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EMG and postural stability: parallel vs. semi-tandem foot position 4-Stage Balance Test

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Abstract: There is a lack of research that methodically clarifies baseline muscle tone values and demonstrates their activation during balance tests using selected parts of the 4-Stage Balance Test. The study involved 41 men and 34 women (mean age approximately 22 years (X = 21.83 y, SD 1.5 y)). Data were collected using a questionnaire containing socio-demographic and anthropometric data. Range of motion was measured using a goniometer (SFTR Goniometer Baseline 360 degrees), limb length and circumference were measured using a ADE MZ10021 tape measure and static balance was assessed using two tests from the 4-Stage Balance Test. Eight muscles (Rectus Femoris (RF), Vastus Lateralis (VL), Vastus Medialis (VM), Semitendinosus (S), Biceps Femoris (BF), Tibialis Anterior (TA), Gastrocnemius Medialis (GM), Gastrocnemius Lateralis (GL)) bioelectrical activity data were obtained using a Noraxon MR 400 sEMG device and MyoTrace software. Statistical analysis was performed using SPSS Statistics v25.

In parallel foot position the highest EMG activity was observed in the VM (99.18 mV), S (55.27 mV) and RF (33.06 mV) muscles. In semi-tandem foot position the highest activity was observed in S (120.8 mV), GM (59.03 mV), and TA (47.84 mV) muscles, with the lowest in BF (6.58 mV) muscle.

1. Lowered base of support increases the activity of the semitendinosus and medial gastrocnemius muscles.
2. Maintaining the feet-together stance depends on the synergy between the semitendinosus and medial gastrocnemius muscles.
3. Maintaining semi-tandem positioned halfway in front of the other foot depends on the synergy between the vastus lateralis and tibialis anterior muscles.

Keywords: EMG, posture balance, motor activity, 4-Stage Balance Test.

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Introduction

The PubMed scientific literature database contains 85 papers from the last 5 years. Eight of these were clinical studies (state on 16/11/2024) concerning the electrical activity of muscles responsible for static balance. Han *et al.* [1] demonstrated muscle timing and force during single-leg stance in individuals with chronic ankle instability. Mandalidis *et al.* [2] characterised the difference between muscle tone during single-leg stance. Cimadoro *et al.* [3] highlighted muscle tone inequalities in the presence of an unstable surface. Relatively few studies have focused on muscle activation during balance tests. Examples include studies by Kaur *et al.* and Duarte *et al.* — Kaur *et al.* [4] examined muscle behavior during the Y-balance test while Duarte *et al.* [5] explained in their work on anticipatory postural adjustments that anti-gravity muscles involved in balance recovery increase tone prior to voluntary skeletal muscles. Additionally, Duarte *et al.* observed greater delays in muscle activation during balance recovery in elderly compared to younger adults: erector spinae (MD –31.44), rectus abdominis (MD –31.55), tibialis anterior (MD –44.7), soleus (MD –37.74), gastrocnemius (MD –120.59), quadriceps (MD –17.42), biceps femoris (–117.47). There is a lack of research that would methodically specify the baseline values of muscle tone and show their activation in balance testing using selected parts of the 4-Stage Balance Test.

Material and Methods

This study received ethical approval from the Jagiellonian University Collegium Medicum Ethics Committee (approval code: 118.6120.75.2023). The sample size was calculated using an online calculator from the OpenEpi website (https://www.openepi.com/SampleSize/SSPropor.htm). It was assumed that approximately 93% of people aged 18–24 in Poland (approximately 2.6 million people: https://www.statista.com/statistics/1263998/poland-number-of-people-aged-18-24) do not have balance disorders, assuming a 5% margin of error. The required sample size in this case was 71 individuals [6]. The inclusion criteria were: age (18–25 years), absence of balance disorders (successful completion of a section of the 4-Stage Balance Test), while exclusion criteria included recent injuries or other musculoskeletal conditions (within 6 months of injury), fractures of long bones, ligament damage, meniscus damage or resection, joint capsule damage, Achilles tendon rupture, restricted range of motion in the hip, knee, and ankle joints, neurological conditions with balance disorders, leg length discrepancy >10 mm, lack of consent to participate in the study and withdrawal of consent during the study. Approximately 5% dropout was anticipated, therefore 75 individuals were enrolled in the study.

