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ORIGINAL ARTICLE

Biomechanical load quantification of national and regional soccer players with an inertial sensor setup during a jump, kick, and sprint task: assessment of discriminative validity

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Abstract

Training load quantification methods may help optimize soccer performance. However, whole-body indicators potentially underestimate biomechanical load. A new inertial sensor setup allows joint-specific biomechanical load quantification. Good discriminative validity further supports the use of this method, and therefore the purpose of this study is to assess the discriminative validity of this method during soccer-specific activities. Twelve national and sixteen regional soccer players wore an inertial sensor setup and performed countermovement jumps, soccer kicks, and 30 m sprints. Between-group differences in angular acceleration-based biomechanical load indicators *Knee Load*, *Hip Load*, and performance were assessed using MANOVAs and Cohen's effect sizes. Furthermore, relationships with performance were explored. National players showed higher *Knee Load* during jumping (mean difference: 0.11 A.U., ES = 0.93, $p = 0.02$), kicking (mean difference: 1.94 A.U., ES = 0.94; $p = 0.02$), and almost during sprinting (mean difference: 12.85, ES = 0.77; $p = 0.05$). *Hip Load* did not differ between groups across all tasks, although national players outperformed regional players on all tests. Significant relationships between *Knee Load* ($r_{\text{jump}} = 0.41$, $r_{\text{kick} =}$ 0.65), *Hip Load* ($r_{\text{jump}} = 0.42$), and performance were observed with 95% confidence intervals ranging from trivial to large. The results confirm discriminative validity of *Knee Load* for jumping and kicking, but not for sprinting and *Hip Load* in general. The confidence intervals of the established relationships suggest that the biomechanical loads might not entirely explain between-group differences in performance. The results can be used as reference values for biomechanical load quantification in the field.

Keywords Wearable electronic devices · IMU · Construct validity · Kinematics · Football · Field testing

1 Introduction

Soccer players train regularly to meet the physical demands of the game. Within the training process, exercise volume, frequency, and intensity (i.e. load) are balanced with sufficient periods of rest to induce adaptations in cardiovascular and musculoskeletal systems leading to improved performance [1]. On the contrary, there is risk of injury when load and recovery are imbalanced.

To better control the training process, feedback on external or internal load, and on physiological and biomechanical load can be provided [2]. External load is defined as physical work prescribed in a training plan, while internal load is defined as the consequent response depending on individual player characteristics. A further subdivision can be made between physiological and biomechanical load. Physiological load involves stresses on the cardiovascular and

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metabolic system that induce adaptations in heart, lungs, and oxidative capacity of muscles. Biomechanical load involves stresses on the player's musculoskeletal system leading to adaptations in muscles, tendons, bones, or ligaments.

Many monitoring systems in soccer, such as local or global positioning systems, include trunk sensors to quantify external load [3]. External load in soccer is therefore mainly quantified with whole-body indicators such as accelerations or Playerload [3–5]. Although this might already give insights into the physical load of soccer players, it does not yield information on lower extremity biomechanical loads in the forms of forces, stresses, or strains. For example, jumping, kicking and passing are characterised by joint-specific movements, rather than the general locomotive state of the player [6]. These explosive activities impose high biomechanical loads on the lower extremities that are not captured with conventional load indicators. This potential underestimation in biomechanical load might constrain adequate periodization and performance optimization approaches, because biomechanical load-adaptational pathways differ from physiological pathways [2].

Current technological possibilities have limited ability to quantify internal (repetition of) forces, stresses, and strains of lower extremity tissues [7]. Hence, field-based biomechanical load estimations currently rely on surrogate indicators to quantify forces, stresses, and strains [8–10]. Human movement is driven by an interplay of gravity, contact forces (e.g. with the ground), segment interactions, and muscle contractions [11]. This generates a net torque, resulting in joint angular accelerations that can be measured with inertial sensor technology. The musculoskeletal system is largely responsible for generating net torques during soccer [6, 12, 13]. Consequently, using joint angular accelerations may offer valuable insights into the lower extremity biomechanical loads.

An inertial sensor setup offers a valid approach for capturing lower extremity kinematics in field conditions [9, 10], and therefore provides a feasible option to quantify lower extremity biomechanical load. *Knee Load* and *Hip Load* were introduced as new surrogate external biomechanical load indicators based off inertial sensor measured angular accelerations [14]. Because *Knee Load* and *Hip Load* rely on angular accelerations, the term "load" does not refer to the biomechanical force definition but rather serves as a construct to describe player activities in the field [15]. To prevent confusion these terms will be referred to in italic. Nevertheless, the terms *Knee Load* and *Hip Load* will be used for ease of understanding throughout the manuscript. *Knee Load* and *Hip Load* demonstrated acceptable to good reliability and construct validity in the field [14, 16]. To further support construct validity of these indicators, the ability to discriminate constructs that are expected to differ between groups can be explored during soccer-specific field tests [17–19]. This technique to assess discriminative validity is often referred to as the known-groups difference technique [20].

