EREDETI KÖZLEMÉNY

ORIGINAL ARTICLE

The effect of body position, leg dominance, and automatic releasing mechanism on quadriceps muscle tone assessed by Pendulum Test in able-bodied persons

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| English | https://doi.org/10.18071/isz.77.0303 | www.elitmed.hu

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Érkezett:
2024. április 21.
Elfogadva:
2024. július 28.

Background and purpose – Quadriceps femoris muscle spasticity is commonly measured by the Wartenberg pendulum test. It is generally assumed that lower values of the number of swings of the leg and lower relaxation indexes are associated with higher muscle tone and more spasticity. Still, there is incoherence regarding the test's applications with various body positions and starting mechanisms. This study aims to investigate the influence of body position, leg dominance, and automatic leg-releasing mechanism on muscle tone measured by pendulum test in healthy population whose muscle tone is often compared to the spastic muscle tone of patients with neurologic disorders.

Methods –15 healthy adults (age: 19-32 years, 9 males, 6 females) participated in this study. A Zebris 3D ultrasound-based motion analysis system was used to record kinematic data during the pendulum test. The number of swings of the leg and the relaxation index were computed from the collected data. The pendulum test was completed in eight conditions: in supine and semi-supine positions on the dominant and non-dominant leg separately and with investigator-release and automata-release mechanisms. Paired *t-tests* and Wilcoxon test with the significance level of .05 were applied in comparison of pairs of the pendulum test condition.

A testhelyzet, a végtag-dominancia és az automata elengedési mód hatása az izomtónusra ép testű, fiatal felnőtteknél

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Háttér és cél – A quadriceps femoris izom spasticitasának meghatározására gyakran Wartenberg-pendulumtesztet alkalmaznak. Általánosságban azt feltételezik, hogy a lábszár lengésszámának alacsonyabb értékei és az alacsonyabb relaxációs indexek magasabb izomtónussal és nagyobb spasticitassal járnak együtt, de nincs egységes testhelyzet- és indítási módszer alkalmazás a teszt során. A jelen tanulmány célja megvizsgálni a testhelyzet, a lábdominancia és a láb automata elengedésének hatását a pendulumteszttel mért izomtónusra egészséges populációban, akiknek izomtónusát gyakran hasonlítják össze neurológiai betegek spasticus izomtónusával.

Módszerek – Tizenöt egészséges, felnőtt (életkor: 18–32 év, 9 férfi, 6 nő) önkéntes vett részt a vizsgálatban. A pendulumteszt során kinematikai adatokat rögzítettünk Zebris 3D-s ultrahang alapú mozgásvizsgáló rendszerrel. Ezekből az adatokból számítottuk a láb lengésszámát és a relaxációs indexet. A tesztet nyolc kondícióban végeztettük el: félfekvő helyzetben, háton fekvésben, a domináns és a nem domináns végtaggal külön-külön, a vizsgáló általi és az automata elengedés módszerével. A kondíciók adatainak összehasonlításához páros t-próbát és Wilcoxon tesztet alkalmaztunk, a szignifikanciaszint p < 0,05 volt.

Results – 1) Applying automata-release mode, in the non-dominant leg the number of swings ($p=0.03$) and the relaxation index ($p<0.001$) were significantly higher in semi-supine than in supine position. 2) The non-dominant leg had significantly more swings than the dominant leg in both body positions with automata-release mode ($p=0.009$, $p<0.001$). In investigator-release mode this occurred in supine position ($p<0.001$). 3). Regarding the number of swings in investigator-release versus automata-release mode, no significant differences were found in any test condition, but the relaxation index showed significant difference for the non-dominant leg ($p=0.01$, $p=0.009$). 4) The values of the relaxation index didn't support in all test conditions the results what the number of swings provided about the muscle tone. In automata-release mode, the dominant leg has a lower number of swings and a higher relaxation index than the non-dominant leg.
Conclusion –The effect of body position on the quadriceps muscle tone can be assessed by applying the pendulum test with an automatic leg-releasing mechanism even when the application of conventional investigator-release mode does not show a significant effect. The pendulum test is more sensitive to assess spasticity with automatic-release than with investigator-release mode.

