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The effect of selected lower limb muscle activities on a level of imbalance in reaction on anterior-posterior ground perturbation

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Purpose: We investigated whether an increase in muscular tone induced by the information about imminent posture destabilisation brings a positive result and prevents such destabilisation. *Methods*: We measured forward and backwards movements of 38 participates (27 females and 11 males, aged 23 (SD 2.6)) on the treadmill (forward and backward movements). All participants were subjected to three test condition trials (Tr): 1) subject did not know the nature and time of perturbation (Tr1); 2) subject knew the nature of perturbation but did not know time (Tr2); 3) both the time and nature of perturbation were known precisely (Tr3). The tests resulted in the determination of muscular activity connected with a postural adjustment as well as values of pressure exerted by the forefoot on the ground, and the angle of flexion in the knee joint. *Results*: In terms of postural adjustments, it was possible to observe statistically significant differences in muscular activity between Tr1 and Tr2 with reference to Tr3. No statistically significant differences were identified in all phases regarding values of forefoot pressure and those concerning the angle of flexion in the knee joint. An increase in the muscle tone before perturbation was correlated with the displacement and the velocity of the COP after perturbation. *Conclusions*: The results obtained indicate that knowledge of the expected time of perturbation is responsible for postural adjustment. Furthermore, muscle tone resulting from an adjustment of perturbation and responsible for the stiffening of lower limbs triggered greater displacement of the COP after perturbation.

Key words: *muscle activation, disturbance response, postural stabilization, postural compensation, anticipatory postural control*

1. Introduction

Mechanisms of Anticipatory Postural Adjustment (APA) and mechanisms of Early Postural Adjustment (EPA) are methods enabling adjustments of the body in response to a given stimulus [1], [7], [25], [39]. The above-named adjustments may take various forms, usually affecting movements of the entire body, or its parts. APAs are manifested in a variety of manners, yet many researchers primarily indicate changes of muscular activity [25] or changes concerning the displacement of individual segments of the body, the centre of mass [3], [4], or the centre of pressure [1], [7]. Research performed by Cleworth et al. [7] and Xie et al. [41] revealed that postural adjustments range from changes preceding the performance of a given movement to the moment of a bodily response, as well as subsequent stimulus-evoked reactions. There are two types of stimuli that relate to foregoing. One is connected with the internal initiation of a movement (movement initiated by someone's own intention) as indicated by Shumway-Cook and Woollacott [30] as well as Xie et al. [41] and the other stimulus, con-

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nected with an external factor (frequently leading to postural destabilisation) provoking a bodily movement as indicated by Cleworth et al. [7], Sibley and Etnier [31]. Initially, the researchers focused on the first stimulus type, reducing analyses of APAs entirely to the processes taking place in the body and those followed by the movement. However, recent research suggests that the transfer of energy from an external source (outside the body) can also trigger postural adjustment if it is only known when the expected energy stimulus takes place. For instance, Mohapatra and Krishnan [25] reported a lack of APAs in relation to random moments, when test participants were not informed about possible perturbation and the permanent occurrence of APAs when such information was available. It was also possible to demonstrate the existence of correlation between APAs and the value of force applied from outside. In their research, Berg and Hughes [2] found that APAs were greater when the test participant was not aware of the magnitude of the aforesaid force. The lack of information about the nature and form of perturbation resulted in an increased muscular activity.

APAs have a practical application of discovering postural disorders and the prediction of falls [1], [26], [32], [36]. Ritzmann et al. [36] indicated the practical use of such research in the development of training aimed to reduce fall-triggered injuries. Additionally, the observation of APAs can be utilized during the detection of limb stability and the identification of recovery (e.g., after injuries or surgeries). Oeffinger et al. [26] pointed out to the practical use of APA measurements in the assessment of recovery after ligament reconstruction. In their research, Scariot et al. [29] attempted to correlate APAs and EPAs (taking place slightly earlier) with perturbation reactions or compensatory postural adjustments (CPAs). It can be concluded that the above-named tests were an attempt to answer the question whether the occurrence of APAs positively affected the prevention of destabilisation triggered by external factors. There are multiple interpretations of Scariot and colleague's [29] results. However, when focusing on postural stability, the result could be interpreted in a way similar to that developed in the research by Bax et al. [1], which suggested that the smaller displacement of the COP (center of pressure) and the COM (center of mass) after perturbation reflects greater efficacy in maintaining postural stability. The above-presented assumption is incomplete as it does not include a number of forces and dynamic parameters compensating numerous phenomena which take place in the human locomotor system and whose aim is to restore the bodily posture preceding perturbation [15], [20], [21], [38]. However, the COM and COP displacements are measurable and reflect the correlation with the probability of falling (which was demonstrated in related research) [13], [14], [19], [41], [43].

Inspired by the research described previously, the work described below seeks to determine whether information concerning the time of ground-related perturbation affects the muscular tension of lower limb muscles before the perturbation. An attempt to answer the above-presented question requires the identification of the occurrence of APAs and EPAs. It should also be determined whether increased muscular activity was continuous over a given time or was abrupt and shortly preceded perturbation. Based on these findings, we next sought to determine whether lower limb muscle tone at the initial EPA-related stage leads to the increased muscle tone in the phase connected with APA.