Considering discriminative validity has not been assessed yet, utilizing the known-groups difference technique would be a logical step in the validation process [20]. Good discriminative validity would further support the validity of this method, provide reference values for level of play, and demonstrate the feasibility of using inertial sensors in the field. Furthermore, understanding relationships between training load indicators and sport specific performance outcomes would help improve training practice used to achieve the most optimal performance outcomes. However, perfect outcomes cannot be expected since other factors might play a role, such as task execution. Ideally, trainers, coaches, and sport practitioners will use this information for adequate training load management so that player performance improves.

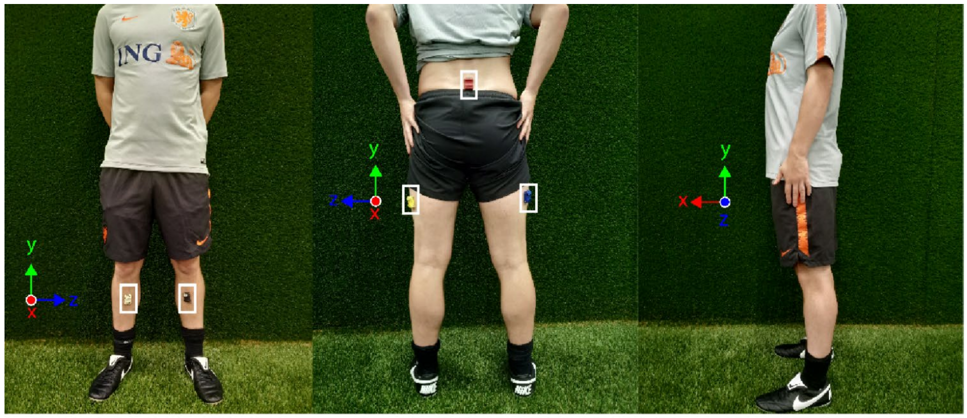
Therefore, this study aims to assess the discriminative validity of two new angular acceleration-based biomechanical load indicators *Knee Load* and *Hip Load*. Discriminative validity was assessed using the known-group difference technique. Biomechanical load and performance of national and regional soccer players was assessed during soccer-specific field tests. Based on superior capacities, it is anticipated that national players demonstrate higher *Knee Load* and *Hip Load*. Second, relationships with performance will be explored to assess whether high *Knee Load* and *Hip Load* values would translate into better performance.

2 Methods

2.1 Equipment

2.1.1 Inertial sensor setup

Five inertial measurement units (MPU-9150, Invensense, San Jose, California, USA) were used to obtain lower extremity kinematics (Fig. 1) [9, 10]. The sensors were placed at the lower back, both thighs and both shanks following procedures detailed elsewhere [9]. An additional sensor was used on a mechanical time gate to time align the data with a local position measurement system, as detailed later. Each sensor measured 3D linear acceleration (± 16 G), 3D angular velocity (± 2000º/s.), and 3D Earth magnetic field strength (± 1200 μT) with a sample frequency of 500 Hz. The data was locally stored on an SD card embedded in a protective plastic casing (size; 35 × 25 × 15 mm, weight; 11.0 g). Before measurements, the inertial sensors were time aligned, as described elsewhere [9, 21].



a b c

Fig. 1 Illustrative example of sensor locations and local coordinate systems. The inertial sensor setup is displayed from the front (**a**), back (**b**), and side (**c**)

2.1.2 Local position measurement system

A local position measurement system (Inmotio, Zeist, The Netherlands) was used to obtain positional data. The system is validated for recording football-specific movements (static accuracy: 3 cm, less than 2% difference with optoelectronic measurement system during movement) [4, 22]. It has a sampling frequency of 1000 Hz divided by the number of transponders present on the field. Five transponders were used during experiments. Participants wore a single vest with a transponder between shoulder blades and two antennas that sent a signal to ten base stations located around an artificial-turf soccer field. Four additional transponders were placed on the soccer field to create a sprint start and finish line. Hence, the system sample frequency was 200 Hz.

2.1.3 Force plate

A floor mounted force plate was used to quantify jump height (MotekForce Link, Amsterdam, Netherlands; dimensions: 0.70 × 0.70 m). The force plate was calibrated following manufacturer instructions. Data was collected using commercially available software (Vicon Nexus, version 2.8.1, Vicon Motion Systems Ltd., Oxford, UK). Each jump was recorded separately with a 1000 Hz sample frequency.

2.2 Participants

Twenty-eight male soccer players participated which were divided into a national group and a regional group (Table 1) in line with regulations of the Netherlands Royal Soccer Association (KNVB). National players competed in national divisions (Eerste Divisie, $n = 4$; Derde Divisie, $n = 1$; Hoofdklasse, $n = 7$), whereas regional players competed in lower ranked divisions (Reserve Hoofdklasse, $n = 1$; 1e klasse, $n = 1$; 2e klasse, $n = 1$; 3e klasse, $n = 3$; 4e klasse, $n = 1$; 5e klasse, $n = 9$). Participants were at least 16 years old, had at least 1 year experience, and trained at least once a week. Participants were injury free during the study. They were informed about the study protocol and written informed consent was obtained before participation. The study was approved by the local ethical committee of the Center for Human Movement Sciences from the University Medical Center Groningen (research register number: 202000503).