Keywords: spasticity, Wartenberg pendulum test, leg swings

Eredmények – 1) Automata elengedés alkalmazásakor a lengésszám ($p = 0,03$) és a relaxációs index ($p < 0.001$) magasabb volt félfekvő helyzetben, mint háton fekvésben. 2) A nem domináns végtagnál a lengések száma magasabb volt, mint a domináns oldalon, mindkét testhelyzetben, amikor automata elengedést alkalmaztunk ($p = 0,009$, $p < 0,001$). A vizsgáló általi elengedés esetén ezt háton fekvésben tapasztaltuk ($p < 0.001$). 3) A lengések számában nem találtunk szignifikáns különbséget a vizsgáló általi elengedés és az automata elengedés között egyik kondícióban sem, de a relaxációs index értékei szignifikáns különbséget mutattak a nem domináns végtag esetén ($p = 0,01$, $p = 0,009$). 4) A relaxációs index értékei nem minden tesztkondícióban támasztották alá a lengések számából következtethető izomtónus-eredményt. Automata elengedéskor a domináns oldali alsó végtag lengésszáma alacsonyabb, relaxációs indexe pedig magasabb volt, mint a nem dominánsé.
Következtetés – A testhelyzet hatása az izom tónusára mérhetővé válik olyan pendulumteszt alkalmazásánál, amelynél automata indítást használnak, még abban az esetben is, ha ezt a hagyományos, vizsgáló által indított teszt nem mutatja. A pendulumteszt érzékenyebb spasticitast mérő módszer automata elengedést alkalmazva, mint a vizsgáló általi elengedést használva.

Kulcsszavak: spasticitas, Wartenberg-pendulumteszt, láblengés

Spasticity is defined as a motor disorder featured by a velocity-dependent increase in muscle tone or tonic stretch reflexes associated with hypermuscletonia[1]. It is commonly the consequence of an upper motoneuron lesion, which is proximal to the alpha motor neurons, therefore within the spinal cord or brain. Spasticity appears as a symptom in many neurological diseases, such as spinal cord injury, stroke, cerebral palsy, anoxia, traumatic brain injury, multiple sclerosis, and other neurodegenerative disorders[2]. Spasticity harms the quality of life with stiff and painful joints[3, 4] and can therefore interfere with daily function, hygiene, and nursing care[5]. It is generally accepted that spasticity is easy to recognize, but not so easy to quantify, which is crucial in determining treatment interventions. The most common and currently used clinical measures for spasticity are quantitative scales such as Ashworth or Tardieu Scale[6–8], but they lack objectivity. This means that small changes in the level of spasticity could be disguised, and this makes it difficult to evaluate the effectiveness of treatment interventions.

The pendulum test was introduced by *Wartenberg* as a simple and reliable clinical test to objectively quantify quadriceps muscle tone in Parkinson's disease[9]. In this test, the patient is placed on a bench with the lower limb hanging freely from the knee. Afterward, the examiner lifts the relaxed lower leg to the horizontal, fully extended knee position and then releases it to swing freely with regular, gradually decreasing movements, like a pendulum. The number of substantial swings is 6 to 7 in healthy subjects and a reduced number of swings could be found in spastic patients.

There is incoherence in the application of various initial body positions and starting mechanisms. Previous studies have used different body postures including upright[10, 11], supine[12, 13], and semi-supine[14, 15]. The semi-supine positions alternated between 15 and 70 degrees of hip flexion. Muscle spasticity is muscle length dependent[16], and the increase of muscle length augments the stretch reflex activity[17–19], therefore the positioning of subjects during measurement could influence the results of the spasticity assessment, particularly when bi-articular muscles are involved. However, *Burke* et al. found in the case of the quadriceps femoris muscle, that the lengthening has an inhibitory effect[20]. There are contradicting findings in the literature about the comparison of different testing positions. Studies[21–23] showed, that a change in body posture from sitting to supine enhanced the spastic state during the pendulum test, with increased muscle activity and changed goniometric parameters. In our previous study, we also found, that the number of swings in the pendulum test performed in semi-supine position was significantly higher than in supine position in the case of a spinal cord-injured (SCI) person[24]. In contrast, others[14, 25, 26] found that the position of the subject has no practical significance.

Features of healthy muscle tone cannot be neglected since healthy subjects are mostly involved in the pendulum test studies as control group[27–30], and there are investigations[21, 31] in which the muscle tone of the healthy, non-affected side of hemiplegic patients is compared to the spastic side. Only a few studies[14, 32] measured during the test the muscle tone solely in healthy subjects irrespective of patients, although knowledge of the characteristics of healthy muscle tone can be useful in research when healthy and spastic muscles are compared.

To the best of our knowledge, it has not been investigated how can leg dominance influence the spasticity of the muscles, while pendulum test is applied. Previous study showed[33] that greater quadriceps muscle volume is associated with higher levels of knee extensor muscle spasticity in children with spastic diplegic Cerebral Palsy (CP).

Due to their loss of sensation, spinal cord-injured people do not perceive the moment of foot release, for them, it is always an unexpected event. During our previous measurements, we found that there is interference between the subject and the investigator and when the examiner releases the foot, the able-bodied test subjects already expect the start from the examiner's small hand movements, and this can influence the movement pattern of the swing. The more times we measure, the more pronounced it is. We wanted to prevent this phenomenon with an automatic releasing mechanism developed by us, which can make the pendulum test more objective. In only a few studies[34–36] were special apparatuses built to hold the limb magnetically[35, 36] or by a light strap around the ankle[34] for the opportunity to release the leg abruptly and make the assessment more objective. In these studies, they did not compare the automatic releasing mechanisms to the usually used hand release.

