Biomechanics of the Lower Extremity in Youth Football League: FIFA 11+ One Leg Squat Analysis

Anna Davidovica[1][a], Sergejs Davidovics[1], Guna Semjonova[1][b], Alexei Katashev[2][c], Alexander Oks[3][d], Linda Lancere[4][e], Signe Tomsone[1][f] and Maksims Zolovs[5][g]

[1]*Department of Rehabilitation, Riga Stradins University, 16 Dzirciema Street, LV-1007 Riga, Latvia*
[2]*Institute of Mechanical and Biomedical Engineering, Riga Technical University, LV-1048 Riga, Latvia*
[3]*Institute of Architecture and Design, Riga Technical University, LV-1048 Riga, Latvia*
[4]*Department of Sociotechnical Systems Modelling, Vidzeme University of Applied Sciences, LV-4201, Valmiera, Latvia*
[5]*Statistical Unit, Faculty of Medicine, Riga Stradins University, 16 Dzirciema Street, LV-1007 Riga, Latvia*

Keywords: Lower Extremity, Biomechanical Variables, Youth Football League Players, One Leg Squat, FIFA 11+, Wireless Sensor Systems, Smart Socks.

Abstract: Background: Football carries substantial injury risks, especially for youth players. Providing biofeedback of lower limb motion during functional tasks is a crucial part of injury prevention programs such as FIFA 11+. While the FIFA 11+ warm-up program providing individualised feedback remains challenging, wireless sensor systems such as the DAid® Pressure Sock system, NOTCH® Inertial Sensor System, and PLUX Wireless Biosignals (muscleBAN kit) System offer potential solutions. Aim: This study aims to explore the correlation of lower limb biomechanical variables during the FIFA 11+ Part 2 exercise "One Leg Squat" in youth football players using wireless sensor systems and video recordings. Methods: Using wireless sensor systems and video recordings, we analysed lower limb biomechanics during the "One Leg Squat" exercise in youth football players. Results: Strong positive correlations were identified between hip joint adduction and the changes in the centre of pressure of the plantar surface of the foot (COP1y), as well as between hip joint internal rotation and COP1y. COP2x correlated strongly with gluteus medius activity. Conversely, COP2y showed a negative correlation with gluteus maximus activity. Conclusions: The results support the potential of wireless sensor systems in monitoring the biomechanical changes of the lower extremity movements and lay the groundwork for future biofeedback methods based on the DAid® smart socks system technology for evaluating lower limb motion, especially the changes in the centre of pressure of the plantar surface of the foot, during functional tasks in Football Youth League players.

1 INTRODUCTION

Football, a globally renowned sport boasting approximately four hundred million players across 208 countries, carries a significant injury risk for participants of all ages, both professional and amateur. Injuries not only lead to player withdrawals but also impede team performance across various levels (Sadigursky et al., 2017). Among youth aged 9-21, non-contact injuries account for 53% to 72% of all injuries, with lower extremity injuries prevailing in 72% to 93% of cases (Jones et al., 2019).

Today, the leading preventive exercise program for correctness of the movement in football is the

[a] https://orcid.org/0000-0002-3141-7998
[b] https://orcid.org/0000-0002-6554-0716
[c] https://orcid.org/0000-0001-8894-3748
[d] https://orcid.org/0000-0001-6925-1842
[e] https://orcid.org/0000-0003-0524-5106
[f] https://orcid.org/0000-0002-7836-2672
[g] https://orcid.org/0000-0001-9120-5869

Davidovica, A., Davidovics, S., Semjonova, G., Katashev, A., Oks, A., Lancere, L., Tomsone, S. and Zolovs, M.
Biomechanics of the Lower Extremity in Youth Football League: FIFA 11+ One Leg Squat Analysis.
DOI: 10.5220/0012894900003828

In *Proceedings of the 12th International Conference on Sport Sciences Research and Technology Support (icSPORTS 2024)*, pages 131-139
ISBN: 978-989-758-719-1; ISSN: 2184-3201

FIFA 11+ warm-up program, the application of which reduces the risk of injuries by 30% (Sadigursky et al., 2017), where the FIFA 11+ program 2nd Part's task "One Leg Squat" is targeted entirely at the development of the correct lower limb motion pattern and balance (Bizzini et al., 2015). Simultaneous assessment by coaches of the entire team during movement execution does not provide an individual approach to each athlete, but an individual approach is essential for the athlete to progress to the more advanced set of exercises within the FIFA 11+ program and more intensive training (Bizzini et al., 2015). The individualized objective approach could be realized using objective motion capture biofeedback systems (Kim et al., 2021; Hribernik et al., 2022; Di Paolo et al., 2023).