Table 1 Main characteristics of the participants (mean values ± standard deviation)

	Age (years)	Weight (kg)	Height (m)	Training	Position		
				(h/week)	D	M	A
National (N = 12)	22.2 ± 2.1	77.3 ± 7.3	1.83 ± 0.04	**5.71 ± 5.4**	4	2	6
Regional (N = 16)	24.1 ± 4.7	78.3 ± 8.6	1.87 ± 0.07	**0.94 ± 1.1**	6	6	4
Mean difference	−1.96	−1	−0.04	**4.77**			
95% CI	−4.9–1.0	− 7.4–5.3	− 0.09–0	**1.9–7.6**			
Effect size	0.51	0.13	0.73	**1.31**			
P value	0.19	0.73	0.07	**0.001**			

D defender; *M* midfield; *A* attacker

Significant differences are displayed in bold ($p < 0.05$)

2.3 Design

This cross-sectional cohort study used a between-groups design. National and regional soccer players performed three counter movement jumps, five maximal instep kicks, and three linear 30 m sprints in this fixed order. Between-group differences in *Knee Load* and *Hip Load* were assessed to evaluate discriminative validity. To further evaluate these results, between-group differences in performance and relationships between *Knee Load*, *Hip Load,* and performance were assessed. The study was conducted during the COVID pandemic between February 2021 and May 2022.

2.4 Procedures

Players performed a 10 min warming-up routine including jumps, kicks, runs at submaximal intensity, and sprints. Thereafter, a short calibration procedure was performed to ensure accurate data registration of the inertial sensor setup [9, 10]. The calibration procedure involved a 5 s static calibration where participants stood still in upright pose, followed by a dynamic calibration where participants raised their left upper leg, raised their right upper leg, and bowed their trunk forward. This procedure was repeated between tests.

After calibration, participants performed three counter movement jumps. The test is able to identify performance differences between level of play and is highly reliable [17, 23]. Participants were instructed to jump with hands on their hips and as high as possible. Trials were interspersed with 30 s rest to avoid fatigue effects. The trial with highest jump height was included for further analysis. Biomechanical load was calculated for the concentric phase (Fig. 2) since instructions were focussed on maximal performance. Also, high forces, muscle moments, joint powers occur during this phase [24]. Consequently, it was expected that between-group differences in angular accelerations would be the largest in this phase.

Thereafter, participants performed five maximal instep kicks with a rest period of 30 s. Participants kicked a ball 5 m from a normal full-sized goal as forcefully as possible without accuracy demands. Participants were free in how to approach the ball. The test is reliable [25] and discriminates between level of play [18]. Based on the relationship between ball speed, the kick with highest knee extension velocity of the kicking leg was included for further analysis [18, 26]. Analysis was conducted for the full instep kick, without the run-up, from minimal hip angle until peak knee extension (Fig. 3).

Thereafter, participants performed three 30 m linear sprints interspersed with a 1 min resting period. The 30 m linear sprint test discriminates between levels of play and is reliable [19]. Participants stood with their preferred foot in front of a marked line on the field and ran 30 m distance as fast as possible. The fastest trial was included for statistical analysis. *Knee Load* and *Hip Load* were calculated for the complete 30 m sprint (Fig. 4).

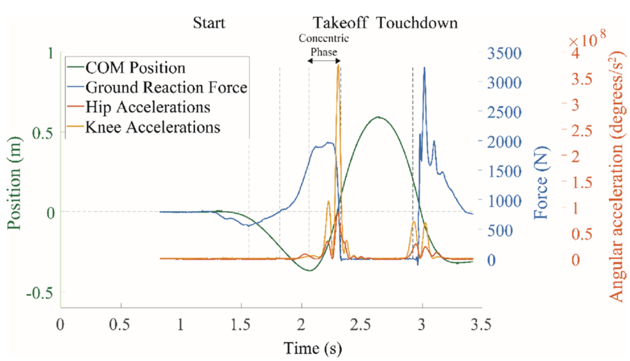


Fig. 2 Representative example of centre of mass (COM) position, counter movement force plate data, and squared magnitude of angular accelerations**.** Data of concentric phase was included for analysis. Abbreviations: m = metre; s = seconds; N = Newton