It was therefore the aim of this study to investigate the effects of body positions, leg dominance, and automatic releasing mechanism on leg kinematics during the Wartenberg pendulum test in healthy young adults. We hypothesized that body positions and leg dominance would change the kinematic pattern of the lower limb and an automatic leg releasing procedure would increase the sensitivity and objectivity of the test.

Methods

Participants

Fifteen able-bodied, college-aged students volunteered in the present study (age range: 19-32 years, 9 male and 6 female). **Table 1** summarizes the characteristics of the subjects. All participants gave their informed consent before participating in the study, which was approved by the Medical Research Council, Hungary (Approval Number: BM/8964-1/2024). Neurologic disorders, pre-

Table 1. *Characteristics of the participants*

Participant	Age (years)	Lower leg length	M-Ashworth score	Leg dominance
		right/left (cm)		right/left leg
1	21	45/45	0/0	right
2	22	36.5/36	0/0	right
3	22	40/40	0/0	right
4	25	36/36	0/0	right
5	32	36.5/36.5	0/0	right
6	23	36.5/36	0/0	right
7	24	40/40	0/0	right
8	21	40/40	0/0	right
9	19	46/46	0/0	right
10	21	45/44,5	0/0	left
11	23	49/49	0/0	right
12	21	45,5/46	0/0	right
13	26	41/41	0/0	right
14	21	46/46	1/1	right
15	27	46/45,5	0/0	right

M-Ashworth score 0: No resistance in skeletal muscle tone; M-Ashworth score 1: Slight increase in muscle tone vious trauma or prior surgery of the knee joints, active knee arthritis or pain, and deformities over knee joints were excluded.

Measurements

For each participant, we collected anthropometric data including age, leg dominance, and lower leg length, furthermore, we evaluated the quadriceps muscle tones with a spasticity scale **(Table 1)**.

Leg dominance was determined as the leg used to kick a soccer ball. Van Melick et al. found that the leg what is used to kick the ball had 100% agreement between the self-reported and detected dominant leg for both women and men[37]. According to this, we asked our participants to denote which foot they would kick the ball with, to determine their leg dominance.

Lower leg length was measured in a seated position as the distance between the head of the fibula and the sole, assessed by measure band. Quadriceps muscle tone was assessed by a physiotherapist using a modified version of the Ashworth scale[7].

Pendulum test is a Zebris 3D ultrasound-based motion analysis system (ZEBRIS, CMS10, Medizintechnik GmbH, Isny, Germany). It was used to collect and record the kinematic data during the pendulum test. The Zebris system consists of a central measuring unit, three ultrasound-emitting heads, and small markers with ultrasonic microphones. The central measuring unit sampled the marker position data at 50 Hz. The system provides the Cartesian coordinates (x, y, and z) of the markers. Four small (diameter of 5 mm) markers were attached to anatomical landmarks of the leg: the head of the fibula, the greater trochanter of the femur, the lateral epicondyle of the femur, and the lateral malleolus of the fibula. All collected data was saved for processing with WinData software (Zebris Company) on Windows 7 (Microsoft, Redmond). The same Zebris system simultaneously recorded the EMG activity in the vastus lateralis, vastus medialis, rectus femoris, and biceps femoris muscles in both legs using surface electrodes. The EMG activities were recorded at 900 Hz.

Procedure

For the pendulum test, each subject sat at first in a comfortable position on a specially designed couch with his or her trunk reclined 45 degrees from vertical in a semi-supine position and then in a supine lying position and with the lower leg hanging over the edge of the couch. All participants wore shorts and were barefoot. Four Zebris markers were attached on the lateral side of the subject's legs. EMG surface electrodes were placed over the above-mentioned tight muscles of both legs. Before placing the electrodes, the skin was shaved if necessary,

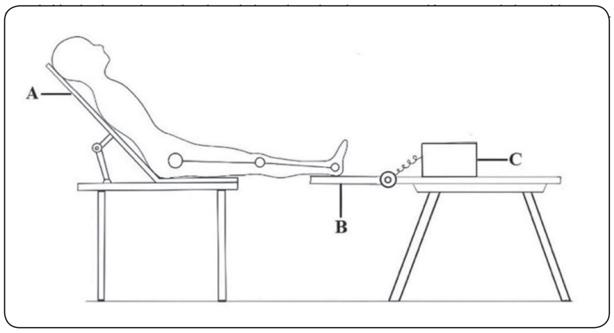

Figure 1. *Experimental setup for pendulum test with automata foot-releasing apparatus*

A: adjustable backrest in 45 degrees semi-supine position, B: plate with electromagnet, C: control unit

investigator-release mode the investigator held the foot and fully extended the knee joint, and then released the leg to swing freely. In automata-release mode the leg was released automatically by a foot-releasing apparatus: the foot was supported on a plate, which folded down abruptly, randomized by a computer **(Figure 1)**.