Most golden standard objective biofeedback methods for motion capturing, such as optical systems, Microsoft Kinect camera systems (Bawa et al., 2021), 3D kinematic analysis with optical motion capture (OMCs) (Longo et al., 2022) and force plates (Chen et al., 2021) have drawbacks that make them challenging to implement in football players' daily motion evaluation routines. Optical motion capture systems, for example, are unsuitable for field applications, requiring a stationary setup with a limited spatial field of view (Suo et al., 2024). Force plates used for measuring ground reaction forces and foot plantar pressure are applicable only in laboratory environments (Ahn et al., 2024), rendering them impractical for daily football practice.

An alternative approach for providing biofeedback of lower limb motion and biomechanical parameters to athletes could be based on the use of wireless smart sensor systems. For example, Inertial Measurement Unit (IMU) systems measure a body's specific force, angular rate, magnetic field, and acceleration of a body in real-time (Khan et al., 2024). Muscle activity capturing wireless sensors providing real-time data on muscle performance and condition based on electromyographic (EMG) signals (Tanaka et al., 2022). For lower extremity distal segment observation the smart insole systems (Khandakar et al., 2022), such as Pedar (Brindle et al., 2022), PODOSmart® (Ziagkas et al., 2021) and smart socks such as the DAid® Pressure Sock systems could be used, enabling the measurement of biomechanical parameters of the foot, including the centre of pressure (CoP) and pressure on various parts of the foot plantar surface (Brindle et al., 2022; Oks et al., 2020; Januskevica et al., 2020).

However, sensor systems present challenges, particularly when multiple wireless devices are used simultaneously. Synchronising data flow can be complex and time-consuming, with potential signal overlap leading to inaccuracies. Managing device activation timing adds further complexity (Masalskyi et al., 2024). The numerous sensors required for comprehensive monitoring can restrict an athlete's movement and impact biomechanics of lower extremity. For instance, smart insoles, though useful for gait analysis, are often rigid, causing discomfort and limiting natural movement (Masalskyi et al., 2024). So far DAid® smart socks, which incorporate piezoresistive knitted textile pressure sensors embedded in the sole, have demonstrated several advantages to use them: enhanced comfort, unobtrusiveness, accurate pressure measurement, have no impact on foot biomechanics, and ease of use, making them a promising tool for monitoring and improving athletic performance (Oks et al., 2020; Januskevica et al., 2020; Semjonova et al., 2022).

There is a correlation between lower limb biomechanical variables during functional tasks (Claiborne et al., 2006). For instance, increased hip abductor (*musculus gluteus medius*) strength is associated with reduced knee valgus angle during functional exercises (Neamatallah et al., 2020). For foot biomechanical variables there is a positive correlation between greater foot pronation and increased front to medial plantar pressure during functional squat activities (Ahn et al., 2024).

Therefore, the aim of this study is to investigate the correlation of biomechanical variables of the lower extremity measured by separate wireless sensor systems during the exercise "One Leg Squat" in a population of youth league football players. We hypothesised that by using three separate sensor systems (DAid®, NOTCH® and PLUX®) during the FIFA11+ Part 2 exercise "One Leg Squat", strong correlations will be observed among main biomechanical variables: joint angles, muscular activation and foot plantar pressure, supporting the possibility of using smart socks as the sole biofeedback system for evaluating lower limb motion, during functional tasks.

2 MATERIALS AND METHODS

2.1 Study Design and Participant Recruitment

A cross-sectional correlation study involved 32 male and female soccer players from the Latvian Youth Soccer League (U-14 and U-15).

Participants met the following inclusion criteria: at least 5 years of experience in the sport, no pain or previous knee injuries or surgeries, no current knee pain, no lower extremity injuries or surgeries in the past six months, no lower extremity deformities, and no vestibular dysfunction.

They performed the FIFA11+ Part 2 "One Leg Squat" exercise using the DAid®, NOTCH® and PLUX®, along with video analysis.

Informed consent was obtained, and the study was approved by the Research Ethics Committee of Riga Stradiņš University (approval received on 21 March 2023, No. 2-PĒK-4/294/2023).

Participants wore tight T-shirts or undershirts and shorts that did not cover the knees and performed the measurements in sports shoes with proper insoles.