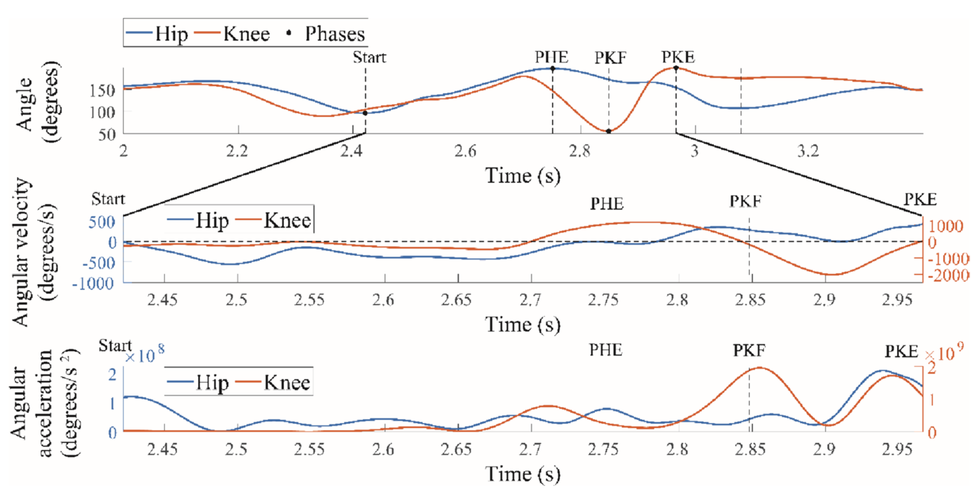


Fig. 3 Representative example of flexion and extension angles (top), flexion (+) and extension (−) angular velocities (middle) and squared magnitude of angular accelerations (bottom) for instep kick. The lines represent peak hip extension (= PHE), peak knee flexion (= PKF), and peak knee extension (= PKE). Abbreviations: s = seconds

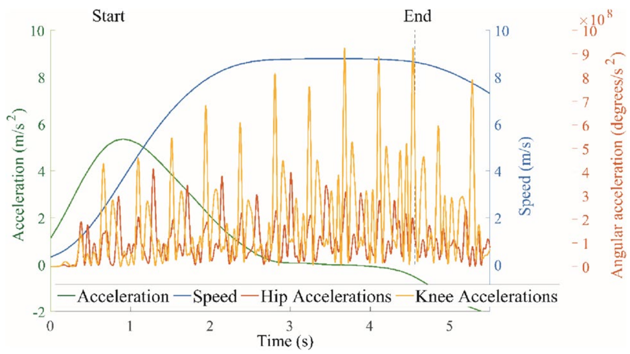


Fig. 4 Representative example of sprint data. Acceleration, speed, and magnitude of joint accelerations are displayed. Abbreviations: m/s^2 = metre/second^2; s = second; m/s = metre/second; degrees/s = degrees/second^2

2.5 Data processing

2.5.1 Knee load and hip load

Lower extremity kinematics were obtained with gyroscope data, filtered with a 12 Hz second-order low-pass Butterworth filter, which was based on visual inspection of the data and similar studies [10]. Sensor orientation with respect to the global earth frame was obtained using a gradient descent algorithm with filter gain β set to 0.043 following recommendations for dynamic measurements [27]. Joint angles and angular velocities were then obtained by expressing the difference in sensor orientation between distal and proximal body segments [10].

Angular accelerations of the knee and hip joint from the preferred kicking leg were used to quantify lower extremity biomechanical load. Following previous work [14], gyroscope signals were filtered using an 8 Hz fourth-order low-pass Butterworth filter. This was determined through fast Fourier transform and visual inspection of the data. Joint angular accelerations were then obtained by differentiation of the filtered angular velocities. The magnitude of 3D joint accelerations was calculated at each time point. Then, the magnitude was squared to emphasize high intensity movements in the outcome, since these activities are more demanding [14]. The cumulative sum of the squared magnitudes was then divided by an arbitrary scale factor for readability, representing *Knee Load* or *Hip Load* (Eq. 1):

$$\text{Knee load and hip load} = \frac{\left|\alpha_{\text{Knee,Hip}}\right|^2}{10^8}, \tag{1}$$

where $\alpha_{\text{knee, Hip}}$ denotes the knee or hip joint angular acceleration magnitudes (degrees per second^2).

2.5.2 Local position measurement system

Inmotio software (version v6.2.0.383, Inmotio, Zeist, The Netherlands) was used to extract player position, velocity, and acceleration data at 50 Hz using a weighted Gaussian average filter set at 85%. Four extra transponders were used during the tests to determine start and end points for the sprint test. Two local position measurement transponders formed a time gate, both at start and finish line. Sprint times were obtained by subtracting the difference in time between finish line and start.

2.5.3 Force Plate

Vicon Nexus software (version 2.8.1, Vicon Motion Systems Ltd., Oxford, UK) was used to export the force plate data. Take-off and touchdown were determined from the vertical ground reaction force data, based on a fixed threshold of 20 N. From these instances, jump height could be determined with Eq. 2 [28], where g stands for the gravitational constant (9.81 m/s^2), and t for flight time (s).

$$\text{Jump height} = \frac{gt^2}{8}. \tag{2}$$

2.5.4 Time alignment

A custom-written algorithm in MATLAB (R2020b, The MathWorks, Inc., Natick, MA, USA) was developed to time align and process the data. Inertial sensor data of the lower back were used to determine touchdown during the counter movement jump. The vertical angular acceleration was filtered with a 2 Hz low-pass fourth-order Butterworth filter. Trapezoidal integration of the vertical acceleration signal was used to determine velocity, which was subsequently filtered with a 0.1 Hz fourth-order zero-lag Butterworth filter to minimize integration drift [29]. The minimal velocity then defined touchdown. Touchdown caused a peak in both datasets, used to time align the inertial sensors and force plate.

