Evaluation of the Foot Performance in "Single Leg Squat" Test of Female Athletes using Smart Socks

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Abstract: Increased plantar pressure on the medial side of the plantar surface of the foot in female athletes is one of the risk factors for lower extremity injuries. Functional tests single-leg squat tests (SLST), are one of the ways to assess changes in foot plantar pressure. The main disadvantage of clinical functional tests is their subjectivity. Moreover, as a rule, these tests are performed under laboratory conditions, which is expensive and time-consuming. This paper demonstrates the evaluation of lower foot behaviour in several SLST variations by the DAid Pressure Sock System (DPSS). The research was based on the cross-sectional study, where a group of healthy female athletes was requested to perform SLST exercises under the supervision of a physiotherapist, while simultaneously the feet plantar pressure was measured with the DPSS. Based on the observations of the physiotherapist, the participants were sorted in the test group and control group, depending on their ability to perform the exercises with or without increased inversion of the foot. Meanwhile, the application of the DPSS provided an estimate of the lateral-medial deviations of the centre of plantar pressure (COP) for evaluation of the feet functionality during the SLST. A clear correlation between the medial shift of the COP value, obtained from the DPSS measurement, and the physiotherapist's decision on the quality of the SLST was observed. It was observed that the average COP value for the test group was shifted medially, while for the control group the position of COP was shifted laterally. Therefore, the application of DPSS with SLST has a potential for athlete functional testing, as well as for the development of feedback-based training aid in the training environment to help coaches and athletes to monitor the accuracy of the foot position in various squat exercises.

1 INTRODUCTION

One of the risk factors for lower extremity injuries in female athletes is altered lower limb biomechanics, characterized by the redundant increase of the pressure on the medial side of the foot plantar surface (Numata et al., 2018). Such alteration could cause overuse injuries, such as tibial stress syndrome (Razak et al., 2012; Neal et al., 2014; Buldt et al., 2018), iliotibial syndrome, *m. tibialis posterior* dysfunction, anterior cruciate ligament rupture (Kagaya et al., 2015; Ugalde et al., 2015; Hughes et al., 2019) and patellofemoral pain syndrome, and plantar fasciitis (Razak et al., 2012; Neal et al., 2014; 2015; Buldt et al., 2018).

In clinical practice, to assess the risk of lower limb injuries and to assess the potential risk factors associated with future injuries, lower limb functional tests are used. Among them is a variety of single leg squat tests (SLST) used in periodic health examinations in the clinical setting to identify problems of the lower extremity biomechanics and reveal incorrect movement patterns (Ugalde et al., 2015; Khuu et al., 2016; Kagaya et al., 2015; Hughes et al., 2019; Khuu et al., 2019).

The typical distorted movement patterns during SLST include increased internal rotation and adduction of the hip joint, internal rotation of the lower leg, a medial deviation of the knee joint or knee position of the knee joint, and increased foot pronation, also known as dynamic valgus position (Ugalde et al., 2015; Khuu et al., 2016; Wyndow et al., 2016; Kagaya et al., 2017; Hughes et al., 2019).

The main drawback of the SLST is that the tests are based on subjective visual assessment. This limits observable parameters and makes test results depend

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on the experience of the involved clinician. Also, functional tests are generally performed under laboratory/clinic conditions, which can be comparatively time-consuming and expensive.

Development of reliable lower limb movement tracking systems for sports, medicine, or rehabilitation could enable the measurement of limb movement, identification of altered movement patterns, and analysis of long-term data, and, therefore, could help to significantly reduce the risk of lower limb injuries (Kianifar et al., 2017; Khuu et al., 2019). One such system, DAid Pressure Sock System (DPSS), is based on the application of entirely textile smart socks with integrated knitted-in plantar pressure sensors (Oks et al., 2016, Eizentals et al., 2019). DPSS was demonstrated to be an effective tool for gait analysis in a wide range of gait types and velocities (walking, race walking, jogging, fast running) (Oks et al., 2017). One of the main advantages of the DPSS is the ability to be used as a gait monitoring system both barefoot and with different types of shoes.

The aim of the present research was an assessment of the applicability of the DPSS for objective evaluation of the feet functionality during an SLST through quasi-static measurements of the foot plantar pressure. A modified version of the center of pressure (COP) calculation was applied for quantification of the characteristic plantar pressure during the SLST exercise. The obtained result demonstrated that a clear difference in the characteristic COP measurement can be observed if the SLST exercise is performed with increased foot pronation when compared to the result from the control group.