Video recordings were made simultaneously with the sensor data while participants performed the FIFA11+ "One Leg Squat". Three independent sports physical therapists evaluated the correctness of the movements, comparing their assessments with the sensor data and verifying with video records.

2.2 Daid® Pressure Sock System

The DAid® Pressure Sock System consists of a pair of socks, each with six pressure sensors in the sole: two under the heel, two under the arch, and two under the metatarsals, labelled as: (1) front medial, (2) front lateral, (3) middle medial, (4) middle lateral, (5) heel medial, and (6) heel lateral (Figure 1). This setup monitors gait and detects supination/pronation.

Conductive pathways link the sensors to a data acquisition unit that transmits data via Bluetooth to a smartphone at up to 200 Hz per channel. For more details see (Oks et al., 2019; Januskevica et al., 2020; Semjonova et al., 2022).

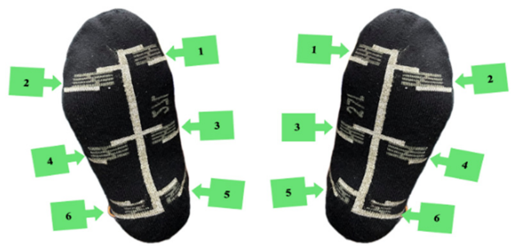

Figure 1: DAid® smart socks sensor placement.

2.2.1 Calculating Centre of Pressure Using Daid® Pressure Sock System Data

The data recorded from DAid® Pressure Sock System provide monitoring of relative pressure values under each sensor and calculation of coordinates of centre of pressure (COP) for each foot along mediolateral (COPx) and anteroposterior (COPy) axes, as well as summarised COP position (COPw).

Positive COPx values indicate a medial shift, while negative values denote a lateral shift. Positive COPy values signify an anterior shift, while negative values indicate a posterior shift. COPw values provide a general indication of COP location. The COPx component on the X-axis (COPx) is crucial in assessing the overpressure on the medial plantar surface of the foot.

In this study, two methodologies COP1 and COP2 were used to calculate COP, where COP1x, COP1y, COP1w and COP2x, COP2y, COP2w were obtained, using DAid® Pressure Sock System data.

The socks generate a dataset consisting of the resistances of sensors R1 to R6, measured in kiloohms (kOhms) and recorded as ADC0 to ADC5 in the consolidated files. As applied pressure increases, the sensor resistances decrease.

Therefore, two values were introduced for the calculation of COP:

$$Ui = 100 - Ri \quad (1)$$

$$Vi = 100 / Ri \quad (2)$$

Values U and V increase when plantar pressure increases.

The position of sensors over the foot were defined by six vectors (see Figure 2):

$x_1 = 0.26,\ y_1 = 0.97$
$x_2 = -0.26,\ y_2 = 0.97$
$x_3 = 0.26,\ y_3 = 0$
$x_4 = -0.26,\ y_4 = 0$
$x_5 = 0.26,\ y_5 = -0.97$
$x_6 = -0.26,\ y_6 = -0.97$

where coordinates are defined in arbitrary units, accounting the length of the foot is equal to 2 arbitrary units. Therefore, the coordinates of COP are also measured in arbitrary units.

The COP1 (COP_X1, COP_Y1, COP_W1) are calculated using values $U_i = 100 - R_i$ as follows:

$$COP_X = \frac{\sum U_i x_i}{\sum U_i}$$

$$COP_Y = \frac{\sum U_i y_i}{\sum U_i}$$

$$COP_W = \frac{\sum U_i}{6}$$

The COP2 (COP_X2, COP_Y2, COP_W2) are calculated using values $V_i = 100 / R_i$ as follows:

$$COP_X = \frac{\sum V_i x_i}{\sum V_i}$$

$$COP_Y = \frac{\sum V_i y_i}{\sum V_i}$$

$$COP_W = \frac{\sum V_i}{6}$$

These two types of processing were used to determine which method better distinguishes differences in COP positions.

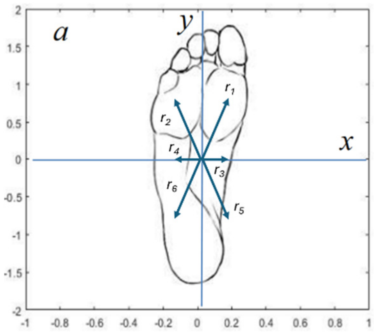

Figure 2: Nominal position of sensors over the foot plantar surface.