The automatic foot release mechanism consists of a plate (38 cm by 34 cm), that is attached by hinges to a sturdy table. When locked, the plate is held in a horizontal position by a strong electromagnet (similar to those that keep doors locked in buildings). For safety reasons the magnet does not snap in the plate, mechanical switches detect when the plate is rotated by hand to the up positions, and the electromagnet only switches on when contact has already been made with the armature plate. When the examiner sends a ready signal to the control unit, it waits between 5 and 15 seconds (chosen uniformly randomly), then switches off the electromagnet thus releasing the plate, which abruptly swings down, away from the participant. Participants completed three trials for each condition with five seconds between trials and five minutes between conditions.

Data processing

Recorded marker position data were processed by self-developed computer programs using MATLAB (The MathWorks, Natick, MA) and Python (Python Software Foundation, Wilmington, DE, USA). Knee joint angles were calculated from marker coordinates by trigonometric equations.

Outcome measures

The number of swings: The time course of the knee angle was analyzed. The extreme values (minimal and maximal knee angles) were identified consecutively in each swing, and the swings were counted until the difference between two consecutive extreme values was bigger than 3% of the difference between the first minimum and maximum values.

Relaxation index (RI): An index, as the measure of spasticity, is the ratio between the amplitude of the first knee angle flexion and the difference between the starting angle and resting angle[12]. This index has been verified as an indicator of spasticity[14, 39, 40], and in healthy subjects, RI was found to be 1.6 or more[12] (**Figure 2)**.

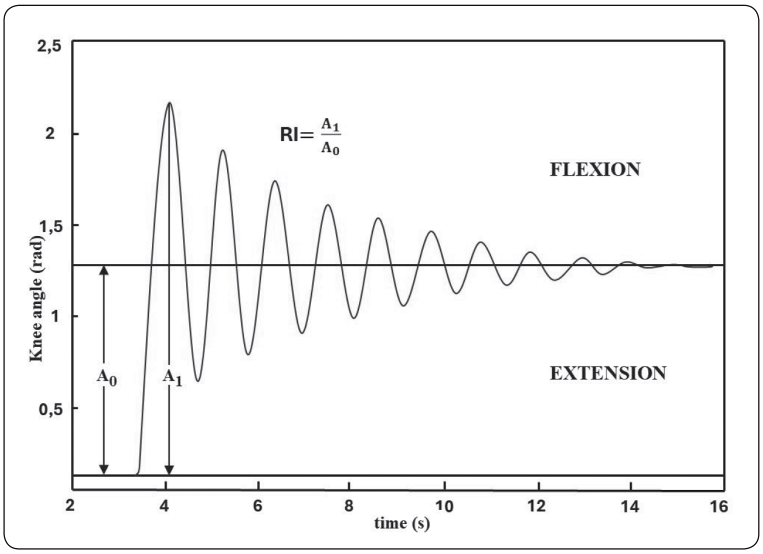

Figure 2. *Knee angle during the pendulum test in subject number 14 on non-dominant leg with investigator release in semi-supine position*

Fully extended knee means 0 knee angle. RI: relaxation index, A_0: Amplitude between the starting angle and resting angle, A_1: Amplitude between the first knee angle flexion and the starting angle

Statistical analysis

The data were analyzed using SPSS Statistics software (Version 29.). We compared data from the supine position with that from the semi-supine position and data of the dominant leg with the data of the non-dominant leg, furthermore, data was obtained in investigator-release and automata-released mode. The normality of the data sets was assessed using the Shapiro-Wilk test. Data sets that followed a normal distribution ($p > 0.05$) were analyzed using a paired t-test, while non-normally distributed data sets ($p \leq 0.05$) were analyzed using the Wilcoxon signed-rank test. To perform a proper statistical analysis, different numbers of trials were included in the comparison of different pairs of test conditions, as some measurements were excluded due to measurement errors.

To assess the relationships between the number of swings and the relaxation indexes in our study, both Pearson and Spearman correlation coefficients were utilized based on the data distribution characteristics. Pearson's correlation coefficient was applied to data sets that were normally distributed ($p > 0.05$) to evaluate the linear relationships between them. For data sets that did not follow a normal distribution ($p \leq 0.05$), Spearman's rank correlation coefficient was used to determine the monotonic relationships.

Cohen's d was calculated to determine the effect sizes of the differences in the number of swings and relaxation index between the compared conditions and categorized as low (0.2–0.49), moderate (0.5–0.8), or strong (> 0.8). All analyses were performed using SPSS Statistics (Version 29.), and the significance threshold was set at $p \leq 0.05$.