Participants

Seventy-five individuals participated in the study — 41 men and 34 women (54.7% and 45.3% respectively). The mean age was approximately 22 years (X = 21.83 years, SD 1.5 years), mean body mass 69.36 kg, with a minimum of 49 kg and a maximum of 91 kg. The standard deviation was 11.9 kg. Participants' mean height was 1.72 m (minimum 1.59 m, maximum 1.9 m), standard deviation 0.38 m. The mean body mass index (BMI) was 23.22 kg/m^2, with a minimum of 19.38 kg/m^2 and a maximum of 28.1 kg/m^2. The mean absolute length of the left lower limb was shorter than the right (78 cm vs. 79 cm; 1 cm difference). However, the relative length was identical in both limbs (64 cm). Statistical analysis showed no significant differences between limbs in terms of both absolute and relative measurements ($p > 0.05$). The mean thigh circumference was similar in both — left and right lower limbs (64 cm and 64 cm respectively), while the average calf circumference was 51.8 cm on the left and 51.2 cm on the right. Statistical analysis showed no significant differences between limbs ($p > 0.05$). The average range of motion (ROM) for hip flexion was 128°, extension 9.7°, internal rotation 39.5°, external rotation 49.1°, adduction and abduction 29° and 39.1° respectively (Table 1).

Table 1. Baseline characteristic.

Variable	N = 75
Sex [f/m] N(%)	34 (45.3) / 41 (54.7)
Age [y] X(SD)	21.83 (1.5)
Weight [kg] X(SD)	69.36 (11.9)
Height [m] X(SD)	1.72 (0.38)
BMI [kg/m^2] X(SD)	23.22 (2.55)
Absolute length of lower limb [cm] X(SD)	
Right	79 (12)
Left	78.6 (11.2)
Relative length of lower limb [cm] X(SD)	
Right	64 (11)
Left	64 (10.5)
Circuit of thighs [cm] X(SD)	
Right	51.2 (4.3)
Left	51.8 (4.8)
Circuit of calf [cm] X(SD)	
Right	51.2 (4.3)
Left	51.8 (4.8)
Hip joint range of motion [°] X(SD)	
Flexion	128 (2.1)
Extension	9.7 (0.5)
Internal rotation	39.5 (0.7)
External rotation	49.1 (0.7)
Adduction	29 (0.4)
Abduction	39.1 (1.1)
Knee joint range of motion [°] X(SD)	
Flexion	139.2
Extension	1.2 (0.4)
Interial rotation	12.01 (0.3)
External rotation	15.7 (0.7)
Ankle joint range of motion [°] X(SD)	
Dorsiflexion	29.8 (1.3)
Plantar flexion	44.7 (1.4)

f — female, m — male, y — years, kg — kilogram, m — meter, BMI — body mass index, cm — centimeter, [°] — degree, X — average, SD — standard deviation

Table 1. Cont.

Measures

Data were collected using a questionnaire containing socio-demographic and anthropometric data: height, weight, age, sex, and questions regarding health status (especially neurological diseases affecting balance) and musculoskeletal system. Range of motion was measured using a goniometer (SFTR Goniometer Baseline 360 degrees, USA). Limb length and circumference were measured using an ADE MZ10021 tape measure (Germany). Static balance was assessed using two tests from the 4-Stage Balance Test [7]. Both tests involved standing on a narrow base, with foot position differing between tests. Test no. 1 involved taking a starting position of standing with feet hip-width apart, then moving to a feet-together stance. Time spent standing on a narrow base until loss of balance or use of hands was measured in seconds (maximum 30 seconds). Test no. 2 involved taking a starting position of standing with feet hip-width apart and then placing one foot in front of the other, halfway along its length. Time spent standing on a narrow base until loss of balance or use of hands was measured in seconds. Muscle bioelectrical activity data were obtained using a Noraxon MR 400 sEMG device (Scottsdale, Arizona, USA) and MyoTrace software. Electrode application and skin preparation followed SENIAM guidelines. The following muscles were assessed: Rectus Femoris (RF), Vastus Lateralis (VL), Vastus Medialis (VM), Semitendinosus (S), Biceps Femoris (BF), Tibialis Anterior (TA), Gastrocnemius Medialis (GM), Gastrocnemius Lateralis (GL) [8]. Values are expressed as mean mV.