2.3 Notch® Inertial Sensor System

The NOTCH ® IMUs system (Wearnotch by Notch Interfaces, Inc., NJ, USA) used in this study features wireless IMUs with nine-axis inertial sensors (three-axis gyroscope, accelerometer, and magnetometer). The Notch Pioneer app, installed on an iPhone 12 (iOS Version 1.7.1.1), processes data and sends it to LabVIEW software, which computes average angles and angular acceleration, then transfers the results to an Excel sheet. Data recording occurs at 40 Hz. During "One Leg Squat" recordings, the "Lower body + hip" configuration was selected in the app.

2.4 PLUX Wireless Biosignals (MuscleBAN Kit) System

The wireless electromyography PLUX Wireless Biosignals (muscleBAN kit) system was prepared to monitor four muscles. The Plux application on a computer captured muscle activity readings via Bluetooth. Motor points were located using SENIAM guidelines (Hermens et al., 2000). After electrode placement, participants performed a maximum voluntary contraction (MVC) to assess activities of the *musculus quadriceps femoris vastus lateralis, musculus gluteus maximus, musculus gluteus medius* and *musculus biceps femoris.* In this study, the normalisation of electromyographic (EMG) signals (Halaki et al., 2012) from a specified muscle utilized the EMG recorded from the same muscle during a maximal voluntary isometric contraction (MVC) as the reference value. Subsequently, the EMG signals underwent processing by calculating the root mean square from the rectified signal, the window for root mean square calculation was 0.2 sec.

2.5 Task Description for Participants

Each participant was informed about the procedures of the study (Bizzini et al., 2015). Before executing the “One Leg Squat” exercise. Participants were instructed to execute the "One Leg Squat", by wearing a wireless DAid®, NOTCH®, PLUX® and sports shoes (see Figure 3). Each participant executed “One Leg Squat” 10 times 2 repetitions on both sides.

Figure 3: Study participants interact with the DAid®, PLUX® and the NOTCH®, performing “One Leg Squat”.

2.6 Systems Synchronisation

The following steps were taken to synchronise the three systems before starting “One Leg Squat" task. Each "One Leg Squat" was recorded by video camera.

The used data acquisition systems provided data record at the sample rate 40 Hz (NOTCH® system) and 140 Hz (socks data acquisition system). During the measurement, all systems reported data together with internal device time. The data from each system were recorded in separated files. The all signal processing was performed after recording, but not in real time. The systems were not synchronised; therefore, synchronisation was made at postprocessing. The participants were asked to make specific movement – bending the supporting leg knee, the accelerometric and sock signal were aligned, using the pattern of this movement as a marker. The inaccuracy of time alignment does not exceed 25 milliseconds. The potential delay for output signals was compensated by alignment procedure.

2.7 Expert Protocol

Each FIFA11+ "One Leg Squat" was analysed by three certified physiotherapists with over five years of experience working with athletes. They assessed the performance by watching video recordings at 0.25x slow motion. The experts determined whether an adduction and internal rotation of the thigh, knee abduction, lower leg external rotation, ankle eversion, and excessive foot pronation was noted in 6 out of 10 squats, the full set was classified as incorrect. In total of 32 videos from 32 participants were analysed.

2.8 Statistical Methods of Research

Leveraging LabView software, data synchronisation was achieved from three systems. Each of the 32 participants yielded 64 data files, encompassing separate sets from all three systems for each lower extremity during the FIFA11+ "One Leg Squat" exercise. A total of 2,048 data files were collected and consolidated into a single Database.txt file for correlation analysis. Quantitative analysis was conducted using Microsoft Excel v.16.77.1 and "jamovi" v.2.3.28.0, an open-source graphical interface for R programming. Descriptive statistics such as mean and standard deviation were employed to characterize participant data and results. Spearman's correlation analysis, a non-parametric method, was applied to explore relationships between biomechanical variables derived from the three systems. Statistical significance was considered at $p < .05$.

3 RESULTS AND DISCUSSION

3.1 Participant Description

Thirty-two participants, comprising 16 women and 16 men, who were athletes and youth league football players, took part in this correlational investigation. Participants meeting specific inclusion and exclusion criteria were selected for the study (see Table 1).