2 MATERIALS AND METHODS

2.1 DAid Pressure Sock System

The DAid Pressure Sock System, used in the present research, consists of pair of socks with 6 pressure sensors, knitted into the sole part of each sock: two on the heel, two under the arch, and two under the metatarsals (Fig.1a). Such positioning of sensors enables monitoring of temporal gait characteristics as well as detection of the supination/ pronation of lower feet. Conductive pathways are designed to provide the connection between sensors and the data acquisition units. The sampling frequency of data acquisition is up to 200 Hz. A more comprehensive description of the system is presented in (Eizentals et al., 2019, Oks et al., 2019).

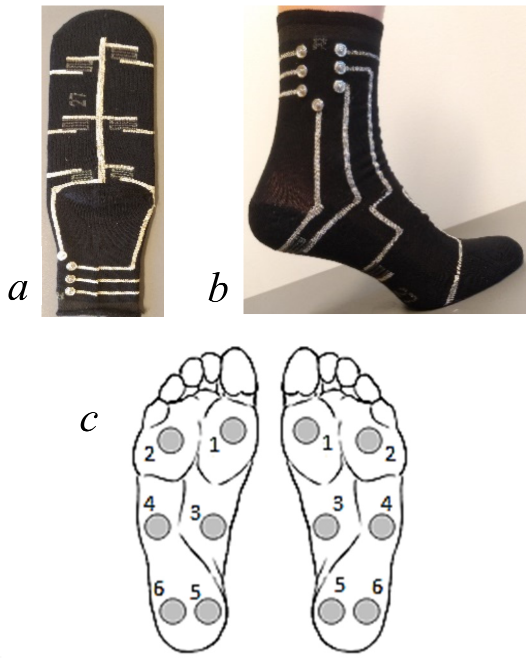

Figure 1: Smart Sock. a-sole part, b-conductive pathways with contact snaps, c - placement of sensors (Eizentals et al., 2019).

2.2 Participants

The study involved volunteers – healthy female athletes from the FS Metta football club. The inclusion criteria were age (range 18-25 years) and experience in sports (at least 10 years). The exclusion criteria were health-related issues, including:

- Pain in any knee joint during movement
- Lower limb disease, deformity, injury, and/or surgery in the last 12 months.
- Vestibular disorders

On the base of these criteria, 20 participants were included in the study. The mean age of the participants was 20.4 years (SD 2.1) years, the mean body mass index (BMI) was 21.0 (SD 1.7). Informed consent was obtained from all individual participants included in the study. The study was conducted following ethical standards comparable to the Declaration of Helsinki and its later amendments. The study protocol was approved by the Ethics Committee of Riga Stradins University (6-2/11, 19.12.2019).

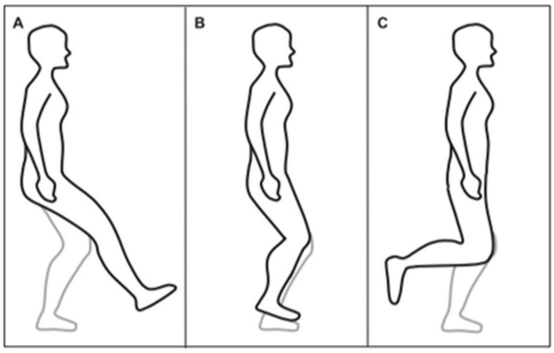

Figure 2: Body position in SLST: a- single leg squat-front test; b- single-leg squat-middle test; c- single-leg squat-back test (*Khuu et al., 2019*).

2.3 Trial Design and “Single Leg Squat” Functional Tests Description

SLST was performed with smart socks and sports shoes. To provide visual observation, surface markers were placed symmetrically on both lower extremities - *spina iliaca anterior superior*, the midpoint between *femur condylus medialis* and *condylus lateralis*, the midpoint between *malleolus medialis* and *malleolus lateralis* (Ugalde et al., 2015; Khuu et al., 2016; Hughes et al., 2019).

