Correlation of biomechanical variables of lower extremity movement during functional tests and functional tasks in a population of youth league football players: a cross-sectional correlation study

Anna Davidoviča, Sergejs Davidovics, Guna Semjonova, Alexei Katashev, Alexander Okss, Linda Lancere, Signe Tomsone, Maksims Zolovs

Submitted to: JMIR Formative Research
on: November 20, 2024

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Abstract

Background: Football, the world's most popular sport, carries significant injury risks, especially for youth players. Real-time monitoring of movement patterns is crucial for reducing these risks. Traditional methods often require multiple sensor systems to measure various biomechanical parameters, making the process complex and challenging. The DAid® smart sock system offers a user-friendly alternative, but its effectiveness as a standalone tool for comprehensive lower extremity monitoring requires validation.

Objective: This study aims to investigate the correlations between biomechanical variables of lower extremity movements during the "Single Leg Squat" functional test and its variations in youth league football players, using wireless sensor systems in field tests.

Methods: Thirty-two youth league football players (aged 14-15; 16 males, 16 females) participated in the study, performing the "Single Leg Squat" test and its variations using the NOTCH® inertial sensor system, DAid® smart socks, and PLUX Wireless Biosignals (muscleBAN kit). Correlations between lower limb biomechanical variables were analysed using data from these systems.

Results: The study found a strong positive correlation between hip adduction and changes in the centre of pressure on the medial plantar surface (COP1X: r=0.785, p<.001). Hip internal rotation also showed a significant positive correlation with centre of pressure changes (COPY1: r=0.585, p<.01).

Conclusions: Significant correlations exist between the foot centre of pressure, lower limb movement, and muscle activity during the "Single Leg Squat". These findings demonstrate the relevance of the wireless sensor systems used in this study for assessing correlations in lower limb biomechanics in football players, with the DAid® smart sock system serving as one of the tools to facilitate this assessment.

(JMIR Preprints 20/11/2024:69046)
DOI: https://doi.org/10.2196/preprints.69046

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Abstract

Background: Football, the world's most popular sport, carries significant injury risks, especially for youth players. Real-time monitoring of movement patterns is crucial for reducing these risks. Traditional methods often require multiple sensor systems to measure various biomechanical parameters, making the process complex and challenging. The DAid® smart sock system offers a user-friendly alternative, but its effectiveness as a standalone tool for comprehensive lower extremity monitoring requires validation.
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Conclusions: Significant correlations exist between the foot centre of pressure, lower limb movement, and muscle activity during the "Single Leg Squat". These findings demonstrate the relevance of the wireless sensor systems used in this study for assessing correlations in lower limb biomechanics in football players, with the DAid® smart sock system serving as one of the tools to facilitate this assessment.
Keywords: youth football league players; Single Leg Squat functional test; lower extremity; biomechanics; wireless sensor systems; DAid® smart socks.

