09 ± 0.1
	GC [%]	36.9 ± 3.2	38.7 ± 3.7	36.2 ± 2.3
TUG	stand-to-sit VTA [m/s²]	6.3 ± 3.5		7.5 ± 0.7
	sit-to-stand VTA [m/s²]	4.1 ± 1.6*		7.1 ± 2.3

Abbreviations: GCAD – gait cadence, GSP – gait speed, GC – a single stance/support time ratio measured as a ratio of a single stance time to gait cycle time and expressed in percent of the affected and contralateral limb, M – mean, SD – standard deviation, TUG – Timed Up and Go test, VTA – average value of vertical acceleration without correction for gravity.

* Statistically significant differences at $p < 0.05$.

3.2. Plantar flexion torque parameters

The mean values of the torque of ankle plantar flexors, on both the affected and healthy sides of post-stroke patients, are presented in Fig. 3. The relative torques of the plantar flexor muscles for the affected and healthy limbs during static conditions were 0.38 Nm/kg and 0.4 Nm/kg, respectively. They were statistically significantly lower than the torque in the control group, which was 0.96 Nm/kg (by 63% and by 58%, $p \leq 0.01$). The relative torque for the affected and healthy limbs during dynamic conditions at 30°/s also yielded a statistically significant difference: 0.36 Nm/kg for the affected limb, 0.49Nm/kg for the healthy limb, and 0.71 Nm/kg for the control group (by 49% and by 31%, $p = 0.04$). In movements at an angular velocity of 60°/s, the differences were statistically significant between the affected limb, at 0.27 Nm/kg, and the control group, at 0.64 Nm/kg, (by 58%, $p = 0.01$). In high-speed movements of 120 °/s, statistically significant differences again occurred between the two limbs in stroke patients – 0.27 Nm/kg for the affected side and 0.32 Nm/kg for the healthy side – and people in the control group – 0.57 Nm/kg (by 53% and by 44%, $p = 0.01$).

3.3. Dorsiflexor torque parameters

The dorsiflexor muscles were characterized, as expected, by lower relative torque values compared to plantar flexor muscles (Fig. 4). The only statistically significant difference in the recorded torque was for isometric work of the affected limb, which was 0.3 Nm/kg, compared to the control groups where it was 0.48 Nm/kg (by 38%, $p = 0.04$). Interesting results were observed in the fast dorsiflexion movements of 180°/s. The affected limb obtained higher relative torque values than the healthy limb (by 15% and by 14%, $p = 0.46$, $p = 0.28$). In the other tested velocities, no statistically significant differences were recorded, and, as expected, higher relative torque values were recorded for the healthy limb than for the affected limb.

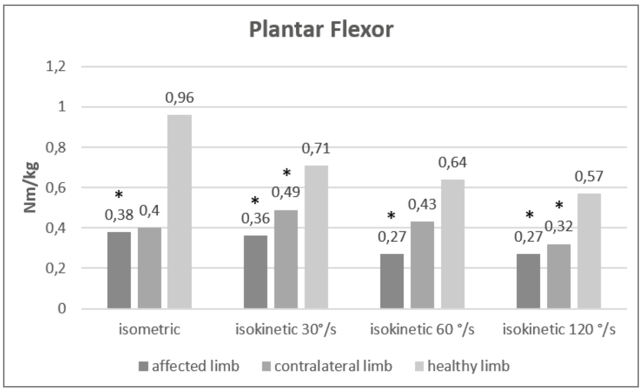

Fig. 3. Plantar flexor torque under static conditions and three angular velocities for the affected and contralateral limbs in post-stroke patients and for the healthy limb.
* Statistically significant differences at $p < 0.05$

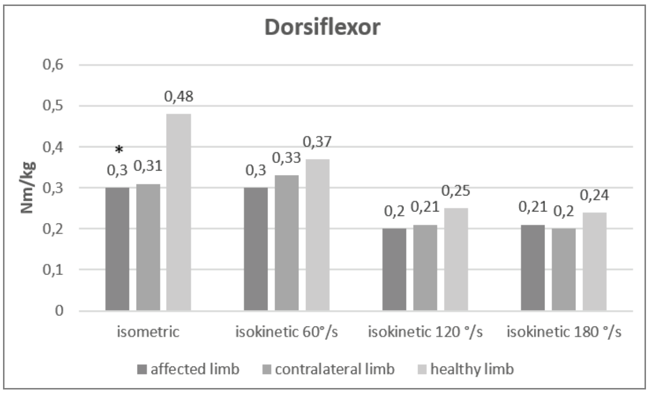

Fig. 4. Dorsiflexion torque under static conditions and three angular velocities for the affected and contralateral limbs in post-stroke patients and for the healthy limb.
*Statistically significant differences at $p < 0.05$