Three different variations of the “Single Leg Squat” test were performed (see Fig. 2). The participants were asked to place their hands on their hips or along their sides and stand on one leg, while the other leg (not the supporting one) was placed in one of three positions. From this position, they were instructed to squat the supporting leg to approximately 60-degree flexion position in the knee joint and return to the starting position by straightening the knee joint.

Three variations of SLST were:

- the single leg squat-front test (further SLS-F) was performed with the non-supporting leg stretched fully forward in front position (Fig. 2a);
- the single leg squat-middle test (further SLS-M) was performed with the non-supporting leg bent 90 degrees in the knee joint and aligned along the supporting leg, in the middle position (Fig. 2b);
- the single leg squat-back test (further SLS-B) was performed with the non-supporting leg bent 90 degrees in the knee joint and pulled behind the back in a backward position (Fig. 2c).

In every test, at the beginning of the first squat, the test (supporting) leg was lifted from the floor to indicate the starting point of the squat, after which the participant performed three squats in a row. In total, three squats were performed for each leg for each variation of SLST.

The squats performed by participants were visually inspected by a certified physiotherapist, who assessed participants' feet performance. Alongside, the data from DPSS were recorded, however, the results of recording were not communicated to the physiotherapist. On the base of visual inspection, the physiotherapist provided a reference conclusion concerning test results, hereby separating participants into two groups: control group (6 athletes), where participants demonstrated correct SLST foot performance, and study group (14 athletes), where participants performed tests with excessive pronation of the lower feet. In the control group, the mean age was 20.6 years (SD 2.2 years), a mean BMI was 20.7 (SD 1.7), while in the study group, the mean age was 20.3 years (SD 2.2 years), and the mean BMI was 21.1 (SD 1.8).

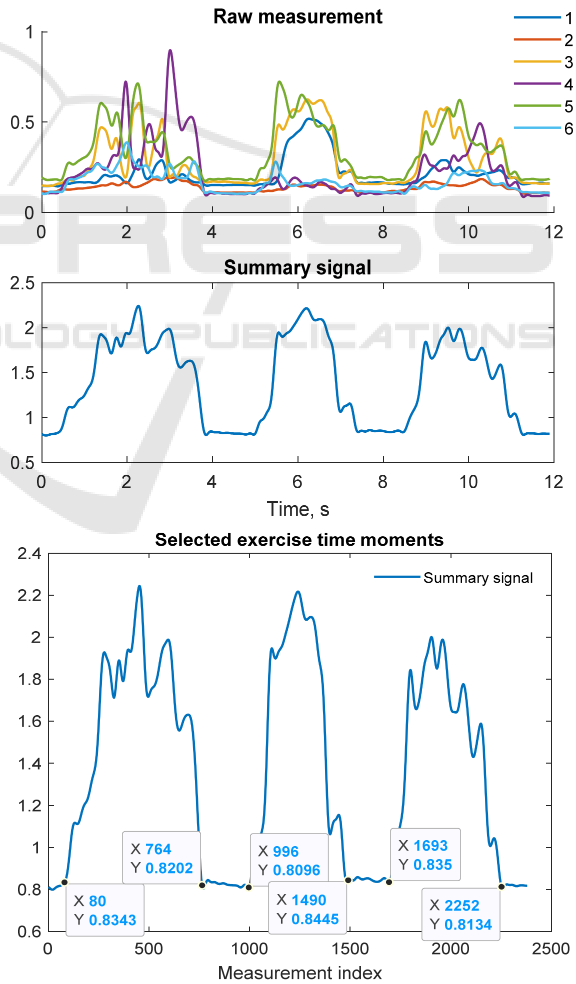

Figure 3: The raw measurement from each sensor during three separate SLST exercises, the sum of all signals, and the manually selected time moments for analysis.