Introduction

Football is the most widely played sport globally, with around 400 million participants across 208 countries (Sadigursky et al., 2017). Among the 38 million registered players, over half are under 18 years old (Mandorino et al., 2023). Due to the high-intensity nature of football, it ranks among the top five sports with the highest injury risk (Robles-Palazón et al., 2022; Mandorino et al., 2023). Injuries commonly involve the lower extremities, particularly the thighs, ankles, knees, and hips, with frequent issues including muscle damage, strains, and contusions (Wik et al., 2022). Youth football players are especially vulnerable to injuries, particularly during growth spurts, with one in three players experiencing injuries each season, many of which are non-contact (Jones et al., 2019; Robles-Palazón et al., 2022). Altered movement patterns such as dynamic knee valgus is a significant biomechanical risk factor for injuries, such as ACL tears (Hewett et al., 2005). Understanding and managing this risk factor is crucial for effective injury prevention. Preventive exercise programs like FIFA 11+ have proven effective in reducing injury risk by focusing on muscle strength, balance, and dynamic stability (Barengo et al., 2014). Specifically, the FIFA 11+ program has been shown to lower injury rates by approximately 30% (Sadigursky et al., 2017). A key component of this program, the “Single Leg Squat” exercise, is designed to improve lower limb movement patterns and balance. Football players are typically trained to execute FIFA 11+ exercises correctly over 2-3 sessions (Bizzini et al., 2015). While preventive programs like FIFA 11+ have shown success, there remains a gap in providing personalized, real-time biofeedback on lower limb biomechanics during training, particularly with respect to the functional tasks that expose youth players to injury risks. Assessing an entire team simultaneously during these exercises and tests limits the ability to provide personalised feedback, which is essential for progressing athletes to more advanced exercises within the FIFA 11+ program and more intensive training sessions (Bizzini et al., 2015). Coaches often provide individualised feedback during training sessions, but this feedback can be subjective and varies based on the coach’s experience (Di Paolo et al., 2021). An objective approach to providing feedback can be achieved through motion capture biofeedback systems (Kim et al., 2021; Hribernik et al., 2022; Di Paolo et al., 2023). However, the most reliable methods for motion capture, such as optical systems, Microsoft Kinect cameras (Tipton et al., 2019; Haimovich et al., 2021), 3D kinematic analysis with optical motion capture (OMCs) (Longo et al., 2022), PhaseSpace systems (Schmitz et al., 2014), and force plates (Chen et al., 2021), have limitations that hinder their use in routine football training. For example, optical motion capture systems require a fixed setup with a restricted field of view, making them unsuitable for on-field use (Jackson et al., 2016; Suo et al., 2024). Force plates, which measure ground reaction forces and foot plantar pressure, are typically confined to laboratory settings (Zamankhanpour et al., 2023; Ahn et al., 2024), limiting their practicality for daily football practice. Given the limitations of optical motion capture systems in field settings, wireless smart sensor systems present a promising alternative for providing real-time biofeedback on lower limb motion and biomechanics. Inertial Measurement Unit (IMU) systems can capture data on specific body forces, angular velocity, and magnetic fields (Rodríguez-Martín et al., 2013; Khan et al., 2024). Wireless sensors that monitor muscle activity in real-time, using electromyographic (EMG) signals, can provide insights into muscle performance and condition (Rodriguez et al., 2022; Tanaka et al., 2022). Additionally, smart insole systems like Pedar (Brindle et al., 2022), PODOSmart® (Ziagkas et al., 2021), and smart socks such as DAid® Pressure Sock systems measure biomechanical parameters of the foot, including the centre of pressure (CoP) and pressure distribution across the foot's plantar surface (Brindle et al., 2022; Oks et al., 2020; Januskevica et al., 2020). These sensor systems offer significant benefits in sports medicine due to their cost-effectiveness, ease of use, and lightweight design. Their affordability makes advanced monitoring technology accessible to a broader range of sports teams and medical professionals without compromising on quality. The user-friendly design allows for quick adoption and seamless integration into training and rehabilitation protocols. Additionally, their lightweight nature makes them portable and suitable for use in various environments, including on the field and in training facilities, supporting comprehensive health and performance monitoring for athletes (Li et al., 2016; Liu et al., 2022). However, there are challenges associated with these systems, particularly when multiple wireless devices are used simultaneously. Synchronising data from multiple sensors can be complex and time-consuming, with the risk of signal interference leading to inaccuracies. Managing the activation timing of these devices adds another layer of complexity (Masalskyi et al., 2024). Additionally, using multiple sensors for thorough monitoring can restrict an athlete’s movement and potentially alter lower limb biomechanics. For example, while smart insoles are valuable for gait analysis, they are often stiff, causing discomfort and limiting natural movement (Masalskyi et al., 2024). In contrast, DAid® smart socks, which feature piezoresistive knitted textile pressure sensors embedded in the sole, offer several advantages: they are comfortable, unobtrusive, accurately measure pressure, do not interfere with foot biomechanics, and are easy to use. Their lightweight design ensures minimal impact on natural movement, making them a promising tool for monitoring and enhancing athletic performance (Oks et al., 2020; Januskevica et al., 2020; Semjonova et al., 2022). There is evidence of a relationship between lower limb biomechanical variables during functional tasks. Previous studies have shown that increased knee muscle strength is associated with reduced knee valgus motion (Claiborne et al., 2006). Additionally, higher levels of lower limb muscle pre-activity are linked to a greater peak knee valgus angle (Palmieri-Smith et al., 2008). Regarding foot biomechanics, a positive correlation exists between greater foot pronation and increased pressure on the front to medial plantar surface during functional squat activities (Ahn et al., 2024). Considering the difficulties involved in using multiple wireless sensors at once and the importance of accurately tracking foot biomechanics and limb movement, this study aims to investigate correlations between plantar pressure measurements, electrical activity of muscles and lower extremity movement angles during functional tests like the “Single Leg Squat” in youth league football players, using simultaneously multiple wireless sensor systems in training field tests. The hypothesis states that there will be a significant correlation between the position of the centre of pressure on the plantar surface, lower limb movement, and muscle activity during the "Single Leg Squat" test, using measurements from wireless sensor systems in field tests. This study will demonstrate the relevance of the wireless sensor systems used in this study for assessing correlations in lower limb biomechanics in football players, with the DAid® smart sock system serving as one of the tools to facilitate this assessment.