The local position measurement system and IMU data were time aligned manually using a time gate located at the 30 m sprint finish. This time gate consisted of two local position measurement transponders laying on the field, and an inertial sensor attached to a mechanical gate [21]. Participants passed this gate three times during the protocol, which caused a peak in both datasets. The mean time difference between measurement systems was used to manually time align the data.

2.6 Statistical procedures

Outcome measures were presented as means, and standard deviations. Data were checked for outliers and subsequently normality with skewness, kurtosis, and the Shapiro–Wilk test. In some cases (2/18), assumptions were violated, but since this did not influence main findings, we decided to present parametric analysis only. Between-group differences in participant characteristics, *Knee Load*, *Hip Load*, and performance were assessed by MANOVA tests, followed by pairwise comparisons with Bonferroni corrections in case of significance. Cohen's effect sizes and 95% confidence intervals were calculated to interpret the magnitude of differences. Pearson correlation analysis was performed to explore relationships between performance and *Knee Load* or *Hip Load*. Effect sizes and correlation coefficients were interpreted following Cohen's recommendations [30]. Statistical analysis was performed in R Studio (Version 3.0.3), and statistical significance was accepted when $p<0.05$.

3 Results

3.1 Counter movement jump

National players had higher *Knee Load* (mean difference: 0.11 A.U., CI (95%): 0.01 to 0.21, ES = 0.51, $p=0.02$) than regional players, but *Hip Load* was similar between groups (mean difference: 0.04 A.U., CI (95%): −0.02 to 0.09, ES = 0.51, $p=0.2$). Furthermore, jump height was higher for national players (mean difference: 0.04 m, CI (95%): 0 to 0.08, ES = 0.93, $p=0.02$) and moderately related to *Knee Load* ($r=0.47$, CI (95%): 0.12 to 0.72, $p=0.01$) and *Hip Load* ($r=0.42$, CI (95%): 0.05 to 0.69, $p=0.03$) (Fig. 5).

3.2 Instep soccer kick

National players had higher *Knee Load* (mean difference: 1.94 A.U., CI (95%): 0.23 to 3.65, ES = 0.94, $p=0.02$) than regional players. However, *Hip Load* was similar between groups (mean difference: 0.01 A.U., CI (95%): −0.72 to 0.70, ES = 0.02, $p=0.97$). Furthermore, knee extension velocity was higher for national players (mean difference: 214°/s, CI (95%): 26 to 402, ES = 0.95, $p=0.02$) and strongly related with *Knee Load* ($r=0.65$, CI (95%): 0.36 to 0.82, $p<0.001$). However, *Hip Load* did not relate to knee extension velocity ($r=0.20$, CI (95%): −0.19 to 0.53, $p=0.31$) (Fig. 6).

3.3 Sprint test

Knee Load (mean difference: 12.85, CI (95%): −1.2 to 26.9, ES = 0.77, $p=0.05$) and *Hip Load* (mean difference: 3.74 A.U., CI (95%): −5.1 to 12.6, ES = 0.35, $p=0.37$) were similar between groups, although national players sprinted faster (mean difference: 0.22s, CI (95%): 0.36 to 0.09, ES = −1.36, $p=0.002$). Furthermore, both *Knee Load* ($r=0.26$, CI (95%): −0.57 to 0.13, $p=0.19$) and *Hip Load* ($r=-0.03$ CI (95%): −0.4 to 0.34, $p=0.87$) did not relate to sprint time (Fig. 7).

4 Discussion

The main findings were that national players had higher *Knee Load* during the counter movement jump, while *Hip Load* was similar between groups. Moreover, *Knee Load* and *Hip Load* had moderate relationships with jump performance. Second, national players had higher *Knee Load* during the instep kick, but *Hip Load* remained similar between groups. National players reached higher knee extension velocities, which were strongly related to *Knee Load*. Third, *Knee Load* and *Hip Load* were similar between groups during the sprint task, despite better sprint performance by national players. In addition, no significant relationships were observed between *Knee Load* and *Hip Load* and sprint performance. The results confirm the hypothesis for *Knee Load* in jumping and kicking tasks, while the hypotheses were not confirmed for *Knee Load* during sprinting and *Hip Load* in general.

4.1 Counter movement jump

National players had higher *Knee Load* and better performance than the regional counterparts. A well-known discriminative factor for countermovement jump performance is the amount of force application and its duration (i.e. net impulse) [24, 31]. This can be achieved by generating high hip net extensor moments or knee power production during the concentric phase of the counter movement jump [24, 32]. It was therefore expected that players with better explosive jump abilities would demonstrate larger joint accelerations. In line with expectations, national players displayed higher *Knee Load* during the concentric phase. However, *Hip Load* remained similar between groups and only moderate relationships between *Knee Load* or *Hip Load* and jump height were observed. Consequently, the explained variance was only 22 and 17% with confidence intervals ranging from trivial to large. Other factors than *Knee Load* and *Hip Load* might therefore be more related to jump performance and explain the remaining variance, such as the proximal-to-distal timing sequence of joint and segment actions [33]. Furthermore, the current inertial sensor setup does not measure ankle joint accelerations and thus important information might be missing.