It is also worth considering that muscular activity is not the only manifestation of postural adjustment, research-related tests should also include changes of the COP as well as postural changes connected with anticipatory ("pre-perturbation") adjustments. Another research question is whether an increase in the muscular tension of lower limb muscles before perturbation (i.e., an increase in APAs) results from postural changes triggering the displacement of the COM forwards or backwards, and, consequently, an increase or decrease of pressure exerted by the forefoot on the ground. The final question is whether an increase in the muscular tension of lower limbs a moment before perturbation (an increase in APAs) results from postural changes connected with an increase in the angle of flexion in the knee joint.

The occurrence of APAs entails certain consequences connected with the manner of a response to perturbation (identifiable by measuring some parameters after the occurrence of perturbation). Therefore, it should be considered whether an increase in the muscle tone preceding perturbation (an increase in APAs) leads to an increase in the COP velocity and movement range after perturbation. Finding the answers to the questions formulated above should allow for understanding of neurological mechanisms that control postural responses to expected or unexpected destabilising factors. These studies are a continuation of previous research on the analysis of motor behavior using only visual disorders [38], [39], [40]. Tests concerning correlations between selected parameters identifying responses to perturbation and postural changes as well as changes of muscular activity triggered by APAs facilitate the development of strategies to maintain both balance and readiness of quick responses to imbalance. Well-trained balance and the ability of motoric reactions to balance disorders make it possible to minimise the risk of falling and sustaining injuries in representatives of all age groups involved in daily activities as well as in relation to sports people in events characterised by particularly high susceptibility to falling [19], [38], [39]. Diagnostics, informed from the reactions of healthy individuals, will be developed for individuals experiencing problems with their lower limbs and neurological system dysfunction resulting in balance-related mechanism disorders. Widely defined prediction of falls and the further development of traditional methods supporting diagnostics and therapy constitute a utilitarian objective of this research [3], [20]. The research results might make it possible, among other things, for the development of both rehabilitation methods after injuries and fall prevention training.

2. Materials and methods

2.1. Study group

The study group included 38 participants (27 females and 11 males) aged 23 ± 2.6 years, with an average height of 172 ± 9.6 cm and an average weight of 70 ± 17 kg. None of the participants had a history of an extreme lower limb injury nor suffered from motor system dysfunctions or balance disorders.

This study was previously approved by the Ethics in Research Committee of the Academy of Physical Education in Katowice (report number 5/2020).

2.2. Experimental procedure

The measurement stand consisted of a platform enabling measurements of the distribution of pressure exerted by feet on the ground (WinFDM-S, Zebris Medical GmbH, Germany, sampling frequency of 100 Hz, 2560 tension meter sensors, sensors area = 34 × 54 cm), a treadmill for training and preventing postural perturbation (BalanceTutor, MediTouch, Israel), a cordless set for electromyography (EMG, Ultium EMG, Noraxon, USA, sampling frequency of 2000 Hz) and a cordless set of IMU (Inertial Measurement Units) sensors (Ultium Motion, Noraxon, USA, sample frequency 200 Hz). The stabilographic platform was located in the central part of the belt of the treadmill for training and preventing postural perturbation and it was attached using a two sided tape to the treadmill. In front of the platform, in a special grip, there was an IMU sensor used for the detection of each movement of the treadmill.

All systems were synchronized with each other with the use of Noraxon MR3 (Noraxon, USA) devices and the designed synchronization adapter using the mini

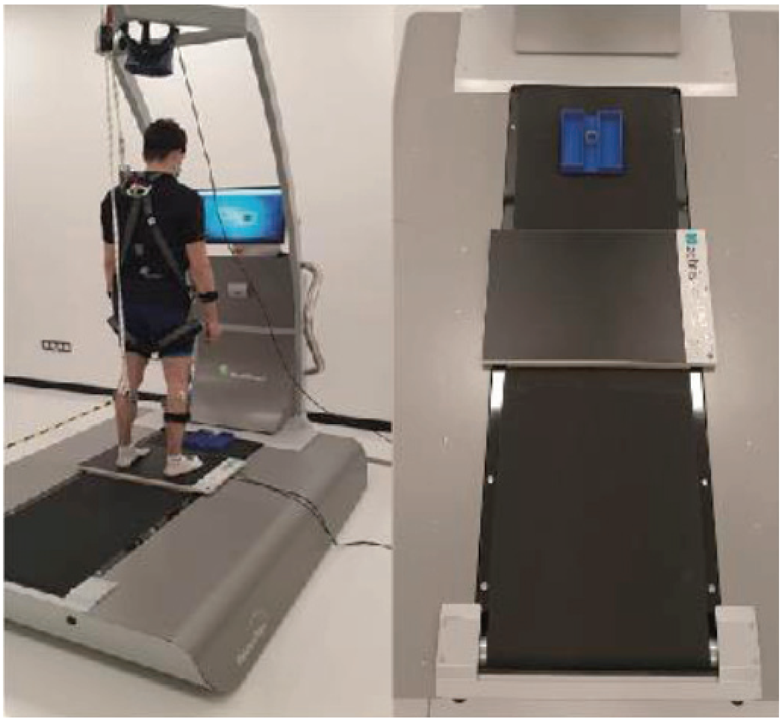

Fig. 1. Measurement stand with a test participant and the treadmill with the sensor and direction of perturbation