Results

Number of swings

Comparing the number of swings in semi-supine versus supine positions **(Table 2)**, in investigator-release mode, there were marginally significant differences, meaning a slightly bigger number of swings in semi-supine position (p=0.06, p=0.07). In automata-release mode, the number of swings was significantly higher in semi-supine than in supine positions, in the case of the non-dominant leg (p=0.03). This indicates higher muscle tone in supine position.

Comparing the number of swings in the dominant leg versus the non-dominant leg **(Table 3)**, it was found that the non-dominant leg had significantly more swings with automatic-release mode in both body positions (p=0.009, p<0.001) and also in hand-release mode in supine body position (p<0.001). This indicates higher muscle tone in the dominant leg.

Comparing the number of swings in investigator-release mode versus automatic-release mode **(Table 4)**, there were no significant differences in either test condition.

Relaxation index

Comparing the relaxation index obtained in semi-supine versus supine positions **(Table 2)** the RI values were similar in the case of investigator-release mode and RI was significantly smaller in supine than in semi-supine position when automata-release mode was applied (p=0.005, p<0.001). This indicates higher muscle tone in supine position.

Comparing the relaxation index in the dominant leg versus the non-dominant leg **(Table 3)**, the RI was significantly smaller for the non-dominant leg in both release modes and positions (p=0.02, 0.01, 0.02, 0.04). This indicates a higher muscle spasm in the non-dominant leg.

Table 2. *Means of the outcome measures of the Pendulum Test in 2 body positions. (Means across trials and participants). The (n) is the total number of trials of all of the participants considered in the comparison of the paired conditions. The (d) denotes the Cohen's effect size*

Outcome measures and conditions	Supine	Semi-supine	p	d	n
Number of swings Mean ± SD					
†Investigator-release mode, dominant leg	6,17±1,8	6,71±1,9	0.06″	0.001	32
#Investigator-release mode, non-dominant leg	6,66±1,9	7,1±1,6	0.07″	0.31	33
†Automata-release mode, dominant leg	6,21±1,8	6,48±1,7	0.2	0.22	32
#Automata-release mode, non-dominant leg	6,68±2	7,04±1,8	0.03*	0.36	35
Relaxation index					
†Investigator-release mode, dominant leg	1,8±0,25	1,8±0,03	0.4	-0.12	34
#Investigator-release mode, non-dominant leg	1,8±0,2	1,75±0,2	0.1	-0.28	34
#Automata-release mode, dominant leg	1,77±0,17	1,86±0,22	0.005*	0.53	31
#Automata-release mode, non-dominant leg	1,74±0,25	1,87±0.3	<0.001	*0.88	37

(#): Paired t-test used for normally distributed data.
(†): Wilcoxon signed-rank test used for non-normally distributed data.
(*): p<0.05, (″): marginally significant

Table 3. *Means of the outcome measures of the Pendulum Test for the Dominant and Non-dominant legs. (Means across trials and participants). The (n) is the total number of trials of all the participants considered in the comparison of the paired conditions. The (d) denotes the Cohen's effect size*

Outcome measures and conditions	Dominant leg	Non-dominant leg	p	d	n
Number of swings Mean ± SD					
†Investigator-release mode, supine	6.08±1,7	6.65±1,7	<0.001	*0.56	35
#Investigator-release mode, semi-supine	6.71 ±2	7.11 ±1,1	0.09	0.28	35
†Automata-release mode, supine	6.23±1,8	6.76±2	0.009*	0.44	34
†Automata-release mode, semi-supine	6.33±1,7	7.08±1,7	<0.001	*0.62	34
Relaxation index					
†Investigator-release mode, supine	1.88±0.27	1.81±0.23	0.02*	0.39	33
#Investigator-release mode, semi supine	1.89±2	1.8±1,5	0.01*	-0.44	35
†Automata-release mode, supine	1. 83±0,24	1.75±0,21	0.02*	0.39	35
†Automata-release mode, semi-supine	1.97±0,48	1.87±0,31	0.04*	0.35	33

(#): Paired t-test used for normally distributed data.
(†): Wilcoxon signed-rank test used for non-normally distributed data.
(*): p<0.05

There were contradicting results comparing the relaxation index in investigator-release mode versus automata-release mode **(Table 4)**. In supine position the index was higher in investigator-release mode, but lower in automata-release mode, significantly on the non-dominant side (p=0.01). Thus, assessment in supine position with automata-release mode suggested higher muscle tone than in investigator-release mode. This was not the case in a semi-supine position, and the RI was significantly higher on the non-dominant side (p=0.009).