4.2 Instep soccer kick

National players had higher *Knee Load* and better performance, while *Hip Load* was similar. Kicking requires players to generate muscle moments to accelerate the lower leg

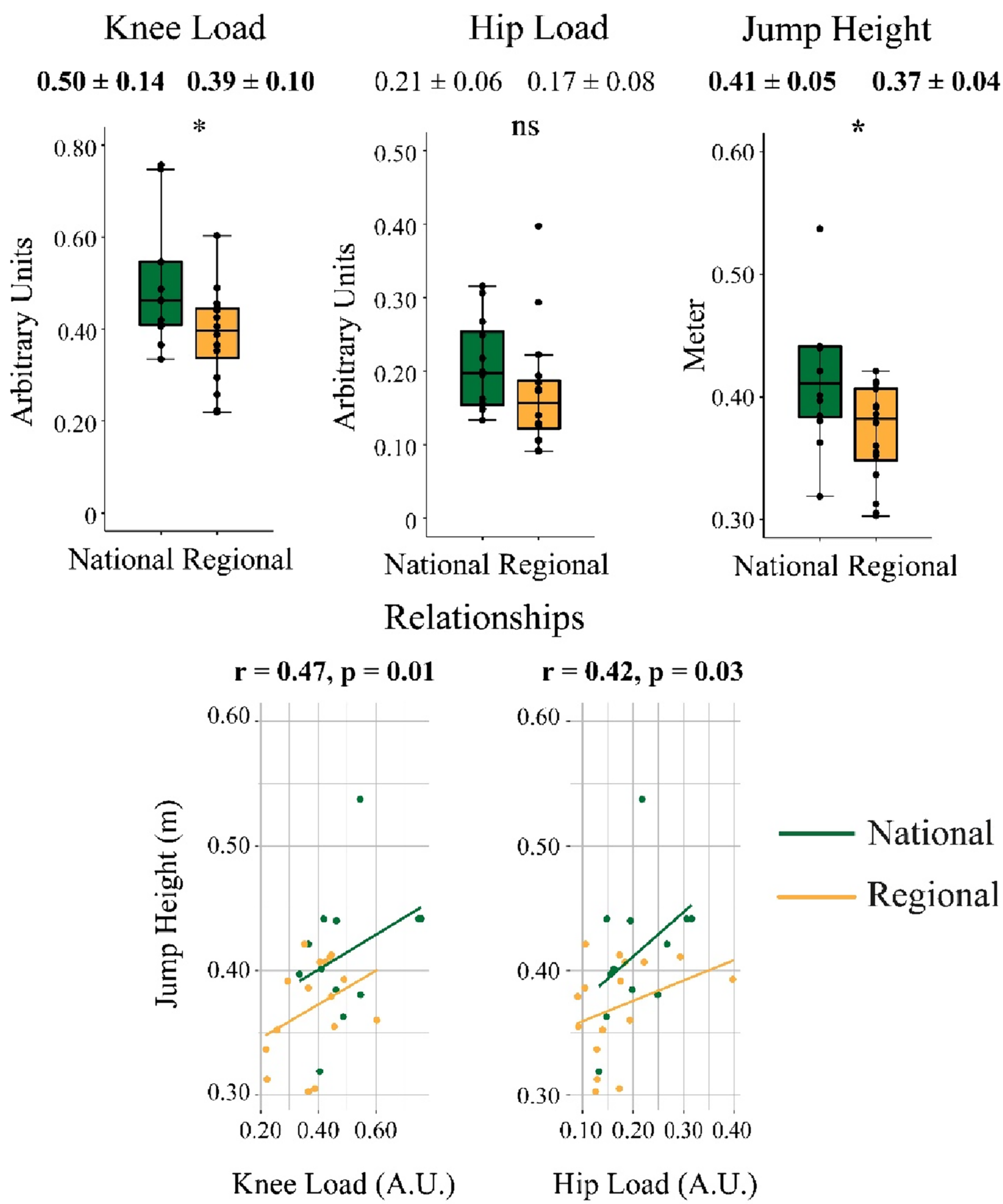


Fig. 5 Boxplots of counter movement jump performance, Hip Load, and Knee Load and their relationships. Means ± SD, and statistical significance in bold are presented. Abbreviations: * = $p < 0.05$, ns = not significant, A.U. = arbitrary units; m = metre

[6, 34]. Thus, expectations were that players with better strength capacities would generate higher muscle moments which would consequently lead to higher joint accelerations. However, *Hip Load* did not differ between groups, nor was it related to performance. A potential explanation could be how players formed a tension arc (i.e. task execution), which is an important factor for instep kicking performance [6, 18]. Players can increase hip extension, knee flexion or trunk rotation to the non-kicking side to accelerate segments, and release energy to the ball into a proximal-to-distal sequence. It might be that national players achieved better performance by increasing knee range of motion, while using similar hip strategies. By doing so, more time is available to produce force, which