3.2 Prevalence of Dynamic Knee Valgus in "One Leg Squat"

From the analysis of all the observed videos, in which participants each performed the exercise "One Leg Squat" 10 times for 2 repetitions with each leg, all experts noted that a dynamic knee valgus position characterized by adduction and internal rotation of the thigh, knee abduction, lower leg external rotation, ankle eversion, and excessive foot pronation was observed in 68.75% of cases. In 31.25% of cases, a dynamic knee valgus position was not observed (see Figure 4).

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

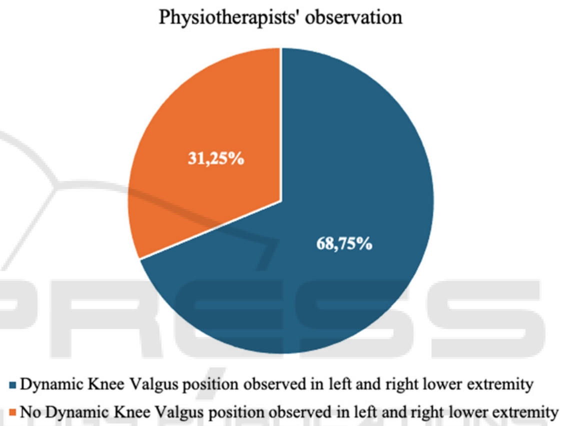

Figure 4: Physiotherapists' assessment of the watched videos for the left and right lower extremity.

3.3 Correlation Analysis of Lower Limb Biomechanics

The study analysed various correlations involving the right and left lower limbs, with significant findings indicated by correlation coefficients (r) and corresponding p-values. Correlations were categorized as weak ($r \leq 0.2$), moderate ($0.2 < r \leq 0.5$), or strong ($0.5 < r \leq 1$) (refer to Appendix (Table 2 and Table 3).

3.3.1 Left Lower Extremity

Strong Positive Correlation

A statistically significant strong positive correlation was found between the changes in the centre of pressure of the plantar surface of the foot COP2x, which represents the position of the centre of pressure in the medial part of the plantar surface of the foot, and the electrical activity of the *musculus gluteus medius* (r=0.543; p < .001).

Moderate Positive Correlation

A statistically significant moderate positive correlation was found between hip adduction and hip joint internal rotation (r=0.408; p < .001); between changes in the centre of pressure of the plantar surface of the foot COP1x, which represents the position of the centre of pressure in the medial part of the plantar surface of the foot, and the electrical activity of the *musculus quadriceps femoris vastus lateralis* (r=0.401; p < .001) (see Figure 5).

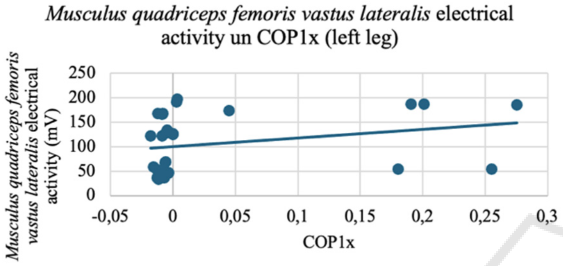

Figure 5: Moderate positive correlation between COP1x and the electrical activity of the *musculus quadriceps femoris vastus lateralis* (left leg).

3.3.2 Right Lower Extremity

Strong Positive Correlation

A strong positive correlation was found between hip internal rotation and hip adduction (r=0.591; p < .001); between internal rotation of the hip joint and changes in the centre of pressure of the plantar surface of the foot, COP1y (r=0.599; p < .001) (see Figure 6).

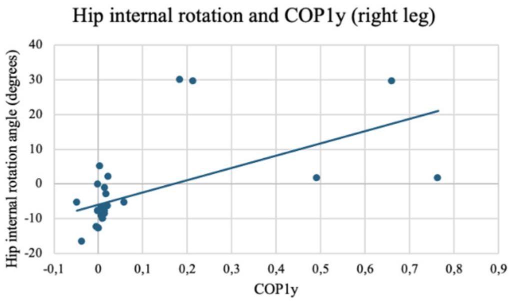

Figure 6: Strong positive correlation between internal rotation of the hip joint and COP1y (right leg).

Strong Negative Correlation

A strong negative correlation was found between changes in the centre of pressure of the plantar surface of the foot COP2y, and the electrical activity of the *musculus gluteus maximus* (r=-0.603; p < .001) (see Figure 7).