To illustrate the differences in the results of the pendulum test parameters under various conditions, we utilized a box plot representation. The differences in the mean values of the number of swings, comparing pairs

Table 4. *Means of the Parameters of the Pendulum Test in Investigator-release and Automata-release modes. (Means across trials and participants). The (n) is the total number of trials of all of the participants considered in the comparison of the paired conditions. The (d) denotes the Cohen's effect size*

Outcome measures and conditions	Investigator-release	Automata-release	p	d	n
Number of swings Mean ± SD					
†Supine, dominant leg	6.39±1.8	6.21±1.8	0.24	0.2	33
#Supine, non-dominant leg	6.64±1.8	6.47±1.8	0.4	0.14	35
#Semi-supine, dominant leg	6.76±2	6.44±1.6	0.13	0.26	34
#Semi-supine, non-dominant leg	7.15±1.8	7±1.7	0.4	0.14	36
Relaxation index					
†Supine, dominant leg	1.86±0.21	1.83±0.25	0.11	-0.27	33
#Supine, non-dominant leg	1.82±0.22	1.75±0.27	0.01*	0.42	36
#Semi-supine, dominant leg	1.88±0.2	1.98±0.4	0.09	0.23	34
#Semi-supine, non-dominant leg	1.79±0.2	1.89±0.3	0.009*	-0.45	37

(#): Paired t-test used for normally distributed data.
(†): Wilcoxon signed-rank test used for non-normally distributed data.
(*): $p<0.05$

of conditions are presented on the left panels of **Figure 3** and the differences in the mean values of the relaxation indexes are presented on the right side.

Correlation analysis

Spearman's correlation coefficients revealed significant positive correlations between the two investigated outcome measures (the number of swings and the RI) in the condition of automata-release mode, dominant leg, supine position ($r=0.45$, $p<0.05$), in the condition of automata-release mode, non-dominant leg, supine position ($r=0.35$, $p=0.05$), in the condition of investigator release mode, dominant leg, supine position ($r=0.41$, $p<0.05$). No significant correlations were found between the number of swings and RI ($p>0.05$) for all other comparisons.

Effect size analysis

Effect sizes were calculated to determine the magnitude of differences between the compared conditions during the pendulum test. The effect size was assessed using Cohen's d, and the Cohen's d value indicated a large effect size for the difference in the values of RI between the supine and semi-supine positions in automata-release mode, on the non-dominant leg ($d=0.88$), suggesting a substantial impact of the body osition on the test performance in this condition. All the other effect size values indicated a range of low to medium effects **(Tables 2–4)**.

Discussion

This study aimed to investigate the effect of two different body positions, leg dominance, and automatic releasing mechanism on the kinematic parameters, such as the number of leg swings and relaxation index during pendulum test in able-bodied young adults. Our results supported our hypothesis on the effect of leg dominance and partially on the effect of release mode on knee joint kinematics, but not on the effect of body positions when the pendulum test is performed with conventional investigator-release mode. The effect of body position was observed only by applying an automata-release mode.

The results of our study demonstrated no differences in the number of swings between the two body positions in the case of investigator-release mode. These results are supported by earlier investigations[14, 26] but not in line with our hypothesis and with previous findings[21, 24, 25], where it was found that spasticity is influenced considerably by body position that can affect the leg swing during the pendulum test in healthy young adults and in poststroke or SCI patients with spasticity. Body position could theoretically influence the passive swinging motion during the pendulum test[16, 19] because the rectus femoris muscle is a biarticular muscle, that crosses both the hip and the knee joint. This muscle has a different resting length, according to which it is more elongated in supine than in semi-supine positions at the start of the test and the stretched-out condition has higher stretch reflex activity[17–19] that is reflected in higher muscle tone. The greater difference in rectus femoris muscle length between the