3.4. Correlations of muscle torque with gait speed

The next stage of the study analyzed correlations between the torque values of muscles acting on the ankle joint in static and dynamic conditions during plantar flexion and dorsiflexion movements with GSP parameters. A statistically significant positive correlation was observed between the absolute peak torque of the dorsiflexor muscles in static conditions and gait speed ($Rs = 0.65$, $p = 0.04$). It was the only statistically significant correlation. Concerning the absolute peak torque of the plantar flexor muscles, the statistical analysis showed a limited positive correlation ($Rs = 0.53$, $p = 0.11$). A positive correlation was also demonstrated between GSP and plantar flexor muscles ($Rs = 0.55$, $p = 0.09$). However, there were no statistically significant correlations between GSP and dorsiflexor muscle torque ($Rs = 0.47$, $p = 0.17$).

4. Discussion

Physiotherapy offers a wide range of anti-spastic procedures including neurophysiological methods such as neurodevelopmental treatment (NDT Bobath) or proprioceptive neuromuscular facilitation (PNF), as well as conventional ones constrained-induced movement therapy (CIMT), postural control training, passive stretching, hydrotherapy, hippotherapy, kinesiology taping (KT), and orthopedic devices [21]–[23]. Also, biophysical agents, including neuromuscular stimulation (NMS), electromyography-triggered neuromuscular stimulation (EMG-NMS), transcutaneous electrical nerve stimulation (TENS), functional electrical stimulation (FES), or mechanic therapies such as ultrasound therapy and shock waves (ESWT) are commonly used as supplementary treatments [24]–[27].

Rehabilitation of people after a stroke always starts with a physical examination, especially assessment of gait. In the early stage after stroke, the determination of individual and achievable goals is a priority. In neurological rehabilitation departments, gait assessment is often performed on the basis of visual assessment. In the case of people with low neurological deficits, this assessment may not be sufficient or even flawed. As noted in the introduction, each type of stroke involves to a chronic phase that can last for many years. In this paper, in the study group, despite the low intensity of neurological deficits and the early post-stroke stage, changes in the gait parameters and the torques of muscle acting on the ankle joints were observed.

The aim of the present study was not to assess dependence, but only to assess the power-velocity capabilities of post-stroke patients with early alterations in the motor system. Despite the low intensity of spasticity, differences in the muscle torque production and temporo-spatial parameters were noticeable. At the time of measuring the muscle torque and the selected temporo-spatial parameters, the patients from the post-stroke group were staying in the neurological rehabilitation ward for the first time. The short period after stroke onset – between one and three months – allowed for the assessment of gait and power-velocity capabilities before the formation of compensation phenomena.

A non-standard measurement protocol was used to assess the torque of muscles acting on the ankle joint under isokinetic conditions in the affected and unaffected sides of post-stroke patients. For the high-speed movements of 120 °/s and 180 °/s in post-stroke patients, an increase in torque was noted in the affected side. In the control group, the mean relative torque of the ankle plantar flexor and dorsiflexor muscles presented the correct relationship between the torque and angular velocity, i.e., as angular velocity increased, torque decreased. No similar relationship was observed in the group of people after a stroke. In the higher angular velocity values tested, the muscle torque did not decrease with increasing angular velocity. This relationship may correspond to a change in the recruitment of motor units in the muscle groups tested as a consequence of a recent stroke.

In isokinetic testing of the control group, only the values obtained from the plantar flexor muscles differed statistically significantly from those obtained in the post-stroke group. The results published by Kim et al. [6] (ankle plantar flexion of 30 °/s and 0.19 Nm/kg; dorsiflexion of 30 °/s and 0.15 Nm/kg), by Lomaglio et al. [9] (ankle plantar flexion of 30 °/s and 0.18 Nm/kg, dorsiflexion of 30 °/s and 0.11 Nm/kg), and by Hsu et al. [28] (ankle plantar flexion of 30 °/s and 0.21 Nm/kg) for the affected side were lower than those obtained in our study(ankle plantar flexion of 30 °/s and 0.36 Nm/kg and of 60 °/s and 0.27 Nm/kg, dorsiflexion of 60 °/s and 0.25 Nm/kg and of 120 °/s and 0.21 Nm/kg). Flansbjer et al. [29] noted the largest difference in the affected limb's dorsiflexor muscle torque – 13.5 Nm. The papers assessing the relationship of the torque of the muscles acting on the ankle joint to the gait parameters (mainly the GSP) were consistent as to their statistically significant interdependencies [4].