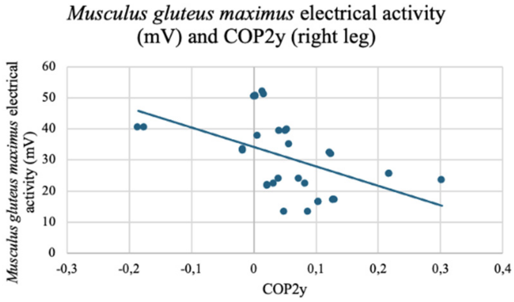

Figure 7: Strong negative correlation between COP2y and the electrical activity of the *musculus gluteus maximus* (right leg).

3.4 Discussion

The study's results demonstrate that the COPx, COPy, and COPw parameters derived from the DAid® during "One Leg Squat" exercise are reliable indicators of the changes in the centre of pressure of the plantar surface of the foot. Additionally, joint angles measured by the NOTCH® and muscle activity recorded by the PLUX® serve as reliable indicators of lower limb performance during the task. These findings underscore the potential of using one smart sensor systems to provide an individualised approach during functional tasks.

The statistically significant strong correlations between hip joint adduction, hip joint internal rotation angles, gluteus muscular activation, and COPx, COPy, and COPw values highlight the interconnectedness of lower limb dynamics measured by sensor systems. The consistency of these findings with those of Kim et al. (2021), which demonstrated a relationship between increased dynamic valgus position of the knee joint and increased foot pronation, hip joint adduction, and internal rotation, further validates the use of these parameters in assessing lower limb performance. The use of advanced measurement techniques such as two-dimensional video analysis in previous studies complements our use of smart sensor systems, offering robust evidence for these biomechanical relationships.

However, the practical application of multiple smart sensor systems in real-time biofeedback monitoring presents challenges. The setup of these systems is often time-consuming and restricts the freedom of movement necessary for executing activities (Masalskyi et al., 2024). To address these limitations, the development of smart clothing with integrated motion-monitoring functionality combined with mixed reality (MR) approaches offers a promising solution. By using MR head-mounted displays (HMDs), athletes can receive visual and auditory feedback in real-time, enhancing the utility of biofeedback during training sessions.

Moreover, the integration of smart sensor system information into Virtual Reality (VR) environments can create immersive and interactive 3D simulations. These VR systems can simulate real-world scenarios, providing athletes with biofeedback in a controlled environment conducive to movement and skill development (Hamad et al., 2022). By offering a dynamic and engaging training platform, VR systems can potentially revolutionise how athletes train and develop their skills.

Despite these promising findings, this study has several limitations. First, the sample size was relatively small, which may affect the generalizability of the results.

Additionally, the study was conducted in a controlled environment, which may not fully replicate the complexities and variabilities of real-world athletic settings. Future research should aim to address these limitations by including larger, more diverse populations and by conducting studies in more varied and realistic environments. Investigating the long-term effects of using MR and VR systems for biofeedback on athletic performance and injury prevention would also be beneficial.

4 CONCLUSIONS

Study findings support using the DAid® smart sock system as the sole biofeedback system for evaluating lower limb motion during functional tasks and highlight the potential of wireless sensors in monitoring the biomechanical changes of the lower extremity movements for Football Youth League players.

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.

REFERENCES

Ahn I, Gwak G, Hwang U, Yoo H, Kwon O. (2024). Comparison of Foot Pressure Distribution During Single-leg Squat in Individuals with and Without Pronated Foot. Physical Therapy Korea;31:40-47. https://doi.org/10.12674/ptk.2024.31.1.40

Bawa, A., Banitsas, K., & Abbod, M. (2021). A Review on the Use of Microsoft Kinect for Gait Abnormality and Postural Disorder Assessment. *Journal of healthcare engineering*, *2021*, 4360122. https://doi.org/10.1155/2021/4360122

Bizzini, M., & Dvorak, J. (2015). FIFA 11+: an effective programme to prevent football injuries in various player groups worldwide-a narrative review. *British journal of sports medicine*, *49*(9), 577–579. https://doi.org/10.1136/bjsports-2015-094765

Brindle, R. A., Bleakley, C. M., Taylor, J. B., Queen, R. M., & Ford, K. R. (2022). Validity of estimating center of pressure during walking and running with plantar load from a three-sensor wireless insole. *Wearable technologies*, *3*, e8. https://doi.org/10.1017/wtc.2022.5

Chen, B., Liu, P., Xiao, F., Liu, Z., & Wang, Y. (2021). Review of the Upright Balance Assessment Based on the Force Plate. *International journal of environmental research and public health*, *18*(5), 2696. https://doi.org/10.3390/ijerph18052696