M5stack (development platform, Shenzhen, China) device with the ESP32 microcontroller. Start and stop signals for all devices are provided by the MR3 device. The developed proprietary software for M5stack allows for quick detection of the moment of treadmill movement (the device has an IMU sensor) and transmission of the signal to Noraxon software, which will ensure quick detection of the moment of treadmill movement (reaction time less than 100 μs).

The measurement stand with a patient on it is presented in Fig. 1.

2.3. Arrangement of sensors

The electromyographic tests focused on the four most important groups of muscles responsible for the maintaining balance [12], [33] – musculus tibialis anterior (TA), musculus rectus femoris (RF), musculus gastrocnemius medialis (GM) and musculus gastrocnemius lateralis (GL). Electromyographic tests of the above-named muscles are often used in the investigation of APAs and CPAs. In their research, Curuk et al. [8], [9] measured APAs using unexpected external stimuli and those initiated by a test participant. The authors demonstrated the occurrence of APAs the activity of TA, RF, GM GL. Similar conclusions were reported by Garcez et al. [11] and Krishnan et al. [21].

Fig. 2. Arrangement of EMG electrodes

The tests involved the previously mentioned muscles on both the right and left side of the body. Disposable electrodes for surface electromyography were located on the skin near bellies of the muscles, making allowances for innervation areas – guidelines for innervation zones [10], [16], [34]. The EMG electrode attachment areas were prepared by removing hair and degreasing the skin surface using ethyl alcohol. Afterwards, the electrodes were connected to cordless sensors (Fig. 2).

Additionally, the tests involved using special straps and stickers to attach 17 IMU sensors located all over the body – head, torso along the spine and shoulder, and on the upper and lower limbs. The sensors (accelerometer, magnetometer and gyroscope) were attached to the patient in accordance with the arrangement diagram provided by the producer on the webside [44]. The location of the sensors used in the research for the synchronization and determination of limb movements is shown in Fig. 3.

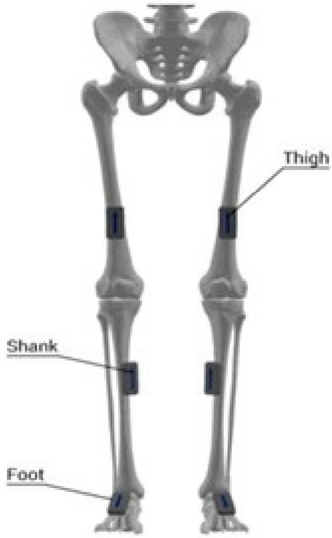

Fig. 3. Arrangement of IMU sensors

2.4. Tests

The testing procedure consisted of two stages, rest and perturbation. During the first stage (rest), the test participant was requested to sit on a chair, place their feet flat on the ground and relax their lower limb muscles (ERx). The test lasted 15 seconds and recorded the activity of the lower limb muscles at rest.

The second stage of investigation involved the use of the treadmill for training and postural perturbation prevention. The test participant was instructed to take off their footwear and enter the stabilographic platform located on the treadmill. Test participants were protected against falls by wearing a special harness attached to the treadmill. A given test participant was supposed to stand still, with their face directed forward and arms lowered freely along the sides. The tests involved three trials (Tr), i.e., Tr1, Tr2 and Tr3. Each trial consisted of two treadmill movements – forward and backward (Fig. 4). The first movement was always forward and was initiated 10 seconds after the start of the measurements. The backward movement of the treadmill was initiated 20 seconds after the start of the measurements. Both forward and backward movements of the treadmill amounted to 9.5 cm and lasted 0.52 seconds.

Breaks between the end of one perturbation and the beginning of another lasted 10 seconds. In the event of the perturbation-triggered loss of balance, the test participant was tasked with returning to the upright position as soon as possible. The test was repeated three times. During the first trial (Tr1), the participant did not know the nature, time and the direction of perturbation. During the second test (Tr2), the participant knew the nature of perturbation but not its time and direction. During the third test (Tr3), the subject knew the time left (countdown) to the occurrence of perturbation and its direction (from a dedicated display). A schematic diagram presenting the successive measurements is presented in Fig. 4.