In most of the available publications, values for angular velocities of 30 °/s and 60 °/s were used for isokinetic testing [6], [22]. The abovementioned angular velocities were selected because they were similar to the peak angular velocity of ankle joints during gait in post-stroke patients. In this study's post-stroke group, the gait speed was higher than in previously published studies. Additional differences were the shorter duration from the onset of stroke and the lower degree of AS spasticity on the affected side. Compared to control group, the affected limb in post-stroke patients was characterized by a statistically significant difference in torque production of the ankle plantar flexor and dorsiflexor muscles during static conditions.

Using inertial sensors to assess temporo-spatial gait parameters in post-stroke patients enabled quick and reliable assessment of the existing differences. Additionally, the inertial sensors made measurements easy to perform and allowed for valuable analysis of the obtained data. In the present study, people in the post-stroke group had experienced a stroke for the first time, and the study started between one and three months after the onset of stroke. Despite the short period after the neurological incident, disorders characterizing hemiplegia, especially in gait patterns, were recorded. Compared to the reference data from the literature [16], there were statistically significant differences between the GSP, GCAD, and lower limb load symmetry during walking. The patients from the post-stroke group achieved results higher (by 15% GCAD and by 45% GSP) than those presented by previous researchers. Milot et al. [32] noted a GSP of 0.62 ± 0.26 m/s and a GCAD of 81.6 ± 12.8 steps/min, while Hsu et al. [28] reported a GSP of 0.62 ± 0.21 m/s and a GCAD of 84.5 ± 14.2 steps/min.

Our results in patients from one to three months post-stroke showed higher GCAD values (Table 3). Also, a single stance/support time ratio measured as a ratio of a single stance time to gait cycle time and expressed in percent of the affected and contralateral limb. This distribution should be approximately 40% of the swing phase and 60% of the stance phase [33]. In the study group the proportion of mid stance and swing phases in the gait cycle was changed. The cause of these changes can be detected at a lower gait speed. Additionally, the study group was characterized by a higher gait cadence, which may indicate a compensation of the slower gait speed.

Importantly, in this study's results, there were differences in limb load between the affected and unaffected sides. Patients from the post-stroke group were loaded on the affected side more lightly than on the unaffected side, and these data correspond with results obtained by other authors. Drużbicki et al. [3] noted a 0.96 ± 1.28 s stance phase for the affected side and a 1.13 ± 1.53 s stance phase for the unaffected side, while Hsu et al. [28] showed a 1.05 ± 0.31 s stance phase for the affected side and a 0.94 ± 0.23 s stance phase for the unaffected side. It should be also emphasized that the spasticity grade of patients in the present study was between zero and one on the AS. Therefore, concerning hemiplegia severity and time from stroke onset, we noticed differences between this study's obtained values for the measured parameters and the data from previously available research.

The present study has some potential limitations. The research was carried out in the clinical conditions of only one center. The size of the post-stroke group was not large and was not representative enough to generalize changes in ankle muscle torque production to the whole population of patients who have experienced their first stroke with accompanying mild spasticity. Therefore, the pilot character of this study should be emphasized. It should be mentioned that only two patients with hemorrhagic stroke were qualified, however, all participants met the same criteria to be included in the study and they presented similar MAS and BI scores. Therefore, it should be considered that the study group was homogenous at baseline. Another issue to discuss is that the results of this study demonstrated significant asymmetry in the torque production of the plantar flexor and dorsiflexor muscles after a stroke, which may be the reason for negative changes in the selected temporo-spatial parameters of gait. Avoiding high-speed movements for ankle dorsiflexion and implementing strength training should be considered in neurorehabilitation programs.

5. Conclusions

The study group consisted of people in the initial period and after the first stroke. Despite the participants of study group having a low level of disability, asymmetries have been noted, which may cause future compensations and their negative consequences. Stroke negatively affects the magnitude of torque asymmetry and changes the selected temporo-spatial parameters for gait and sit-to-stand task. Reduced strength parameters of the muscles acting on the ankle joint are one of the factors that may influence the final gait pattern in post-stroke survivors. Inertial sensors are a valuable method of objectively assessing differences in temporo-spatial parameters in hemiplegic patients.

Therefore, during everyday neurorehabilitation practice, it is important to introduce methods of strengthening the muscles acting on the ankle joint.

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