Methods

Study Design

To obtain the aim of the study, the correlation research design been used, where associations between variables can be positive (variables change in the same direction), negative (variables change in opposite directions), or null (no relationship). According to Fraenkel & Wallen (2009), a minimum sample size of 30 participants is recommended for correlational studies to ensure reliable results.

Participants

The study involved 32 youth football players (both male and female) from the Latvian Youth Football League (U-14 and U-15), recruited between September 2023 and December 2023. Participants met the following inclusion criteria: at least 5 years of experience in football, no history of knee injuries or surgeries, no current knee pain, no lower extremity injuries or surgeries in the past six months, no lower limb deformities, and no vestibular dysfunction. All participants completed the “Single Leg Squat” functional test, wearing tight-fitting sportswear that allowed accurate measurements and sports shoes with appropriate insoles.

Ethical Considerations

The study was conducted in compliance with the Declaration of Helsinki and Latvian laws, adhered to the European Union's General Data Protection Regulation (GDPR) 2016/679. Prior to participation, the study’s procedures were explained to participants and their guardians, and informed consent was obtained. Ethical approval was granted by the Riga Stradins University Research Ethics Committee (Approval No. 2-PĒK-4/294/2023). Participation was voluntary, with the right to withdraw at any time, and participant confidentiality was maintained throughout the study.

Instrumentation and Data Collection

Data collection involved three main instruments: the DAid® Pressure Sock System, the NOTCH® Inertial Sensor System, and the PLUX® Wireless Biosignals system.

DAid® Pressure Sock System

This system, equipped with six sensors in the sole, measured plantar pressure at up to 200 Hz per channel. The sensors were positioned under the heel, arch, and metatarsal heads to monitor gait and assess foot pressure distribution. Data were transmitted via Bluetooth to a remote device for storage. The system was calibrated using participants' weight shifts. Activated before testing, the socks were connected via Bluetooth to "Fastreader" software in the LabView environment. The DAid® records relative pressure values under each sensor to calculate the centre of pressure (COP) coordinates along the mediolateral (COPx) and anteroposterior (COPy) axes, as well as the overall COP position (COPw). For more details about this system, see [Januskevica et al., 2020; Semjonova et al., 2022].

NOTCH® Inertial Sensor System

The NOTCH® IMU system, comprising nine-axis inertial sensors, was employed to measure lower limb angles during movement. Using six sensors placed on the lower body, data were wirelessly transmitted to a mobile device and processed to map a 3D human skeleton. The system recorded at 40 Hz for 10-second intervals during the "Single Leg Squat" test. Sensors were calibrated and placed according to the user manual. Six sensors were attached to the participants: one under the sternum, one around the waist, and one each on the thighs and calves. Sensors were colour-coded and placed according to the app's guidelines. The "Lower body + hip" configuration was used, and participants followed specific positioning instructions to ensure accuracy.

PLUX Wireless Biosignals (muscleBAN kit)

The PLUX Wireless Biosignals system with an EMG add-on was used to collect muscle electrical activity data. The system includes an EMG sensor, triaxial accelerometer, and magnetometer, capturing data at up to 1000 Hz with 16-bit resolution. The device, powered by an internal battery and featuring dual Bluetooth modules, provided real-time muscle activity and movement data for analysis. Four electrodes were placed to measure muscle activity in this study. Electrode's placement was identified according to SENIAM guidelines (Hermens et al., 2000). After placing the electrodes, participants performed a maximum voluntary contraction (MVC) to evaluate the activity of the *quadriceps femoris vastus lateralis* (*QFVL*), *gluteus maximus* (*GMx*), *gluteus medius* (*GM*), and *biceps femoris* (*BF*). This was achieved by having them perform maximal contractions against a stable resistance (Hermens et al., 2000). In this study, electromyographic (EMG) signals were normalised (Halaki et al., 2012) using EMG data recorded during MVC as the reference. The signals were processed by calculating the root mean square (RMS) from the rectified signal with a 0.2-second window. The highest RMS value from all test repetitions was used to normalise the EMG signals, assessing muscle activity relative to its maximum neural activation. During the "Single Leg Squat," the PLUX® measured the electrical activity of the *QFVL*, *GM*, *GMx*, and *BF*.

Study Procedure

Participants' demographic and physical characteristics, such as age, height, weight, shoe size, playing position, and dominant leg, were recorded. Each participant performed the "Single Leg Squat" and its variations three times, with a three-minute rest between repetitions to prevent muscle fatigue. Proper foot contact and balance were emphasized, and any invalid attempts were repeated.

Biomechanical Variables for Determining the Movement of the Lower Extremities

Each youth league football player provided data to assess biomechanical movement variables during the "Single Leg Squat" functional test and its variations.