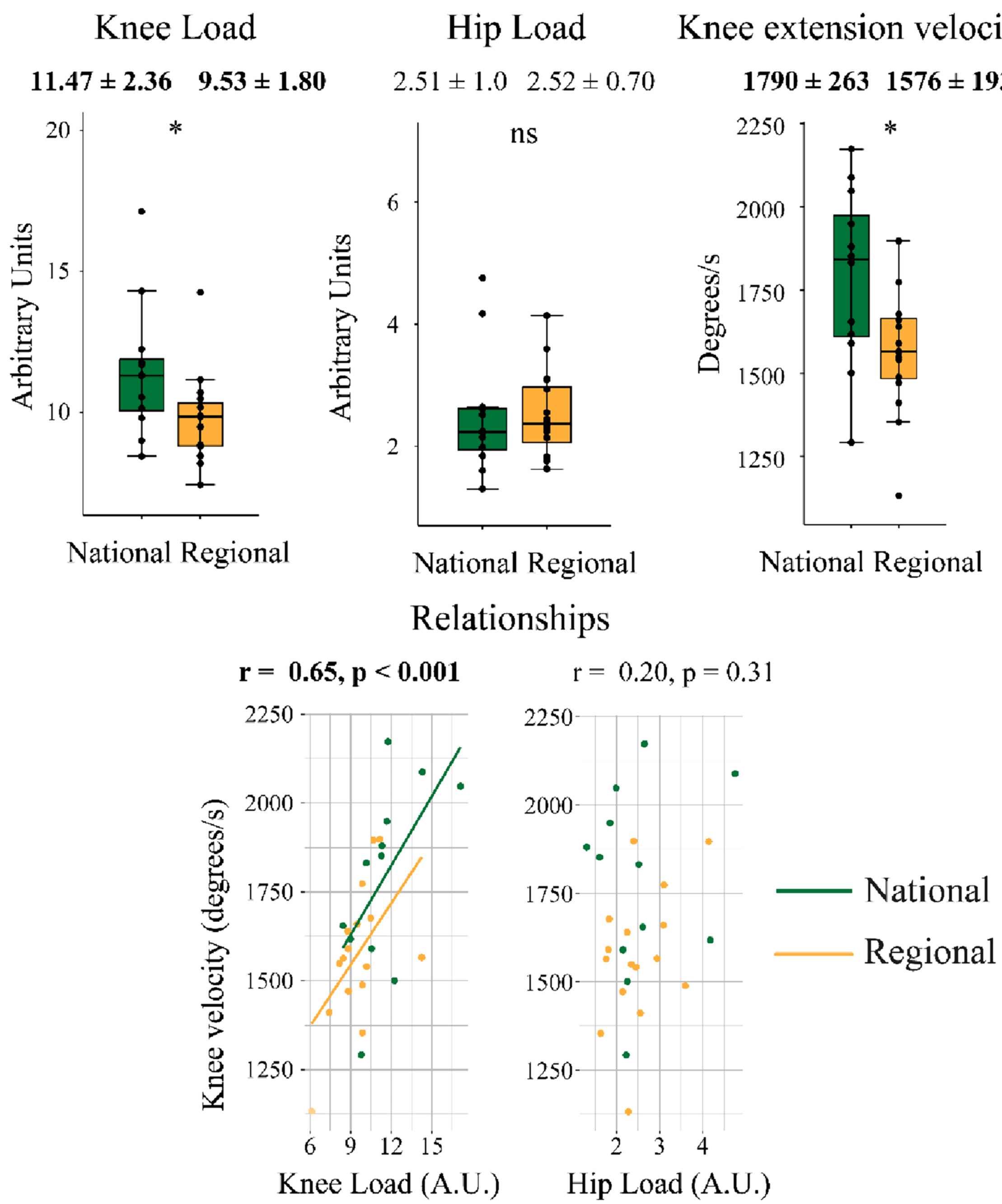


Fig. 6 Boxplots of soccer instep kick performance, Hip Load, Knee Load, and their relationships. Means ± SD, and statistical significance in bold are presented. Abbreviations: degrees/s = degrees/second; A.U. = arbitrary units

would result in higher accelerations around the knee joint and ultimately better performance.

4.3 Sprint test

Knee Load and *Hip Load* were similar between groups, although national players had better performance. Sprint speed is a product of step length and frequency, so players use one or both to achieve maximal performance. Step frequency can be increased through shorter ground contact time during stance or decreasing flight time [35]. Especially a decreased flight time has implications for *Knee Load* and *Hip Load* because joints need to accelerate to prepare the swinging leg for the next ground contact during stance. However, *Knee Load* and *Hip Load* were similar between groups. Furthermore, *Knee Load* and *Hip Load* were unrelated to performance. Other factors might therefore be more relevant to explain the observed difference in sprint