Design and procedures

Participants were tested in a laboratory setting with ambient temperature of 21°C. Each examination lasted 60 minutes. Participants were to arrive at their scheduled time and at first completed anthropometric data forms with a second researcher. Then, static balance was assessed using two selected tests from the 4-Stage Balance Test — first involved feet together, second with one foot positioned parallel to and halfway along the other (Fig. 1). Participants had one

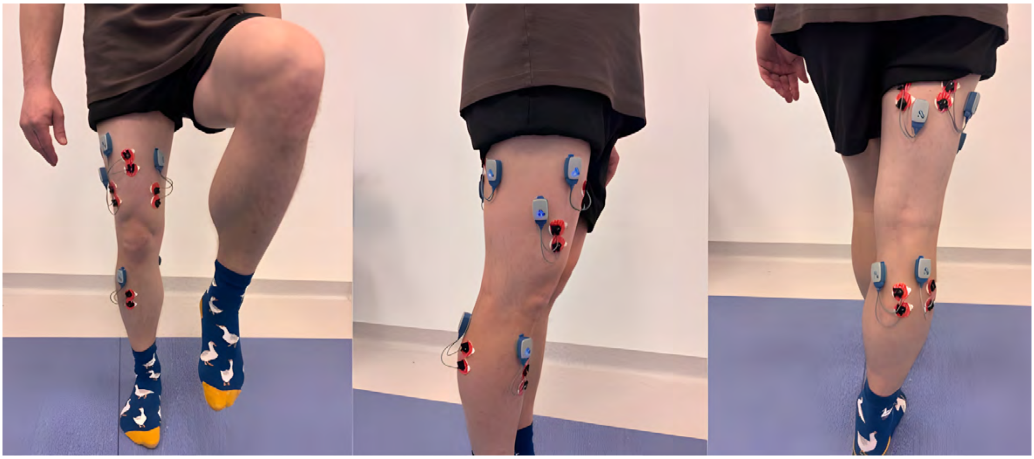

Fig. 1. Examination of the function of the vastus lateralis, vastus medialis, biceps femoris, and semitendinosus muscles (photo by Grzegorz Frankowski).

minute to get acquaint with each position before testing began. Following each test, participants rested for two minutes. Electrodes were then applied to the following muscles: RF, VL, VM, S, BF, TA, GM, GL.

Statistical analysis

Statistical analysis was performed using SPSS Statistics v25 (Polish version). Data normality was tested using the Shapiro-Wilk test (N <100). Descriptive statistics and hypothesis testing were performed. Descriptive statistics were divided according to variable type. Qualitative variables were presented as counts and percentages. For quantitative variables, measures of central tendency (weighted means) and dispersion (standard deviations and ranges) were calculated. Differences in anthropometric data were assessed using the Wilcoxon rank-sum test. Statistical hypotheses were tested using the Student's t-test. Pearson correlation and backward stepwise multiple regression analyses were performed to identify factors influencing electromyography. Alpha was set at 0.05.

Results

All participants completed the balance test (N = 75, 100%), the average time was 29.8s. EMG activity was measured in eight muscles during the parallel stance. In test no. 1, the highest EMG activity was observed in the VM (99.18 mV), S (55.27 mV), and RF (33.06 mV) muscles, while the lowest was observed in VL muscle (7.48 mV). In test no. 2, the highest activity was observed in S (120.8 mV), GM (59.03 mV), and TA (47.84 mV) muscles, with the lowest in BF muscle (6.58 mV). Full results are presented in Table 2.

Table 2. Electromyography results for Test no. 1 and Test no. 2.

Test no. 1 and Test no. 2	N = 75		
Variable	**Test 1 X/SD**	**Test 2 X/SD**	**t/p**
Rectus femoris [mV]	33.06 (12.9)	21.22/16.82	**5.19/<0.001**
Vastus lateralis [mV]	99.18 (19.98)	19.41/11.74	**31.55/<0.001**
Vastus medialis [mV]	7.48 (2.99)	19.28/2.33	**–36.74/<0.001**
Semitendinosus [mV]	53.27 (10.51)	120.8/27.44	**–20.15/<0.001**
Biceps femoris [mV]	8.31 (6.15)	6.58/3.78	**2.58/0.01**
Tibialis anterior [mV]	25.98 (4.63)	47.84/41.59	**–4.63/<0.001**
Gastrocnemius medialis [mV]	26.77 (8.18)	59.03/35.19	**–7.96/0.001**
Gastrocnemius lateralis [mV]	15.069 (8.11)	33.89/3.98	**–18.24/<0.001**

Statistical analysis revealed correlations between muscles during the feet-together stance. The highest correlation was observed between the semitendinosus and the medial gastrocnemius (r = 0.731/<0.01) (Table 3). In test no. 2, the highest positive correlation was found between vastus lateralis and tibialis anterior muscle (r = 0.729/<0.05) (Table 4).