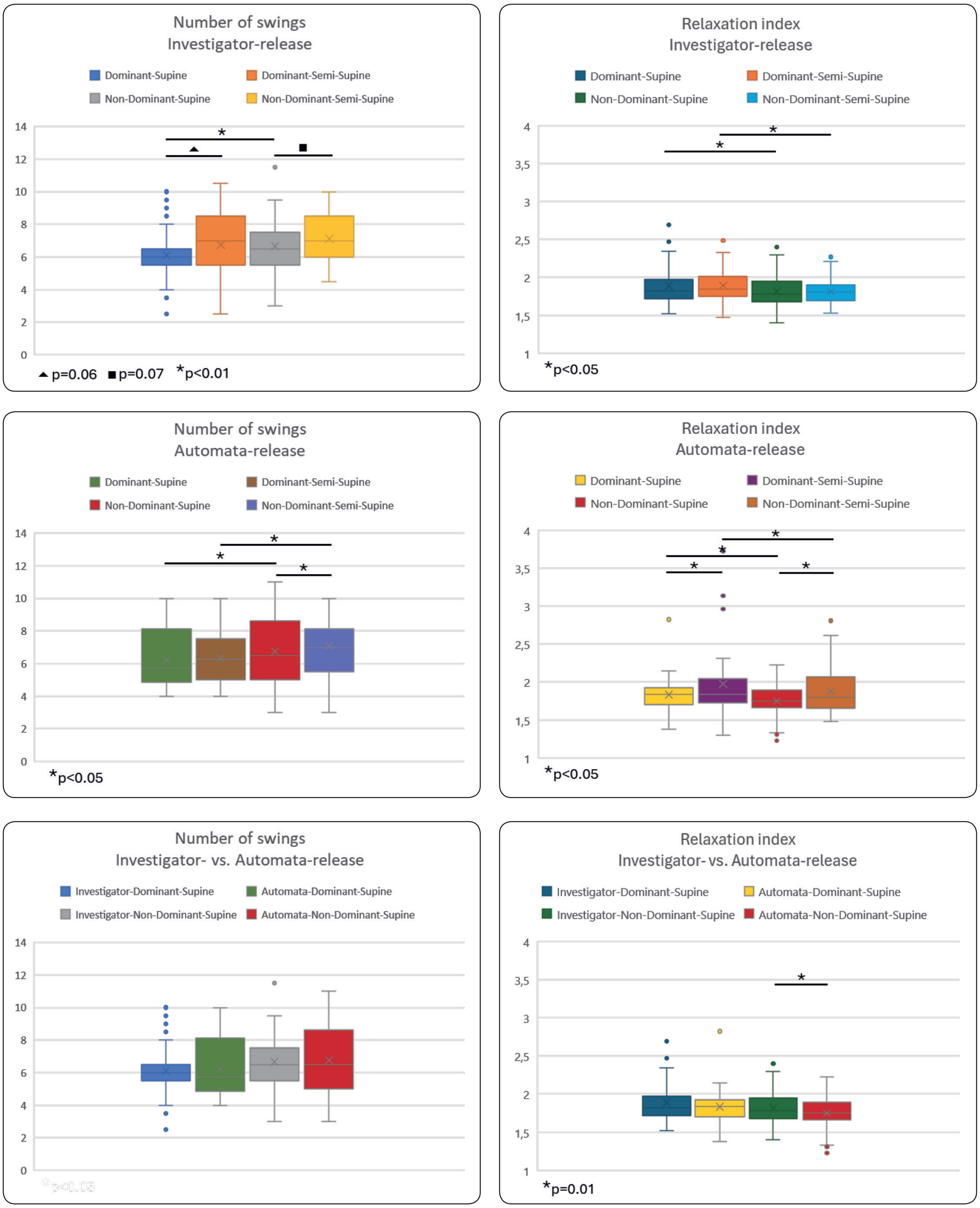

Figure 3. *Differences in mean values of the number of swings and relaxation indexes obtained in various conditions. The dot-whisker plots represent the differences in the number of swings (left panels) and the relaxation index (right panels) values between test conditions. The box indicates the 1st and 3rd quartiles. The horizontal line in the box indicates the median the cross indicates the mean. Whiskers extend to the maximum and minimum of the data. Horizontal lines with asterisks denote significant differences between the compared conditions*

supine and upright positions could result in a significant difference between the kinematic parameters of the pendulum test in the two positions. Our contrary results could be explained by that in the present study supine position was compared to semi-supine and not to the upright sitting position like in the above-named studies.

To the best of our knowledge, this study is the first in which both conventional investigator-release and automatic releasing mechanisms were applied to compare kinematic parameters of the pendulum test between two body positions. A few investigators[34–36] used auto-release in pendulum test with the aim to make the test more exact but they did not utilize investigator-release methods in their same research. We found that the number of swings was higher in the non-dominant leg in semi-supine position compared to supine position when automata-release was applied. This confirms our hypothesis, that the auto-releasing mechanism affects pendulum parameters, at least in the case of the non-dominant leg. We did not find significant difference between the numbers of swings in the two positions when investigator-release was used, so applying automata-release seems to be a more sensitive method for the pendulum test on the non-dominant side.

In the present study, we compared knee joint kinematics of the dominant leg versus the non-dominant leg and found, that there are differences in the numbers of swings in all conditions except in semi-supine position when investigator-release mode was applied. The numbers of swings were lower on the dominant side in all conditions, and this was not significant only in the semi-supine position with investigator-release mode. The number of swings is lower in the case of higher muscle tone[9], thus our data suggest that the quadriceps muscle tone was higher on the dominant side compared to the non-dominant. This could be explained by higher muscle volumes and muscle strength values on the dominant side compared with muscles on the non-dominant. In former studies, a correlation was found between muscle volume and spasticity in patients with cerebral plasy[33] and spinal cord injury[41, 42]. On the contrary, in healthy subjects, *Demura* et al. found no statistically significant difference in muscle power and muscle endurance between dominant and non-dominant leg muscles[43], as well as *Aird* et al. found no difference between quadriceps muscle tone of the dominant and non-dominant legs[44]. These findings indicate that larger studies are warranted to clarify the above-mentioned disagreement. To our knowledge, previous pendulum studies did not take into account the effect of leg dominance, but according to our present findings, there could be a significant difference between the muscle tone of the two sides, which is not negligible in comparative studies.