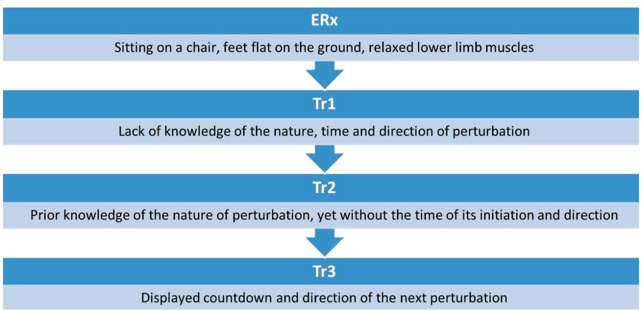

Fig. 4. Sequence of measurements

2.5. Analysis of the results

The data exported from the Noraxon software was preprocessed in accordance with the algorithm embedded in the software (MyoResearch 3.18) – the absolute values were calculated and filtered with a moving average filter with a 50 ms window.

At the first stage of the analyses, based on the results obtained in the ERx test (during sitting on a chair), it was possible to identify the average resting activity of each of the muscles subjected to analysis (EMGRx). Afterwards, the activity of each muscle measured in Tr1, Tr2 and Tr3 were divided by the EMGRx value, performing the standardisation of measured parameters in relation to the values measured at rest.

Afterwards, on the basis of the data obtained from the IMU sensor located on the treadmill belt, it was necessary to determine the beginning of the treadmill movement (t_0) for forward and backward movements.

The subsequent step aimed to answer the question whether information about the starting time and the direction of perturbation leads to an increase in the muscular tension of lower limb muscles. That stage required the investigation of the muscular activity of lower limbs in relation to APAs and EPAs in tests Tr1, Tr2 and Tr3. Time values and activity areas subjected to the analysis are presented in Fig. 5.

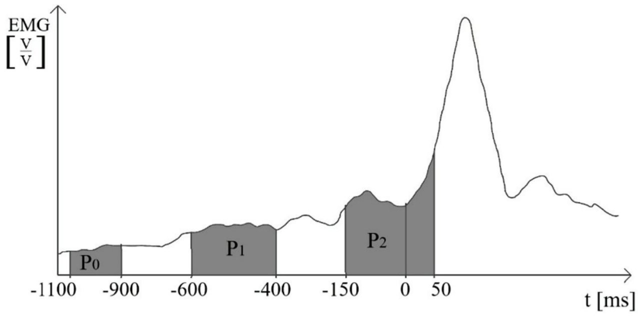

Fig. 5. Analysed time intervals of muscular activity.
The vertical axis represents the multiplicity of the resting value assuming a symbolic value of V/V.
The horizontal axis represents time in milliseconds (ms)

Area P_0 stands for the area of muscular activity during free standing (between 1100 ms and 900 ms before perturbation). Area P_1 represents the area of search for an increase in the muscular activity triggered by EPA (between 600 ms and 400 ms before perturbation). Area P_2 represents the area of an increase in the muscular activity triggered by APAs (between 150 ms before perturbation and 50 ms after perturbation). The muscular activity related to APA and EPA (EMG_{APA} and EMG_{EPA}), was determined using Eqs. (1)–(5). The values of EMG_{APA} and EMG_{EPA} were identified for each of the muscles subjected to the tests.

$$P_0 = \int_{-1100}^{-900} EMG\,dt\,, \tag{1}$$

$$P_1 = \int_{-600}^{-400} EMG\,dt\,, \tag{2}$$

$$P_2 = \int_{-150}^{50} EMG\,dt\,, \tag{3}$$

$$EMG_{EPA} = P_1 - P_0\,, \tag{4}$$

$$\mathrm{EMG}_{\mathrm{EPA}} = \mathrm{P}_2 - \mathrm{P}_0 \,. \qquad (5)$$

Next, to determine whether the occurrence of lower limb muscle tone at the initial phase (EPA) led to an increase in the muscle tone before perturbation (APA), it was necessary to identify correlations between all of the above-named parameters in relation to all the muscles subjected to analysis in test Tr3.

After the initial observation of the increased muscular activity before perturbation, in relation to test Tr3, it was necessary to determine whether APAs did not result from the postural change connected with the forward or backward displacement of the COP and whether it did not result from the change in the flexion of the knee joint. To this end, it was necessary to calculate values of pressure exerted by the forefoot on the ground and values of the angle of flexion in the knee joint in relation to test Tr3. It was also necessary to identify the existence of correlations between the above-named values and APAs.

Finally, it was necessary to verify whether an increase in the APA-related muscular activity affected the displacement and the velocity of the COP after unbalance. The above-named displacement was always reverse in relation to the direction of the treadmill motion. The velocity of the COP was analysed as an increase in displacement 150 ms after perturbation, whereas the displacement of the COP was analysed as the maximum deviation of the COP after perturbation, regardless of its moment of occurrence, yet not later than two seconds after perturbation.

2.6. Statistical analysis

All analyses were performed using Matlab R2022a. The Shapiro–Wilk test was used to determine data normality of the parameters analysed. The lack of normal distributions was observed for Tr1, Tr2 and Tr3 tests. Based on this, it was used Friedman test followed by pairwise Wilcoxon post-hoc test with Holm correction. Additionally, the size of the effect was calculated with the methodology proposed by Rea and Parker [35]. If the difference is statistically significant ($p < 0.05$), but the effect is small, then this significance is due to reasons other than significant differences in the distribution. The difference between the medians was reported as statistically significant as long as the effect was high or at least medium. Small effects were not reported. Due to the lack of normal distributions, the Spearman correlation was calculated and presented as the correlation coefficient.