Table 3. The relationship between muscle electromyography during Test no. 1.

N = 75								
Variable	**Rectus femoris [mV] r/p**	**Vastus lateralis [mV] r/p**	**Vastus medialis [mV] r/p**	**Semitendinosus [mV] r/p**	**Biceps femoris [mV] r/p**	**Tibialis anterior [mV] r/p**	**Gastrocnemius medialis [mV] r/p**	**Gastrocnemius lateralis [mV] r/p**
Rectus femoris [mV] r/p	1	0.027/0.816	–0.084/0.474	–0.143/0.221	0.056/0.632	0.056/0.632	–0.198/0.831	–0.023/0.843
Vastus lateralis [mV] r/p	0.027/0.816	1	0.015/0.9	–0.053/0.649	0.014/0.904	–0.048/0.683	–0.086/0.463	–0.083/0.483
Vastus medialis [mV] r/p	–0.084/0.474	0.015/0.9	1	–0.212/0.068	–0.013/0.912	–0.207/0.074	**–0.273/0.018**	0.118/0.315
Semitendinosus [mV] r/p	–0.143/0.221	–0.053/0.649	–0.212/0.068	1	0.111/0.34	**0.383/<0.001**	**0.731/<0.01**	0.149/0.203
Biceps femoris [mV] r/p	0.056/0.632	0.014/0.904	–0.013/0.912	0.111/0.34	1	–0.011/0.924	–0.024/0.838	0.051/0.663
Tibialis anterior [mV] r/p	0.056/0.632	–0.048/0.683	–0.207/0.074	**0.383/<0.001**	–0.011/0.924	1	**0.442/<0.001**	**0.32/0.005**
Gastrocnemius medialis [mV] r/p	–0.198/0.831	–0.086/0.463	**–0.273/0.018**	**0.731/<0.01**	–0.024/0.838	**0.442/<0.001**	1	**0.257/0.026**
Gastrocnemius lateralis [mV r/p	–0.023/0.843	–0.083/0.483	0.118/0.315	0.149/0.203	0.051/0.663	**0.32/0.005**	**0.257/0.026**	1
r — Pearson correlation coefficient, p — significance level								

Table 4. The relationship between muscle electromyography during Test no. 2.

N = 75								
Variable	Rectus femoris [mV] r/p	Vastus laterali [mV] r/p	Vastus medialis [mV] r/p	Semitendinosus [mV] r/p	Biceps femoris [mV] r/p	Tibialis anterior [mV] r/p	Gastrocnemius medialis [mV] r/p	Gastrocnemius lateralis [mV] r/p
Rectus femoris [mV] r/p	1	**0.546/<0.05**	–0.195/0.093	**0.311/<0.05**	**0.416/<0.05**	**0.59/<0.05**	**0.477/<0.05**	**0.372/<0.05**
Vastus lateralis [mV] r/p	**0.55/<0.001**	1	**0.23/0.045**	**0.401/<0.05**	**0.546/<0.05**	0.729/<0.05	0.68/<0.05	0.357/<0.05
Vastus medialis [mV] r/p	**0.19/0.09**	**0.23/0.045**	1	–0.029/0.81	–0.031/0.789	–0.031/0.789	0.029/0.81	–0.044/0.7
Semitendinosus [mV] r/p	**0.311/<0.05**	0.401/<0.05	–0.029/0.81	1	0.137/0.24	**0.36/0.001**	**0.72/<0.05**	0.162/0.164
Biceps femoris [mV] r/p	**0.416/<0.05**	**0.546/<0.05**	–0.043/0.712	0.137/0.24	**1**	**0.426/<0.05**	**0.4/<0.05**	**0.229/0.048**
Tibialis anterior [mV] r/p	**0.59/<0.05**	**0.729/<0.05**	–0.031/0.789	**0.36/0.001**	**0.426/<0.05**	1	0.65/<0.05	0.35/0.02
Gastrocnemius medialis [mV] r/p	**0.477/<0.05**	**0.68/<0.05**	0.029/0.81	**0.72/<0.05**	**0.4/<0.05**	0.65/<0.05	1	**0.31/<0.05**
Gastrocnemius lateralis [mV] r/p	**0.372/<0.05**	**0.357/<0.05**	–0.044/0.7	0.162/0.164	**0.229/0.048**	0.35/0.02	**0.31/<0.05**	1
r — Pearson correlation coefficient, p — significance level								