Angles from the NOTCH® Inertial Sensor System: The dataset for the "Lower body + hip" configuration included dynamic knee valgus determining angles:

- *Angles_Thigh:* Flexion/extension, abduction/adduction, and internal/external rotation angles of the hip joint.
- *Angles_LowerLeg:* Flexion/extension angles of the knee joint.

Centre of Pressure (CoP) from the DAid® Smart Sock System: This dataset included COP1X, COP1Y, COP1W, COP2X, COP2Y, and COP2W values, which represent the centre of pressure on the plantar surface of the foot. Positive COPX values indicate the medial position, negative values indicate the lateral position, positive COPY values indicate the anterior position, and negative values indicate the posterior position. COPW values represent the total centre of pressure. Two mathematical methods (COP1 and COP2) were used to calculate the centre of pressure.

Electromyography Data from the Wireless PLUX® System:

Electrical activity of *QFVL*, *GM*, *GMx*, and *BF* and maximum voluntary contraction (MVC) values.

Data statistical analysis

To synchronize datasets from the NOTCH®, DAid®, and PLUX® for biomechanical movement analysis of the lower extremities, data consolidation was performed using LabView environment. Each participant provided 64 data files, resulting in 2048 files from 32 participants, which were compiled into a unified Database.txt file for correlation analysis. Data analysis was conducted using Microsoft Excel v.16.77.1 and jamovi v.2.3.28.0 open-source graphical user interface for the R programming language, employing descriptive statistics to describe participant characteristics and results. Spearman's correlation analysis, a non-parametric method, was used to determine correlations, considering the Spearman's correlation coefficient (r_s). Positive correlations indicate that as one variable increases, so does the other, while negative correlations mean that as one increases, the other decreases. The strength of these relationships is measured by the correlation coefficient (r_s): up to 0.2 indicates a weak correlation, 0.2 to 0.5 indicates a moderate correlation, and 0.5 to 1 indicates a strong correlation. Statistical significance was set at $p < .05$, with analyses conducted using jamovi v.2.3.28.0.

Results

Participant description

A total of thirty-two participants, including 16 women and 16 men, all of whom were youth league football players, were involved in this study. Participants were youth football league athletes who met specific inclusion and exclusion criteria (see Table 1).

Table 1: Characteristics of the study participants.

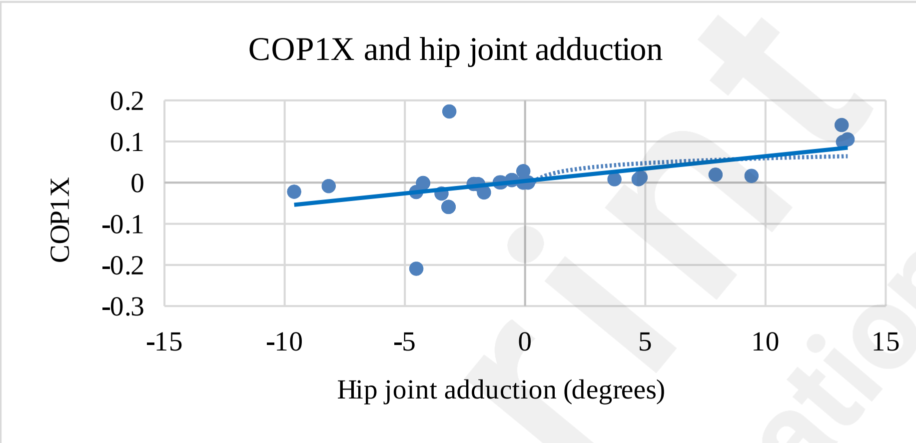
	Mean	Median	Standard deviation (SD)	Minimum	Maximum
BMI	20.8	20.8	2.065	17.3	27.2
Age (years)	14.6	15.0	0.495	14	15
Weight (kg)	59.8	58.0	6.413	50.0	78.6
Height (cm)	169.4	169.0	4.662	159	181
EU size	40.6	40.0	1.961	37.0	44.0

The positions of the youth league football players (study participants) on the field varied—12 players were defenders, 9 were midfielders, and 11 were forwards.