3. Results

The obtained results allowed for an objective determination of the muscle tone gain only when the examined person knew the moment of the disorder's occurrence. The research attempts to define the strategy of postural preparation and its influence on the results of postural compensation after the disorder. It was determined what could influence the speed of postural reactions and the correlation between the measured values was investigated.

3.1. Analysis of the muscular activity triggered by APAs and EPAs

Test results concerning the APA-triggered muscular activity are presented in Fig. 6 whereas those

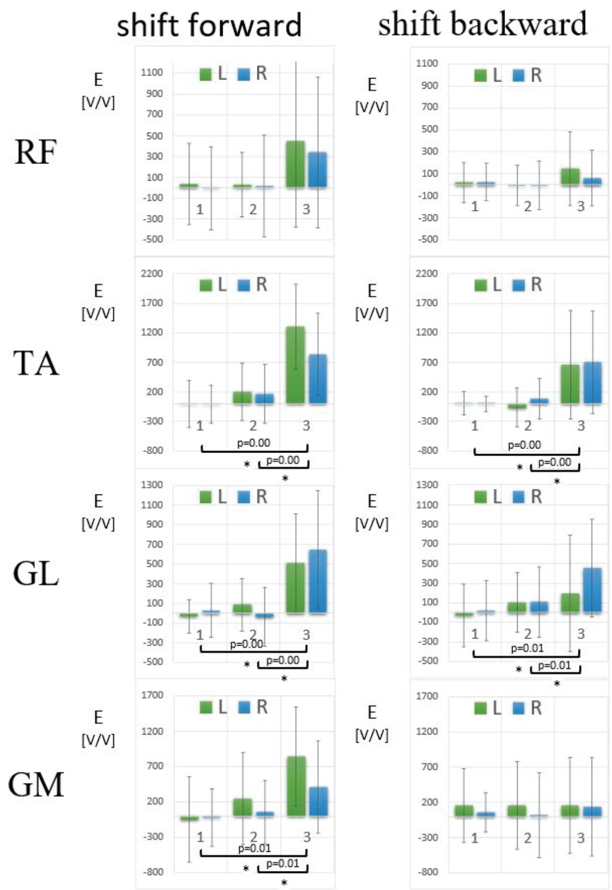

Fig. 6. EMGAPA in relation to selected RF (rectus femoris), TA (tibialis anterior), GL(gastrocnemius lateralis) and GM (gastrocnemius medialis) muscles and successive tests: Tr1, Tr2 and Tr3. Unit [V/V] indicates the multiplicity of the value of muscular activity at rest; *L* – value concerning the left lower limb and *R* – value concerning the right lower limb; Shift forward – forward movement of the treadmill belt, Shift backward – backward movement of the treadmill belt; values represent mean * standard deviation

related to the EPA-evoked muscular activity are presented in Fig. 7. Because of reference to the average value at rest, the test values were expressed in v/v. The aforesaid unit represents muscular activity constituting the multiplicity of the resting value.

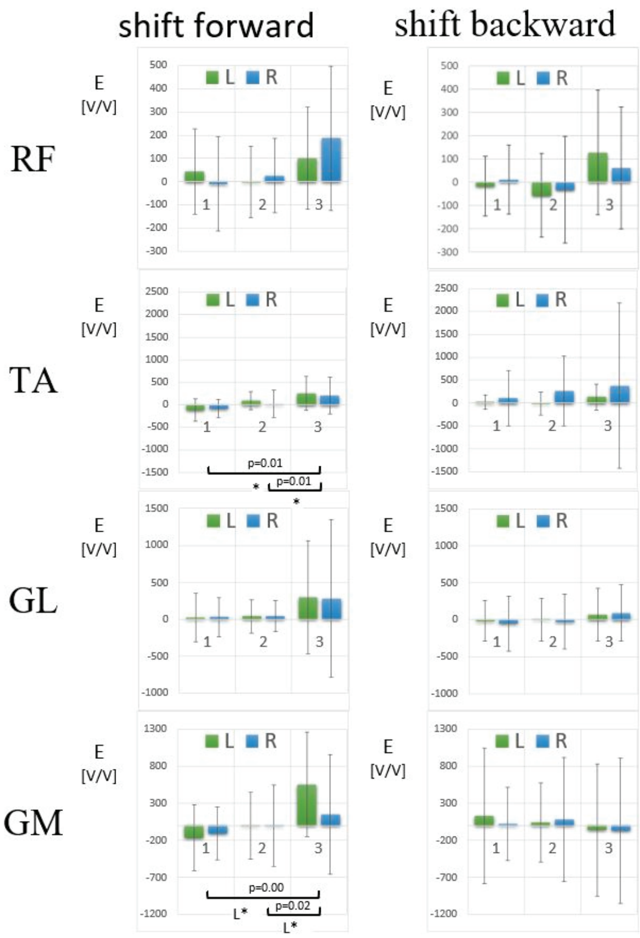

Fig. 7. EMGEPA in relation to selected RF (rectus femoris), TA (tibialis anterior), GL (gastrocnemius lateralis) and GM (gastrocnemius medialis) muscles and successive tests: Tr1, Tr2 and Tr3. The unit [v/v] indicates the multiplicity of the value of muscular activity at rest; *L* – value concerning the left lower limb, *R* – value concerning the right lower limb, Shift forward – forward movement of the treadmill belt, Shift backward – backward movement of the treadmill belt; values presented as mean * standard deviation