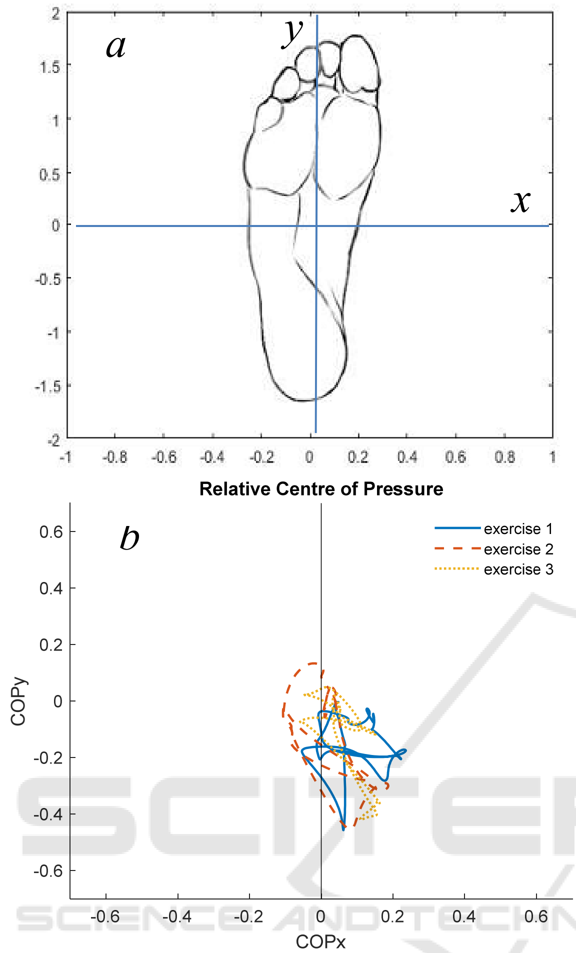

Figure 4: COP coordinates with the center fixed to the center of the foot (a, not to scale), and an example of the calculated COP for 3 SLST measurements (b).

2.4 Data Processing

The evaluation of the change of the plantar pressure of the load-bearing foot during the exercise was performed by analyzing the variation of the center of pressure (COP), which is a widely applied method in gait analysis. Due to a variation of the textile sensor location on the foot, a modified version of COP was used for this application, where sensor positions are defined relative to the center of the foot (P. Eizentals et al., 2018). This technique of the COP calculation assigns dimensionless arbitrary positions of the separate sensors to avoid COP data dependence on the foot size, consequently, the COP coordinates are expressed in arbitrary units.

Before the calculation of the COP, the measurement from DPSS was pre-processed according to the following algorithm. First, the measured resistance of the sensors is converted to the conductance through equation (1):

$$u_i = R_i^{-1} \tag{1}$$

where R_i is the i-th measurement of the raw signal. The calculated values are then filtered with a zero phase-shift low-pass filter (Chebyshev type II, cut-off frequency 10Hz). The signal from all sensors (Fig.3*a*) then was then summed to obtain the total pressure measurement during the exercise (Fig 3*b*), which was employed for manual selection of the start and end moment of each SLST exercise (Fig 3c).

For each of the selected periods, the COP was calculated for the whole movement through the equations (2) and (3):

$$V_x = \sum_{i=1}^{n=6} k_i u \cos \varphi_i \tag{2}$$

$$V_y = \sum_{i=1}^{n=6} k_i u \sin \varphi_i \tag{3}$$

where u is the measurement from each sensor obtained from equation (1), $k = [1, 1, \cos\alpha, \cos\alpha, 1, 1]$ is a vector holding weight coefficients assigned to each sensor, and $\varphi = [75°, 105°, 0°, 180°, 285°, 255°]$ is the angle assigned to each sensor in the arbitrary coordinate system. The sensors numbered in the order presented in Fig. 1c. The coordinate system and an example of a COP for 3 consecutive squats are presented in Fig 4. Figure 4b indicates that only the COP component on X-axis (COPx) is important for determining the over-pressure on the medial part of the foot, which is important for this study, and therefore only this component was used further in the statistical analysis. For the selected coordinate system, the positive values of COPx correspond to the medial shift of COP, negative values of COPx – to the lateral shift of COP.

2.5 Data Analysis

Statistical analysis of the calculated COPx values included two parametric methods – two-factor ANOVA with replication, and unpaired t-test. The independent factors in ANOVA were the participant (identified by the ID number) and the variation of SLST. For each "participant – SLST variation" combination three replicas, corresponded to separate squats were used to estimate repeatability of the DPSS measurement. ANOVA was performed to the control and the study groups separately, and for right and left leg tests, resulting in four separate ANOVA tables. Unpaired t-test was applied to compare the average COPx values of the control group and the study group, separately to each variation of the SLST test for the right and the left leg.

3 RESULTS AND DISCUSSION

The results of COPx calculations for the control group and study group are summarised in Table 1. The table presents data for separate squats, performed in a series of three different variations of the SLST exercises, separately for left and right legs.