Correlation analysis

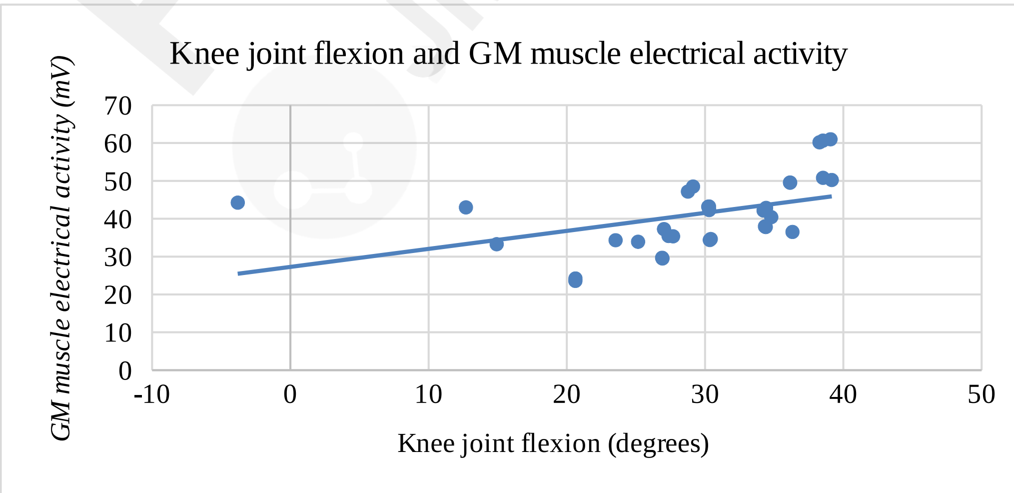
Strong Positive Correlation

A statistically significant relationship was found among the study participants between hip joint adduction movement and changes in the centre of pressure on the plantar surface of the foot COP1X (r=0,785; $p < .001$) representing the position of the pressure centre in the medial part of the plantar surface of the foot (see Figure 3.3).

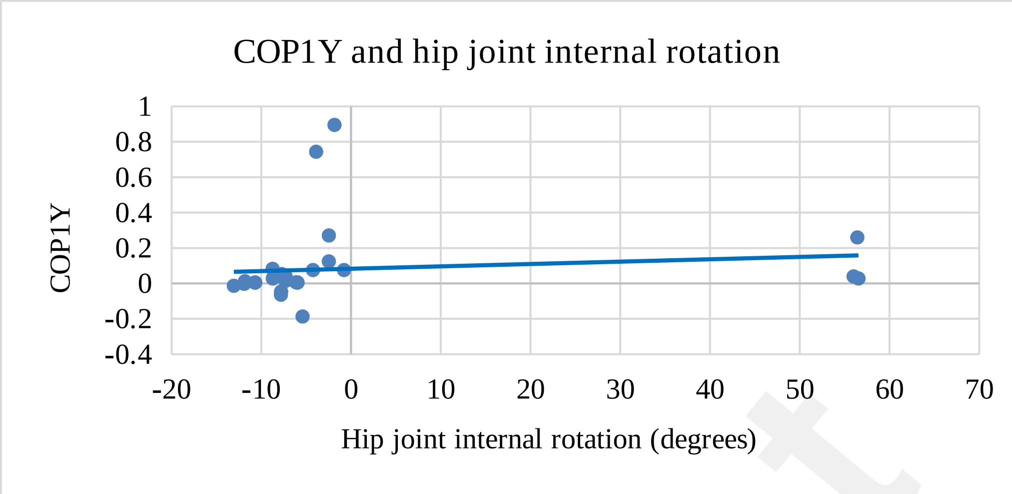


3.3. Figure. Strong positive correlation between hip adduction movement and changes in the centre of pressure on the plantar surface of the foot COP1X.

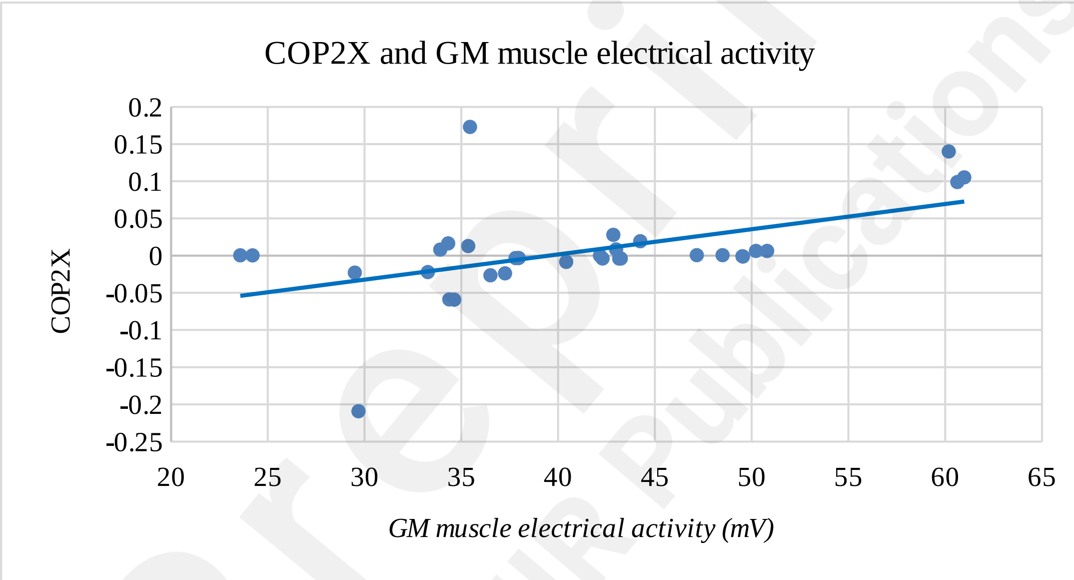
A statistically significant relationship was also found between knee joint flexion and the electrical activity of *GM* muscle (r=0,66; $p < .001$) (see Figure 3.4) and between hip joint internal rotation with changes in the centre of pressure on the plantar surface of the foot COPY1, representing the position of the pressure centre in the anterior part of the plantar surface of the foot (r=0,585; $p < .01$) (see Figure 3.5), and between changes in the centre of pressure on the plantar surface of the foot COP2X, representing the position of the pressure centre in the medial part of the plantar surface of the foot, and the electrical activity of *GM* muscle (r=0,568; $p < .001$) (see Figure 3.6), and between the electrical activities of the *GM* and *QFVL* muscles (r=0,696; $p < .001$) (see Figure 3.7).