Statistically significant differences EMG_{APA} and EMG_{EPA} between tests Tr1 and Tr3, and tests Tr2 and Tr3 were only observed in relation to the forward shift for TA, GL and GM in relation to analyses indicating the APA phase and for TA and GM (only the left lower limb) in relation to the analyses indicating the EPA phase. The test results concerning the above-named muscles point to test Tr3 as the one revealing a significant increase in muscular activity. EMG_{APA} and EMG_{EPA} obtained in Tr3 were investigated for the correlation of muscles subjected to the tests. Correlation coefficients were determined in relation to muscles revealing varying activity between Tr3 and the remaining tests, excluding RF. The results, presented in Table 1, indicate the existence of the statistically significant correlation between the phase of the Early Postural Adjustments (EPAs) and the Anticipatory Postural Adjustment (APAs) in relation to the backward shift. The correlation could indicate that the muscle was activated earlier than the remaining muscles and that its activation increased in time until the occurrence of perturbation.

3.2. Impact of the increased muscular activity on forefoot pressure and the APA-triggered change of the angle of flexion in the knee joint

To analyse whether the increase in the muscular activity between the phase of free standing and that of the search for APAs resulted in postural changes it was necessary to investigate the correlation between the calculated value of APA and the value of increased forefoot pressure as well as the correlation between APA and the change in the value of the angle of flexion in the knee joint. Changes of forefoot pressure and of the angle of flexion in the knee joint were calculated in time intervals adopted as free standing and in the APA area (difference between the value recorded 50 ms after perturbation and the value recorded 1100 ms before perturbation). During analyses, the RF-related values were ignored as its activity was

Table 1. Results of Sperman's correlation in relation to muscular activity in the APA and EPA phase. The *p* values for the significance of the correlation are given in parentheses. The statistically significant values are bolded

	TA_L	TA_R	GL_L	GL_R	GM_L	GM_R
Shift forward	**0.73 (*p* = 0.01)**	**0.70 (*p* = 0.02)**	0.44 (*p* = 0.27)	**0.28 (*p* = 0.03)**	**0.47 (*p* = 0.02)**	0.21 (*p*=0.17)
Shift backward	**0.72 (*p* = 0.01)**	**0.69 (*p* = 0.01)**	0.33 (*p* = 0.30)	0.27 (*p*=0.35)	**0.24 (*p* = 0.04)**	**0.33 (*p* = 0.04)**

Table 2. Results of Sperman's correlation for increased muscular activity during the APA phase and increased forefoot pressure as well as for increased muscular activity during the APA phase and changes in the knee joint flexion. The *p* values for the significance of the correlation are given in parentheses. The statistically significant values are bolded

	APA – an increase in the load on the forefoot					
	TA_L	TA_R	GL_L	GL_R	GM_L	GM_R
Shift forward	**–0.28 ($p = 0.01$)**	**–0.33 ($p = 0.01$)**	0.37 ($p = 0.44$)	**0.27 ($p = 0.01$)**	0.13 ($p = 0.14$)	**0.43 ($p = 0.01$)**
Shift backward	0.22 ($p = 0.22$)	0.43 ($p = 0.71$)	0.17 ($p = 0.40$)	–0.27 ($p = 0.71$)	**0.48 ($p = 0.01$)**	**0.42 (p=0.01)**
	APA – flexion in the knee joint					
	TA_L	TA_R	GL_L	GL_R	GM_L	GM_R
Shift forward	0.11 ($p = 0.54$)	–0.23 ($p = 0.78$)	0.41 ($p = 0.24$)	**0.33 ($p = 0.01$)**	–0.24 ($p = 0.11$)	**–0.32 ($p = 0.01$)**
Shift backward	**0.33 ($p = 0.01$)**	**0.36 ($p = 0.01$)**	–0.25 ($p = 0.51$)	–0.49 ($p = 0.67$)	**0.36 ($p = 0.01$)**	**0.39 ($p = 0.01$)**

not detected in forward and backward translation. The test results are presented in Table 2.

The tests were also concerned with differences between the average values of forefoot pressure in subsequent phases of Tr1, Tr2 and Tr3. The results did not reveal any statistically significant differences between the average values. Similarly, no statistically significant differences were observed between the average values of the angle of flexion in the knee joint in successive tests: Tr1, Tr2 and Tr3.