3.1 Validation of DPSS Applicability for Evaluation of the SLST Foot Performance

Data in Table 1 demonstrates that the COPx value varies between separate squat measurements. To compare these variations with the differences between individual athletes as well as with variation due to modification of the SLST technique, two-parametric ANOVA with replications was used. Table 2 summarizes P–values, associated with the ANOVA test and indicating the contribution of the corresponding source of variance to the overall variability of COPx. The data from Table 2 indicates, that contribution of the SLST variant to the total variance of COPx was significant ($P < 0.05$) in half cases, i.e. for the control group left leg test and for the study group right leg test. This implies that differences in COPx, caused by the change of the SLST mode could be comparable to, or even greater than the differences between COPx for separate squats, caused by repeatability error of the DPSS measurement. In turn, the contribution of the athlete

Table 1: Results of COPx calculations for control group and study group, the mean value for each of three exercises is given in the table.

Participant No	Left leg			Right leg		
	Front test (SLS F Left)	Middle test (SLS M Left)	Back test (SLS B Left)	Front test (SLS F Right)	Middle test (SLS M Right)	Back test (SLS B Right)
Control group						
1	-0.02 -0.02 -0.02	-0.06 -0.09 -0.02	-0.09 -0.06 -0.09	-0.11 -0.1 -0.08	-0.05 -0.06 -0.04	-0.04 -0.03 -0.04
2	-0.09 -0.04 -0.03	-0.04 -0.07 -0.04	-0.09 -0.06 -0.07	-0.04 -0.02 -0.01	-0.02 -0.03 -0.03	-0.06 -0.03 -0.04
3	-0.06 0.00 0.04	-0.07 -0.16 -0.07	-0.08 0.00 -0.04	-0.04 -0.06 -0.06	-0.02 -0.07 -0.01	-0.01 -0.09 -0.05
4	-0.06 -0.03 -0.04	-0.03 -0.02 0.00	0.00 -0.05 -0.06	-0.11 -0.04 -0.08	-0.06 -0.07 -0.1	-0.04 -0.05 -0.06
5	-0.06 0.00 0.04	-0.07 -0.16 -0.07	-0.08 0.00 -0.04	-0.09 -0.06 -0.09	-0.15 -0.11 -0.07	-0.02 -0.06 -0.05
6	-0.03 -0.04 -0.05	-0.02 -0.03 -0.01	-0.06 -0.08 -0.07	-0.04 -0.02 -0.01	-0.02 -0.03 -0.03	-0.06 -0.03 -0.04
Study group						
1	0.02 0.09 0.09	0.03 0.19 0.09	0.09 -0.01 0.06	0.02 0.08 0.04	0.04 0.06 0.05	0.03 0.09 0.08
2	0.21 0.16 0.24	0.14 0.16 0.20	0.16 0.23 0.21	-0.02 0.05 0.04	-0.04 0.02 0.03	0.00 0.02 -0.01
3	0.11 0.11 0.07	0.05 0.00 0.01	-0.01 0.03 0.06	0.06 0.07 0.03	0.06 0.00 0.00	0.11 0.04 -0.04
4	0.04 0.03 -0.02	-0.01 0.05 0.01	0.01 0.00 0.05	0.02 0.04 -0.03	0.01 0.06 0.02	0.00 0.02 0.05
5	0.05 0.05 0.08	0.05 0.03 0.06	0.01 0.03 0.00	0.07 0.05 0.10	0.04 0.06 0.05	0.07 0.06 0.07
6	0.05 0.06 0.07	0.03 0.02 0.04	0.04 0.03 0.02	0.05 0.08 0.06	0.08 0.07 0.09	0.06 0.11 0.06
7	0.10 0.13 0.16	0.07 0.09 0.06	0.11 0.10 0.09	0.07 0.07 0.02	0.05 0.05 0.05	0.07 0.09 0.06
8	0.04 0.03 -0.02	0.11 0.13 0.16	0.06 0.15 0.17	0.03 0.04 0.03	0.03 0.19 0.09	0.03 0.09 0.08
9	0.21 0.16 0.24	0.14 0.16 0.20	0.16 0.23 0.21	0.07 0.05 0.10	0.14 0.16 0.20	0.07 0.06 0.07
10	0.05 0.05 0.08	0.05 0.03 0.06	0.01 0.03 0.00	-0.02 0.05 0.04	0.05 0.00 0.01	0.00 0.02 -0.01
11	0.10 0.13 0.16	0.11 0.13 0.16	0.06 0.15 0.17	0.07 0.07 0.02	0.05 0.03 0.06	0.07 0.09 0.06
12	0.11 0.11 0.07	0.05 0.00 0.01	-0.01 0.03 0.06	0.02 0.04 -0.03	0.03 0.02 0.04	0.00 0.02 0.05
13	0.02 0.09 0.09	0.02 0.08 0.04	0.14 0.16 0.20	0.02 0.08 0.04	0.07 0.09 0.06	0.03 0.09 0.08
14	0.03 0.02 0.04	0.06 0.07 0.03	0.11 0.13 0.16	0.06 0.07 0.03	0.11 0.13 0.16	0.11 0.04 -0.04