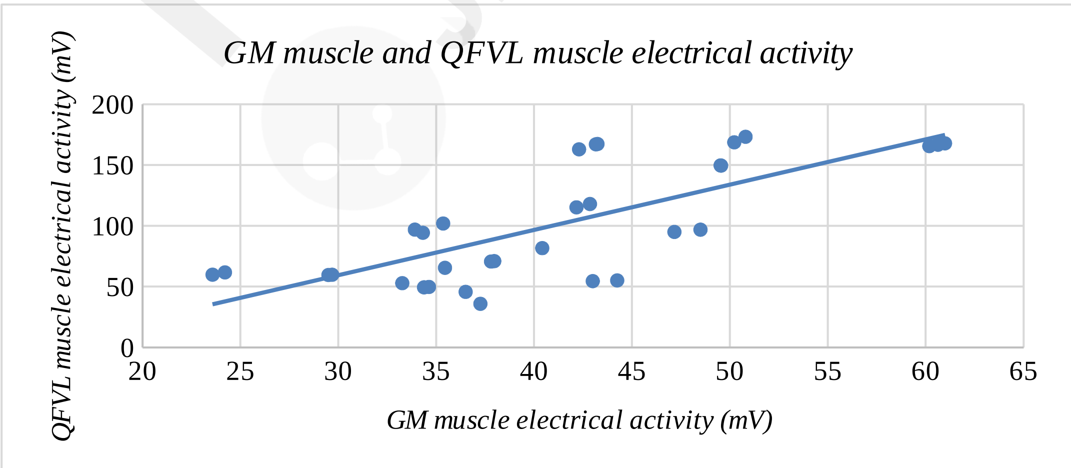
3.4. Figure. Strong positive correlation between knee flexion and the electrical activity of the GM muscle.



3.5. Figure. Strong positive correlation between hip internal rotation movement and changes in the centre of pressure on the plantar surface of the foot COP1Y.



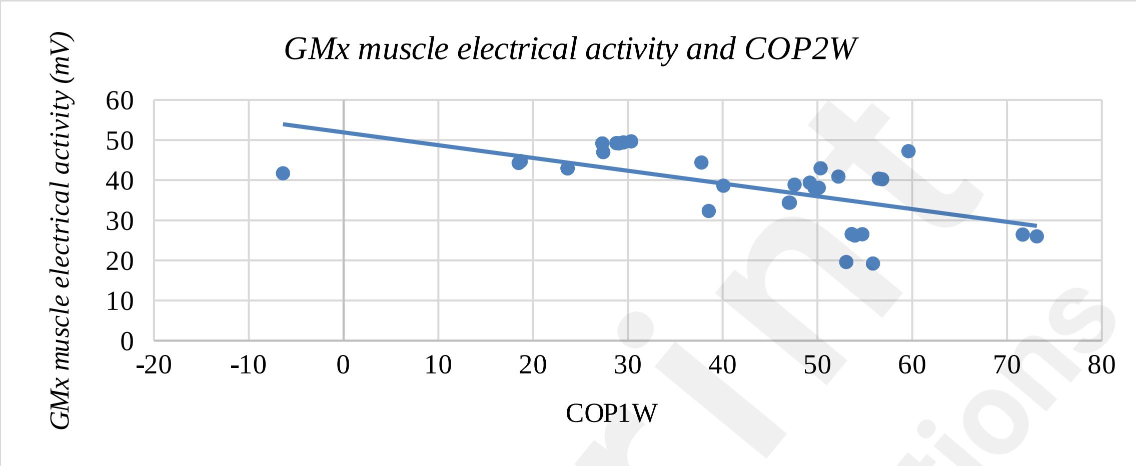
3.6. Figure. Strong positive correlation between changes in the centre of pressure on the plantar surface of the foot COP2X and the electrical activity of the GM muscle.