3.3. Impact of the increased muscular activity before perturbation on the velocity and displacement of the COP after perturbation

During the APA search phase (–150 ms–(+50 ms)), a correlation between the calculated value of APAs and the velocity of the COP at the initial stage of motion as well as between APAs and the maximum displacement of the COP triggered by perturbation was observed (Table 3). The results concerning the correlation of velocity and the maximum displacement of TA revealed a strong correlation between the increased activity of the muscle and the COP displacement velocity and the COP displacement value obtained in relation to the forward motion of the treadmill (Table 3). A slightly lower correlation was obtained in relation to GL and the backward shift of the treadmill.

4. Discussion

The above-presented tests aimed to identify the impact of the forward and backward shift of the ground on the muscular response in lower limbs connected with postural adjustment. Understanding how

Table 3. Results of Sperman's correlation for increased muscular activity during the APA phase and the COP displacement velocity after perturbation as well as for increased muscular activity during the APA phase and the maximum COP displacement. The *p* values for the significance of the correlation are given in parentheses. The statistically significant values are bolded

	APA – V					
	TA_L	TA_R	GL_L	GL_R	GM_L	GM_R
Shift forward	**0.71 ($p = 0.00$)**	**0.73 ($p = 0.00$)**	0.21 ($p = 0.17$)	0.43 ($p = 0.09$)	0.51 ($p = 0.34$)	0.11 ($p = 0.27$)
Shift backward	0.62 ($p = 0.51$)	0.53 ($p = 0.27$)	**0.59 ($p = 0.00$)**	**0.58 ($p = 0.01$)**	0.12 ($p = 0.37$)	0.11 ($p = 0.33$)
	APA – COP displacement					
	TA_L	TA_R	GL_L	GL_R	GM_L	GM_R
Shift forward	**0.71 ($p = 0.00$)**	**0.63 ($p = 0.00$)**	0.21 ($p = 0.13$)	0.43 ($p = 0.22$)	0.61 ($p = 0.55$)	0.12 ($p = 0.87$)
Shift backward	0.62 ($p = 0.59$)	0.63 ($p = 0.21$)	**0.59 ($p = 0.00$)**	**0.54 ($p = 0.00$)**	0.17 ($p = 0.40$)	0.09 ($p = 0.71$)

adjustment to perturbation and the investigation of the effect of the aforesaid manner on the COP displacement after perturbation enabled the determination of the components of a strategy aimed to maintain balance. The identification of the strategy of adjustment to perturbation was restricted to the assessment of the activity of selected muscles, the evaluation of flexion in the knee joint and the assessment of pressure exerted on the ground, which was tantamount to the displacement of the COP. As reported elsewhere [1], [26], [29], [32], [36], muscular activity was used to identify Early Postural Adjustments (EPAs) and Anticipatory Postural Adjustments (APAs).

4.1. Detection of muscular activity before perturbation

The analysis of selected muscles revealed that during APA (Fig. 6) in relation to Tr3, i.e., when test participants were informed about the starting time of perturbation, it was possible to notice an increase in average muscular activity. The aforesaid increase occurred in the case of all tested muscles, i.e., RF, TA, GL and GM in the APA phase. The increase was noticeable in relation to the adjustment to both forward and backward perturbation. However, it should be noted that an increase in the average value was accompanied by an increase of the standard deviation. As a result, some increases did not reveal statistically significant differences. Statistically significant increases were observed between Tr1 and Tr3 as well as Tr2 and Tr3 in relation to the TA, GL and GM muscles for APA before the forward shift and in relation to the TA and GL muscles for APA before the backward shift. Therefore, similarly to research by Cleworthet at al. [7], it was demonstrated that the activity of TA played an important role in APA. In accordance with publications [7], [26], the above-named muscle played an important role in the perturbation-related adjustment. Scariot et al. [29] indicated TA as the muscle which was activated when adjusting to any movements connected with jumps, taking a step or catching a flying ball. Apart from making movements in the ankle joints, the TA also protects against the occurrence of flat feet [5], the occurrence of which may disturb postural reactions. This finding was confirmed by the Shein et al.'s is study, which found a reduced TA cross-section in ultrasonography in a group of patients with flat feet [42]. The greatest changes in the absolute values of muscle forces during performance of tasks related to maintaining posture under various conditions were also observed for the TA muscle [12]. The above fact would mean weaker activity of this muscle with flat feet. The presence of flat feet affects the way the body is balanced and the displacement of the COP [17]. We should also remember that, when positioned medially or laterally in the medial compartment of the extensor retinaculum, it is able to perform supination and pronation movements in the lower ankle joint and participate in postural reactions in the frontal plane by stabilizing the lower ankle joint [5], [24].

Similar conclusions related to forward shifts of the treadmill belt resulted from the analysis of GL and GM. Oeffinger et al. [26] indicated the GL and GM as muscles, whose activation was particularly important in the stabilisation of the body in a response to the temporary dysfunction of lower limbs in patients after anterior cruciate ligament reconstruction.

By observing the anatomy and topography of GM and GL, their relationship with capsular-ligament structures can be noticed in knee joint [22], [27], [28], [37]. The GM connects to the posterior medial capsule of the knee joint [22] while The GL connects to the fabellofibular ligament [27], [28], [32]. The above combination may affect the mechanosensive function of the capsule and ligaments of the knee joint and thus pre-prepare the receptors and thus the whole organism for disorders [18].