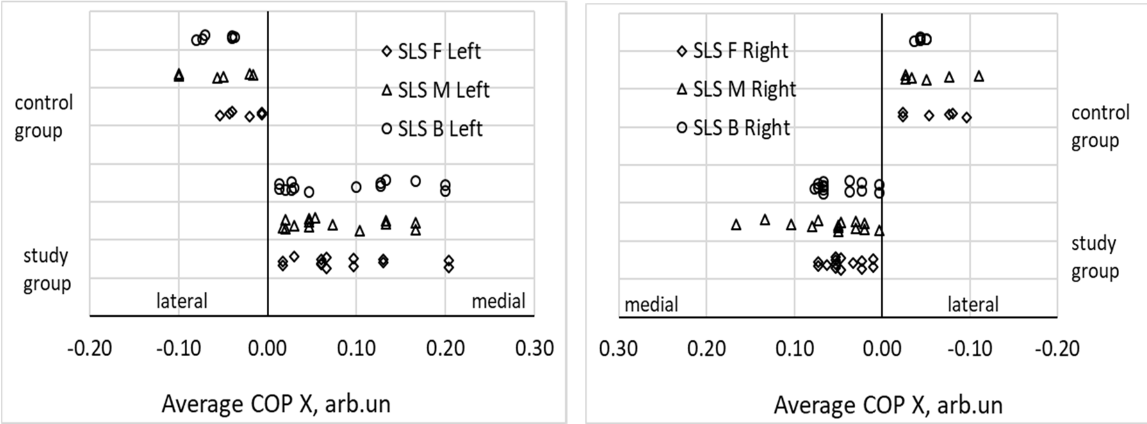

Figure 5: Values of average COPx for (*a*) left and (*b*) right foot for different SLST exercises.

Table 2: Summary of ANOVA analysis: *P*- values associated with influence of the factors.

Factor	Control group		Study group	
	Left leg	Right leg	Left leg	Right leg
SLST variant	0.01	0.14	0.12	0.04
Athlete	0.62	6.4×10^{-5}	1.28×10^{-23}	2.7×10^{-8}
Interaction	0.01	0.006	7.2×10^{-7}	0.03

factor was significant in three cases out of four. This means, that individual variations between athletes are generally higher, then intra-athlete variation due to DPSS repeatability error.

Additionally, it is worth noting that only a “non-significant” case corresponds to the left leg squats in the control group. This may be explained by the fact, that athletes in the control group were right-handed persons, having the leading left leg, therefore they performed squats in a highly stable manner with small variation in the position of the COP. The interaction between SLST mode and athlete factors was significant for all four ANOVA tests. This could be interpreted, that variations in COPx, caused by different combinations “SLST mode – athlete” are generally greater, then variations, caused by DPSS repeatability error. Summarising these arguments, one could conclude, that accuracy of the DPSS measurements is adequate to reveal individual variations between athletes. In other words, differences between athletes' COPx measurements are higher than differences, caused by DPSS repeatability error in single athlete’s measurements. This conclusion validates DPSS applicability for evaluation of the SLST foot performance. Alongside, in the following analysis, one could use COPx, averaged over three squats for characterization of separate athletes.