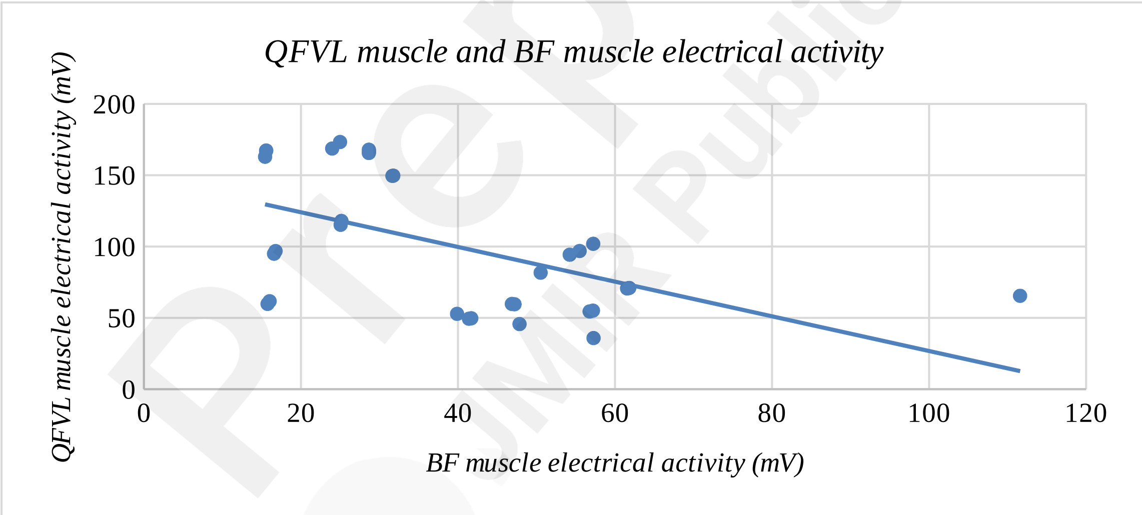
3.7. Figure. Strong positive correlation between the electrical activities of the GM and QFVL muscles.

Strong Negative Correlation

A statistically significant relationship was found among the study participants between changes in the centre of pressure on the plantar surface of the foot COP2W, representing the overall position of the pressure centre on the plantar surface of the foot, and the electrical activity of *GMx* muscle (r=-0,592; p < .001) (see Figure 3.8) and between the electrical activities of *BF* and *QFVL* muscles (r=-0,539; p < .01) (see Figure 3.9).



3.8. Figure. Strong negative correlation between changes in the centre of pressure on the plantar surface of the foot COP2W and the electrical activity of GMx muscle.



3.9. Figure. Strong negative correlation between the electrical activities of BF and QFVL muscles.

Moderate Positive and Negative Correlation

A statistically significant moderate positive and moderate negative correlations were found among the study participants (see Table 2).

Table 2: Moderate positive and moderate negative correlations

Correlation type	**1st parameter**	**2nd parameter**	**Coefficient**	**Significancy (p)**
Moderate	Hip joint adduction	*QFVL* muscle electrical	r= 0,356	p < .05

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		activity		
positive	Hip joint internal rotation	*BF* muscle electrical activity	r= 0,36	p < .05
	COP1Y	*GMx* muscle electrical activity	r= 0,367	p < .05
	COP1X	COP1Y	r= 0,398	p < .05
	COP2X	*QFVL* muscle electrical activity	r= 0,415	p < .05
	Hip joint flexion	COPY2	r=0,426	p < .05
	COP2Y	*BF* muscle electrical activity	r=0,426	p < .05
	COP1X	*GM* muscle electrical activity	r= 0,445	p < .05
	COP1X	*QFVL* muscle electrical activity	r= 0,47	p < .01
	Hip joint internal rotation	*GMx* muscle electrical activity	r= 0,477	p < .01
Moderate negative	Hip joint internal rotation	COP2W	r=-0,368	p < .05
	COP1W	Hip joint internal rotation	r= -0,39	p < .05
	COP2Y	*GMx* muscle electrical	r=-0,394	p < .05

		activity		
	COP2X	COP2W	r=-0,415	p < .05
	COP1Y	COP2W	r=-0,437	p < .05

Correlation Matrix Analysis by Gender

The study also examined correlations based on gender distribution (see Table 3 and Table 4).