Discussion

The study clearly show two different muscle synergies depending on the test performed. During single-leg stance, the semitendinosus and medial gastrocnemius muscles were activated. However, with the feet-together one foot in front stance, the synergy shifted to the vastus lateralis and tibialis anterior muscles. This represents a substantial change in postural stability patterns, from deep posterior-medial thigh muscles during single-leg stance to superficial anterolateral muscles during the near feet-together stance. Sánchez-Barbadora *et al.* [9] demonstrated that during stance the peroneus longus (63.65 mV), tibialis anterior (51.43 mV) and medial gastrocnemius (49.23 mV) showed the greatest activity. In this study, the vastus lateralis (99.2 mV) and semitendinosus (54.27 mV) dominated. Interestingly, the tibialis anterior activity in the current study was half that reported by Sánchez-Barbadora *et al.* (51.43 mV vs. 25.98 mV), and the medial gastrocnemius activity was also similar (49.23 mV vs. 26.77 mV). It is worth noting that the high medial gastrocnemius activity could be associated with knee extension, making it unclear if the Spanish study's results are affected by fatigue and attempts to maintain knee extension during stance [10]. This highlights some inconsistencies in muscle activity distribution. The participants in both studies were of similar age (approximately 22 years in this study, 23 in Sánchez-Barbadora *et al.*'s study [9]). Sánchez-Barbadora *et al.*'s study included 20 participants, while this study had 75. Another difference may be high physical activity reported by Sánchez-Barbadora *et al.* (>200 minutes per week).

The results of this study clearly indicate that muscle synergy varies with movement. Labanca *et al.* [11] defined lower limb synergists responsible for postural control in three regions. Ankle joint balance strategy involved five muscles: peroneus longus, peroneus brevis, lateral gastrocnemius, tibialis anterior, and flexor hallucis longus. The knee joint strategy included three muscles: vastus lateralis, vastus medialis, and rectus femoris. The hip joint strategy comprised five muscles: biceps femoris, semitendinosus, gluteus medius, longissimus thoracis, and quadratus lumborum. In our study, only two muscles were identified in the knee joint strategy and there was no information on hip joint synergists. Labanca *et al.*'s ankle synergists, analyzed using Spearman's rank correlation, showed weak but significant synergy during single-leg stance between the lateral gastrocnemius and tibialis anterior ($rs = 0.32$, $p < 0.005$). A slightly higher correlation ($rs = 0.351$, $p = 0.002$) was found during the near feet-together stance. A much higher correlation was observed during single-leg stance ($rs = 0.42$, $p < 0.001$). This correlates with Labanca *et al.*'s [11] results, which demonstrated similar behavior of the tibialis anterior and lateral gastrocnemius muscles in ankle synergy. No such synergy was observed for the knee joint in either single-leg or feet-together stances, only moderate synergy was found during the near feet-together stance ($rs = 0.55$, $p < 0.001$). The synergy between the vastus lateralis and medialis muscles doubled in this condition. The observed synergy is presented indirectly, based on correlation results.

Conclusion

1. Lowered base of support increases the activity of the semitendinosus and medial gastrocnemius muscles.
2. Maintaining the feet-together stance depends on the synergy between the semitendinosus and medial gastrocnemius muscles.
3. Maintaining the stance with one foot positioned halfway in front of the other foot depends on the synergy between the vastus lateralis and tibialis anterior muscles.

Institutional Review Board Statement

This study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Jagiellonian University Collegium Medicum (approval code: 118.6120.75.2023; approval date: 22 October 2021).

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Conflict of interest

None declared.

Author contributions

Research concept and design, G.F.; Writing the article, J.Z.; Assembly of data, K.B.

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