Claiborne, T.L.; Armstrong, C.W.; Gandhi, V.; Pincivero, D.M. (2006). Relationship between Hip and Knee Strength and Knee Valgus during a Single Leg Squat. J. Appl. Biomech, 22, 41–50

Di Paolo, S., Nijmeijer, E. M., Bragonzoni, L., Gokeler, A., & Benjaminse, A. (2023). Definition of High-Risk Motion Patterns for Female ACL Injury Based on Football-Specific Field Data: A Wearable Sensors Plus Data Mining Approach. *Sensors (Basel, Switzerland)*, *23*(4), 2176. https://doi.org/10.3390/s23042176

Halaki, M., & Gi, K. (2012). Normalization of EMG Signals: To Normalize or Not to Normalize and What to Normalize to? InTech. doi: 10.5772/49957

Hamad, A., & Jia, B. (2022). How Virtual Reality Technology Has Changed Our Lives: An Overview of the Current and Potential Applications and Limitations. *International journal of environmental research and public health*, *19*(18), 11278. https://doi.org/10.3390/ijerph191811278

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of electromyography and kinesiology: official journal of the International Society of Electrophysiological Kinesiology*, *10*(5), 361–374. https://doi.org/10.1016/s1050-6411(00)00027-4

Hribernik, Matevž, Anton Umek, Sašo Tomažič, and Anton Kos. (2022). "Review of Real-Time Biomechanical Feedback Systems in Sport and Rehabilitation" *Sensors* 22, no. 8: 3006. https://doi.org/10.3390/s22083006

Januskevica, A., Semjonova, G., Oks, A., Katashev, A., & Eizentals, P. (2020). Evaluation of the Foot Performance in "Single Leg Squat" Test of Female Athletes using Smart Socks. In icSPORTS (pp. 161-168).

Jones, S., Almousa, S., Gibb, A., Allamby, N., Mullen, R., Andersen, T. E., & Williams, M. (2019). Injury incidence, prevalence and severity in high-level male youth football: a systematic review. Sports medicine, 49(12), 1879-1899.

Khan, D., Al Mudawi, N., Abdelhaq, M., Alazeb, A., Alotaibi, S. S., Algarni, A., & Jalal, A. (2024). A Wearable Inertial Sensor Approach for Locomotion and Localization Recognition on Physical Activity. *Sensors (Basel, Switzerland)*, *24*(3), 735. https://doi.org/10.3390/s24030735

Khandakar, A., Mahmud, S., Chowdhury, M. E. H., Reaz, M. B. I., Kiranyaz, S., Mahbub, Z. B., Ali, S. H. M., Bakar, A. A. A., Ayari, M. A., Alhatou, M., Abdul-Moniem, M., & Faisal, M. A. A. (2022). Design and Implementation of a Smart Insole System to Measure Plantar Pressure and Temperature. *Sensors (Basel, Switzerland)*, *22*(19), 7599. https://doi.org/10.3390/s22197599

Kim, H. S., Yoo, H. I., Hwang, U. J., & Kwon, O. Y. (2021). Comparison of dynamic knee valgus during single-leg step down between people with and without pronated foot using two-dimensional video analysis. *Physical Therapy Korea*, *28*(4), 266-272.

Longo, U. G., De Salvatore, S., Carnevale, A., Tecce, S. M., Bandini, B., Lalli, A., Schena, E., & Denaro, V. (2022). Optical Motion Capture Systems for 3D Kinematic Analysis in Patients with Shoulder Disorders. *International journal of environmental research and public health*, *19*(19), 12033. https://doi.org/10.3390/ijerph191912033

Masalskyi, Viktor, Dominykas Čičiurėnas, Andrius Dzedzickis, Urtė Prentice, Gediminas Braziulis, and Vytautas Bučinskas. (2024). "Synchronization of Separate Sensors' Data Transferred through a Local Wi-Fi Network: A Use Case of Human-Gait Monitoring" *Future Internet* 16, no. 2: 36. https://doi.org/10.3390/fi16020036

Neamatallah, Z.; Herrington, L.; Jones, R. (2020). An investigation into the role of gluteal muscle strength and EMG activity in controlling HIP and knee motion during landing tasks. Phys. Ther. Sport, 43

Oks, A., Katashev, A., Eizentals, P., Rozenstoka, S., & Suna, D. (2020). Smart socks: New effective method of gait monitoring for systems with limited number of plantar sensors. Health and Technology, 10(4), 853-860.