We replicated findings of Scariot et al. [29] and Lee et al. [23] indicating that activation of the TA connected with adjustment to perturbation occurred significantly earlier than in the APA phase and included EPAs. The above-presented observations were confirmed by the analysis of muscular activity in the EPA phase (Fig. 7), revealing the existence of statistically significant differences between Tr1, Tr2 and Tr3 in relation to TA and its adjustment for the forward movement of the treadmill belt. The subsequent stage involved investigation focused on the existence of correlation between increased muscular activity in the EPA and APA phases. The results presented in Table 1 indicate a linear correlation between the activity of TA obtained for both left and right lower limbs of the test participants. The foregoing revealed that the activity of the aforesaid muscles already grew during the EPA phase and the APA phase constituted the continuation of the above-named increase. The results presented in Table 1 did not reveal an increase in GL and GM activity during the EPA phase, which indicated that the muscles were activated shortly before the perturbation. Their activity increased significantly and more intensely than that of the TA and followed the EPA phase. Muscular activation could result in the movements of limbs or changes in the position of limbs, including, e.g., flexion in the knee joint or the forward inclination of the body. Perhaps this is because of the fact that the TA is a highly motorized muscle and does not connect with the ligamentous and capsular structures of the knee joint and ankle joints [5] while GM and GM connect with the ligaments and capsule of the knee joint, as mentioned earlier [22], [27], [28], [37].

4.2. Postural changes triggered by APA

Research by Cleworth et al. [7] indicated slight lower limb flexion by an angle of 0.5° during the phase of adjustment to similar perturbation connected with the forward movement of the ground. In turn, the researchers reported a lack of statistically significant differences connected with the flexion of the upper leg and trunk. The tests involving the analysis of the flexion in the knee joint did not reveal statistically significant changes between phases Tr1, Tr2 and Tr3. Similarly, no statistically significant changes were observed in the displacement of the COP nor in forefoot pressure. Therefore, it could be supposed that a postural adjustment to perturbation was not connected with forward or backward trunk inclination and that the observed increase in the tension of TA, GL and GM did not affect the flexion in the knee joint. The foregoing conclusion was confirmed by the results presented in Table 2, indicating the lacking correlation between muscle tone and the flexion in the knee joint and the increase in forefoot pressure. The increased muscle tone combined with the lack of the COP displacement may indicate the block of the joint, which could translate into a longer adjustment to perturbation or indicate other postural changes, such as backward pelvic girdle inclination and forward shoulder girdle inclination, which requires tests in the scope of kinematics of the upper part of the body.

4.3. Impact of APA on the selected muscle reactions to postural compensation after perturbation

The analysis of correlations between muscle tone and the COP displacement as a well the velocity of the COP after perturbation (Table 3) indicated a strong correlation between the muscle tone of the TA and the COP displacement as well as the displacement of the COP after perturbation. In terms of the GL, the abovenamed correlation was lower. In both cases, the observed increased muscle tone resulted in the extension of the path and velocity of the COP displacement. The aforesaid results, confirmed observations by Mohapatra et al. [25], report tests involving hitting a body trunk with a weight led to the increased displacement of the COP in measurements when the test participant was informed on the occurrence of perturbation. The results could indicate that the increased muscle tone in the APA phase was responsible for block in the joints before perturbation, which, in turn, changed the pattern of postural compensation after perturbation. The higher COP moved significantly further than in the situation when muscle tone did not occur and increased both path and velocity-related values.

5. Conclusions

The data explicitly indicated that the factor triggering postural adjustment and readiness for response to perturbation was the knowledge of the expected time of the perturbation. These data did not reveal differences in the activation of selected muscles, differences in flexion in the knee joint as well as differences in changes of backward-forward pressure between the tests where the participants did not know or knew the nature of perturbation but were unaware of its starting time.

An important factor connected with the adjustment to perturbation was muscle tone responsible for blocking of joints of lower limbs and, consequently, a greater inclination of the COP after perturbation.

The subsequent stages of tests should focus on the search for objective methods enabling the measurements of body kinematics resulting from postural compensation as a response to perturbation and their relationship with the adjustment to perturbation. It is also important to overcome some limitations that can improve the accuracy of measurements. Such limitations include the inability to collect tissues and determine the number of receptors in the muscles, the lack of a needle method for EMG measurement and the lack of isokinetic studies performed. These findings may generate training programme of muscles and body stability aimed to reduce the incidence of traumas and falls due to unexpected perturbation of the body and ground. The determination of a strategy enabling the maintaining of balance before perturbation based on muscular activity and values of ground reaction forces could provide information about proper patterns of response to perturbation. These data may also provide guidelines for persons suffering from balance disorders due to diseases and injuries.

Conflict of interest

The authors declare no conflict of interest. The authors declare that all authors were fully involved in the study and the preparation of the manuscript and that the material within has not been and is not to be submitted for publication elsewhere.

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