According to our findings, when we compared the numbers of swings in investigator-release mode to those in automatic release, we found no significant difference in any condition. However, there were differences in the effect of body positions in the two release modes. Namely, in investigator-release mode, no significant differences were comparing the number of swings in the two body positions in either leg, but in automata-release mode, there was significant difference comparing the two body positions in the non-dominant leg. Furthermore, in investigator-release mode only in the case of supine position was significant difference between the dominant and non-dominant legs, while in automata-release mode there were significant differences between the dominant and non-dominant legs in both body positions. The results can be explained by the subject-investigator interaction, which could be more pronounced in semi-supine position with investigator-release, since in this case the subject can see and also feel the examiner's movements. This interaction could change the results of the test. Previous studies[45, 46] applied pendulum test on subjects with their eyes closed to achieve the test more abruptly and independently from the interaction with the investigators. Our results show that the automata-release mechanism can provide an interaction-independent testing method regardless of eye condition and body position.

Regarding the other outcome measure, the relaxation index, we found that body position had an effect on it in automata-release mode, and its value was smaller in supine than in semi-supine position. This reinforces that in supine position the muscle spasm is higher than in semi-supine position, as it was indicated by comparing the number of swings. This could be shown only by applying automata-release mode.

The values of the two outcome measures suggest not always the same conclusion about differences in muscle tone comparing some test conditions. We found difference in the leg kinematics between the dominant and non-dominant legs comparing test conditions. The number of swings indicated higher muscle tone in the dominant leg while the relaxation index indicated more spasticity in the non-dominant leg.

Thus, our results are contradictory using the number of swings and the relaxation index for comparison of the dominant and non-dominant legs, in terms of which side has higher muscle tone, but there is an obvious difference between the two sides. Further research is needed to discern the physiological mechanisms behind this contradiction. The two outcome measures may quantify two different features of muscle tone. Nevertheless, this difference cannot be ignored when pendulum test is planned to be used in a clinical environment to compare the muscle tone of spastic patients with healthy subjects or with the patient's affected and non-affected legs.

Correlations between the number of swings and the relaxation index were strong in specific conditions (automata-release mode, dominant leg, supine position; automata-release mode, non-dominant leg, supine position; supine position, dominant leg, investigator release mode; supine position, dominant leg, automata release mode). This indicates that the number of swings is a good predictor of the relaxation index in these cases. No significant correlations were found between the number of swings and RI for all other conditions (p>0.05).

We found in the present study, that the pendulum test is suitable for detecting discrepancies in quadriceps muscle tone in healthy individuals, which differences are caused by the varied test positions and side dominance in the case of automatic leg release. While the number of swings did not differ significantly comparing the two release modes, the relaxation index was significantly lower in automata-release mode when the non-dominant leg was considered. This also shows that the automata-release mode may be more sensitive and adequate to quantify spasticity by the Wartenberg pendulum test. The standard deviation of the relaxation index values was very small, the reason for which should be investigated further, as other studies have obtained RI standard deviation values of similar magnitude[47]. In their study about the effect of whole body vibration of children with cerebellar palsy, the RI standard deviation was between 0.07-0.09 while the mean RI values changed between 0.59 and 0.71. In our study about healthy adults, the standard deviation of the RI was between 0.15-0.4 with RI values between 1.75 and 1.98. Thus the relative standard deviation was similar.

Regarding the statistical analysis, we used t-tests and Wilcoxon tests to compare data in pairs of conditions. We did not apply ANOVA for statistical analyses because, for ANOVA, the equal number of trials from each subject in each condition should be included, with an equal number of subjects for each condition. However, the measurements yielded different numbers of evaluable trials for individual subjects under different conditions studied. Thus, the sample size of the data included in the analysis would be low if in all comparisons the same number of subjects and trials would be involved. Further studies with larger sample sizes may extend this investigation.

The large effect size (d=0.88) in the automated release mode, non-dominant leg, comparing supine and semi-supine positions, indicates that body position significantly affects the relaxation index, with the semi-supine position having a pronounced effect. The low to medium effect sizes in other conditions suggest that while body position and release mode do influence the relaxation index, the impact is generally less significant than in the aforementioned condition.

Conclusion

These findings highlight the importance of considering both body position, leg dominance, and release mode when interpreting the results of the pendulum test, particularly for clinical or rehabilitative purposes.

The significant relationships identified can help refine testing protocols and improve the accuracy of muscle tone assessments using the pendulum test.

In summary, the correlation and effect size analyses reveal that both the method of limb release, leg dominance, and body position play critical roles in determining the outcomes of the pendulum test. These factors should be carefully controlled and considered in both research and clinical settings to ensure accurate and reliable assessments.

ACKNOWLEDGEMENT – Research funding was provided by the National Research, Development and Innovation Fund, Hungary, Grant number: GINOP 2.3.3-15-2016-00032, and Grants. KKP133827, TKP2021-NVA-04.

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