Sadigursky, D., Braid, J. A., De Lira, D. N. L., Machado, B. A. B., Carneiro, R. J. F., & Colavolpe, P. O. (2017). The FIFA 11+ injury prevention program for soccer players: a systematic review. BMC sports science, medicine and rehabilitation, 9(1), 1-8.

Semjonova, G., Davidovica, A., Kozlovskis, N., Okss, A., & Katashevs, A. (2022). Smart Textile Sock System for Athletes' Self-Correction during Functional Tasks: Formative Usability Evaluation. Sensors, 22(13), 4779.

Suo, X., Tang, W., & Li, Z. (2024). Motion Capture Technology in Sports Scenarios: A Survey. *Sensors (Basel, Switzerland)*, *24*(9), 2947. https://doi.org/10.3390/s24092947

Tanaka, A., Visi, F., Di Donato, B., Klang, M., & Zbyszyński, M. (2024). An End-to-End Musical Instrument System That Translates Electromyogram Biosignals to Synthesized Sound. *Computer Music Journal*, 1-40.

Ziagkas, E., Loukovitis, A., Zekakos, D. X., Chau, T. D., Petrelis, A., & Grouios, G. (2021). A Novel Tool for Gait Analysis: Validation Study of the Smart Insole PODOSmart®. *Sensors (Basel, Switzerland)*, *21*(17), 5972. https://doi.org/10.3390/s211759.

APPENDIX

Table 2: Correlation of left lower extremity.

Correlation type	1st Parameter	2nd Parameter	Coefficient	Significancy (p)
Strong positive	COP1x	COP2x	r= 0,506	p < .001
	COP2x	*Musculus gluteus medius* electrical activity	r= 0,543	p < .001
	COP1w	COP2w	r= 0,836	p < .001
Moderate positive	Hip joint flexion	*Musculus biceps femoris* electrical activity	r=0,408	p < .001
	Hip joint adduction	Hip joint internal rotation	r=0,408	p < .001
	Musculus gluteus maximus electrical activity	*Musculus gluteus medius* electrical activity	r= 0,462	p < .001
	COP2x	*Musculus gluteus maximus* electrical activity	r= 0,418	p < .001
	Knee joint flexion	*Musculus quadriceps femoris vastus lateralis* electrical activity	r= 0,469	p < .001
	COP1x	COP1y	r= 0,479	p < .001
	COP1x	*Musculus quadriceps femoris vastus lateralis* electrical activity	r= 0,401	p < .001
	COP1y	COP2y	r= 0,456	p < .001
Strong negative	COP1w	*Musculus gluteus maximus* electrical activity	r= -0,517	p < .001

Table 2: Correlation of left lower extremity. (cont.)

Moderate negative	Knee joint flexion	Hip joint flexion	r= -0,45	p < .001
	Musculus quadriceps femoris vastus lateralis electrical activity	Hip joint flexion	r= -0,469	p < .001
	COP2w	*Musculus gluteus maximus* electrical activity	r= -0,42	p < .001
	Musculus quadriceps femoris vastus lateralis electrical activity	*Musculus biceps femoris* electrical activity	r= -0,427	p < .001

Table 3: Correlation of right lower extremity.

Correlation type	1st Parameter	2nd Parameter	Coefficient	Significancy (p)
Strong positive	Hip joint flexion	*Musculus biceps femoris* electrical activity	r= 0,585	p < .001
	Hip joint adduction	Hip joint internal rotation	r= 0,591	p < .001
	Hip joint adduction	COP1y	r= 0,836	p < .001
	Hip joint internal rotation	COP1y	r= 0,599	p < .001
	Knee joint flexion	*Musculus quadriceps femoris vastus lateralis* electrical activity	r= 0,654	p < .001
	COP1w	COP2w	r= 0,783	p < .001
Strong negative	Knee joint flexion	Hip joint flexion	r= -0,639	p < .001
	Musculus quadriceps femoris vastus lateralis electrical activity	Hip joint flexion	r= -0,599	p < .001
	COP2w	Hip joint adduction	r= -0,588	p < .001
	Hip joint internal rotation	COP1w	r= -0,662	p < .001
	COP1w	*Musculus gluteus maximus* electrical activity	r= -0,658	p < .001
	COP2y	*Musculus gluteus maximus* electrical activity	r= -0,603	p < .001
	COP2w	*Musculus gluteus maximus* electrical activity	r= -0,637	p < .001