Table 3: Male gender correlation matrix

Correlation type	**1st parameter**	**2nd parameter**	**Coefficient**	**Significancy (p)**
Strong positive	Hip joint adduction	Hip joint internal rotation	r=0,806	p < .001
	Hip joint adduction	COP1X	r= 0,785	p < .001
	Knee joint flexion	*GM* muscle electrical activity	r= 0,809	p < .001
	Knee joint flexion	*GMx* muscle electrical activity	r= 0,841	p < .001
	Knee joint flexion	*QFVL* muscle electrical activity	r= 0,776	p < .001
	COP1X	COP2X	r= 0,832	p < .001
	COP2X	*GM* muscle electrical activity	r= 0,791	p < .001

Strong negative	COP1Y	COP1W	r= -0,832	p < .001

Table 4: Female gender correlation matrix

Correlation type	**1st parameter**	**2nd parameter**	**Coefficient**	**Significancy (p)**
Strong positive	Knee joint flexion	COP2W	r=0,818	p < .001

Discussion

Principal Results

The key findings of this study reveal strong positive and negative correlations between lower limb biomechanics during the "Single Leg Squat" in youth football players, using wireless sensor systems. A study by Ahn et al. (2024) demonstrated that foot pronation alters biomechanics, such as internal hip rotation and hip adduction. Similarly, Kim et al. (2021) found that foot pronation is a risk factor for dynamic knee valgus, which involves hip adduction and internal rotation, and contributes to medial knee displacement. This study aligns with Kim et al. (2021), showing a correlation between foot pronation and increased dynamic knee valgus, hip adduction, and internal rotation. Data from the DAid® smart sock system indicated significant correlations between the center of pressure (COP) on the medial plantar surface and increased hip adduction ($r = 0.785$; $p < 0.001$). This finding is consistent with Sanchis et al. (2022) and Tran et al. (2016), who also reported links between medial plantar pressure and hip adduction. Furthermore, the study revealed a moderate correlation between hip internal rotation and muscle activity, particularly the biceps femoris ($r = 0.36$; $p < 0.05$) and gluteus maximus ($r = 0.477$; $p < 0.01$), supporting findings by Wilczynski et al. (2020). Increased dynamic knee valgus was associated with greater muscle activity, echoing earlier studies on the influence of gluteus maximus on knee biomechanics (Rinaldi et al., 2022).

Limitations

This study has a potential for future research. The study focused only on youth aged 14-15, a high-risk group for injuries, but it would be beneficial to also examine a broader age range and athletes from other sports, such as basketball players. Future research could include individuals with lower limb pathologies, such as patellofemoral pain syndrome or post-anterior cruciate ligament reconstruction, to provide data on biomechanical parameters and their relationships during functional tasks, aiming to identify risk factors and improve rehabilitation strategies to prevent progressive lower limb injuries. The chosen research design and methodology allowed the study's objectives and goals to be met. The data analysis methods used identified strong positive, moderate positive, strong negative, and moderate negative correlations.

Comparison with Prior Work

Other technologies could have been used in place of the PLUX Wireless Biosignals (muscleBAN kit), such as the Ultium Wireless Surface EMG for muscle electrical activity assessment. The Ultium Wireless Surface EMG is a research-grade wireless EMG system with high sampling rates, low noise levels, and versatile SmartLead options (Wu et al., 2021). For motion capture and analysis, the OptiTrack optical motion capture system could have been used. OptiTrack offers high measurement accuracy and easy-to-use software for 3D motion analysis, though it has limitations related to the quality of captured material and camera perspective (Leardini et al., 2007; Aurand et al., 2017).

Conclusions

Significant correlations were identified between biomechanical variables of lower extremity movements during the 'Single Leg Squat' functional test and selected physical performance measures in youth league football players. The findings revealed strong correlations between foot centre of pressure, lower limb movement, and muscle activity using wireless sensor systems in field tests, providing valuable insights into the biomechanical patterns of these athletes. These findings highlight the relevance of the wireless sensor systems used in this study for assessing correlations in lower limb biomechanics in football players, with the DAid® smart sock system serving as one of the tools to facilitate this assessment.

Acknowledgements

This research is funded by the Latvian Council of Science, project Smart textile solutions as biofeedback method for injury prevention for Latvian football youth league players, project No. lzp-2023/1- 0027.

Conflicts of Interest

The authors report there are no competing interests to declare.

Data Availability Statement

Raw data supporting the conclusions of this article can be obtained from the corresponding author upon reasonable request. Additionally, the codes used for the statistical analysis in this study are available from the corresponding author upon request. Data management plan identification number: DOI 10.5281/zenodo.11082395

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