3.2 Comparative Analysis of COPx Coordinate Deviation during SLST

Figure 5 summarises data on average COPx parameter for the control and study groups for different SLST variations, presenting separately data for the left and right leg. The figure demonstrates that the average COPx in the control group is negative, i.e. center of plantar pressure is placed closer to the lateral side of the foot. This corresponds to the proper, supinated position of the foot. In contrast, in the study group, the average COPx of all athletes was positive, it means that center of pressure is shifted medially, under the foot arch. Indeed, athletes in the study group were prone to excessive pronation. The application of the t-test to compare data in the control and study group for different SLST modes just confirmed the conclusion made by visual analysis of the Figure 5 data (Table 3). Generally, there was no significant difference between left and right leg COPx data both in control and study groups (Table 4). The only case with $P < 0.05$ (front test in the study group) may be a coincidence.

Table 3: *P*–values for the t-test of differences in COPx between control and study groups.

	Left leg	Right leg
Front test	5.0×10^{-6}	1.3×10^{-4}
Middle test	1.8×10^{-5}	2.8×10^{-5}
Back test	2.2×10^{-6}	2.4×10^{-9}

Additional observation made from Figure 5 data is the difference in variability of COPx data for control and study group: the variability in the study group is noticeably higher. This observation correlates well with the general opinion, that athletes in the control group have proper foot functioning and therefore perform SLST exercise in a more stable and controllable manner, while athletes in the study group have difficulties in sustaining proper balance due to poor foot functioning.

To compare COPx data in SLST variations, single-factor ANOVA was applied. For all combinations of co-factors “control/study group” and “left/right leg”, the *P*–values, associated with ANOVA were in the range 0.13 to 0.82. This demonstrates that there was no significant difference in the COPx values, obtained for variations of SLST. Moreover, in the estimation of the foot performance using COPx values, the same criteria could be used for all variations of SLST exercises.

Table 4: *P*–values for the t-test of differences in COPx between left and right leg in control and study groups.

	Control group	Study group
Front-test	0.07	0.02
Middle-test	0.87	0.46
Back-test	0.20	0.07

3.3 Discussion

The obtained results demonstrated that the COPx parameter, derived from the series of DPSS measurements in SLST exercises is a good indicator of the foot performance. The COPx values are negative for athletes with proper foot performance and positive for athletes, prone to excessive foot pronation during the squat exercise. For the present research group, there were no athletes in the control group with positive average COPx, and there were no athletes with negative average COPx in the study group. Therefore, one could claim that the foot performance test, based on the calculation of average COPx over three sequential squats would have 100% sensitivity and 100% specificity. In practice, however, it would be useful to estimate the prognostic value of the test, based on the single squat. This is important for the development of training aid, that provides real-time feedback to an athlete during each squat. To estimate the characteristics of the single – squat test, the distribution of the COPx values over athletes could be approximated with a normal distribution. Bearing in mind results of COPx comparison between left and right foot (no differences) and between variations of SLST (no differences), average COPx and sample standard deviation, calculated using all pool of data, could be used as estimates of the mean and standard deviation of this normal distribution. The corresponding parameters for control group are $\mu = -0.050$, $\sigma = 0.027$ and for study group are $\mu = 0.068$, $\sigma = 0.051$. The sensitivity of the single squat test, estimated as a probability for an athlete with poor foot performance to get the positive value of COPx in a single squat, is equal to 0.906. The specificity, estimated as a probability for an athlete with good foot performance to get the negative value of COPx in a single squat, is equal to 0.968. These parameters demonstrate the good ability of the COPx measurement-based test to distinguish between good and poor foot performance in a single squat exercise. Hereby, the proposed equipment and technique has the potential to be used for feedback that helps athlete to train correct foot position during the single-leg squat exercise.

4 CONCLUSIONS

1. The DAid Pressure Sock System can be employed for quasi-static measurements to collect objective results of functional tests of lower exterminates biomechanics. Its application also essentially simplifies data collection and registration.
2. The study demonstrated that the application of the DAid Smart Sock system for COP monitoring during Single leg squat functional tests provides the possibility to diagnose athletes with an excessive medial deviation of COP position, i.e. increased potential risk of lower exterminates injury. Thus, the application of the DAid Smart Sock system could become a base of simple and inexpensive express tests for lower exterminates injury risk prevention.
3. The method has the potential to be used for feedback that helps athletes to train correct foot positions during the single-leg squat exercise.

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