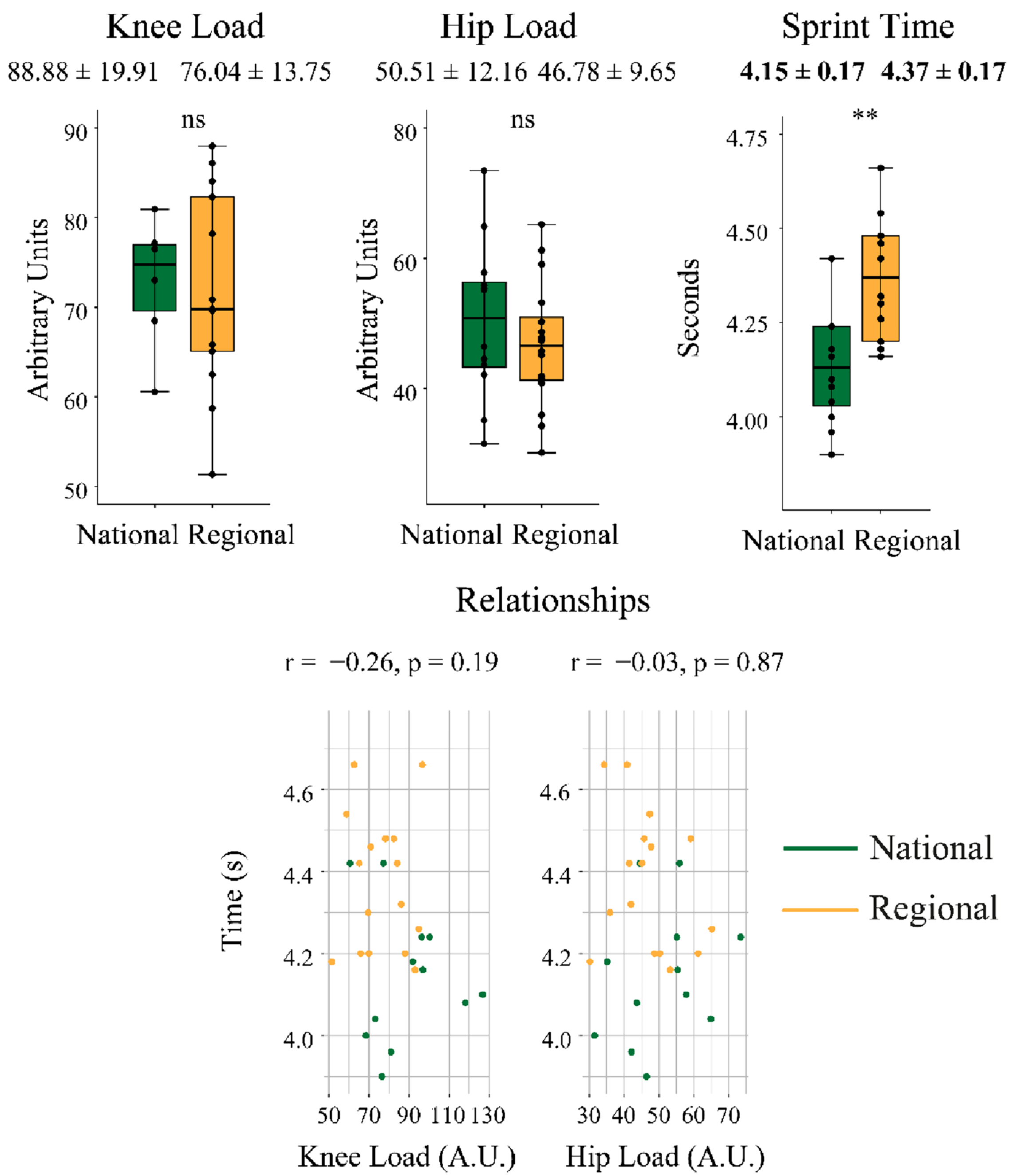


Fig. 7 Boxplots of sprint performance, Hip Load, and Knee Load and their relationships. Means ± SD, and statistical significance in bold are presented. Abbreviations: s = seconds; A.U. = arbitrary units

performance, such as the horizontal force production during stance [35] or the role of the ankle joint during the first steps of the sprint [36].

4.4 Strengths, limitations, and future studies

This study confirmed differences in physical performance between level of play using soccer-specific field tests and assessed the discriminative validity of new biomechanical load indicators in a standardized setting. The activities in this study mimic soccer-specific movements during match play. The participants in this study were chosen from various playing levels, and thus reference values were created for soccer players which can be used by coaches and players for future performance assessments. The inertial sensor setup can be integrated in shorts or tights [37] that might improve future biomechanical load estimations for optimal player performance.

This study has some limitations that must be considered. First, soccer competitions and training were suspended because of the COVID pandemic. Assessment of individual data points showed within-group variation, as well as overlap between the groups. Although national players trained more hours per week, differences in jump, kick, and sprint performance were relatively small. Therefore, the differences between the national and regional players might have been insufficient to provide contrast in biomechanical load between groups. Second, it must be acknowledged that derivation of jump height directly from an inertial sensor could have been a more practical method to obtain jump height. However, we chose not to do this because a force plate is a more accurate method for evaluating counter movement jump performance, ensuring robust and precise performance assessments in this study. Furthermore, kicking performance was based on knee extension velocity. Although knee extension velocity is related to ball speed, an alternative would be to measure ball speed with "gold standard" equipment such as a radar gun. Third, the relationship with adequate periodization strategies has not been explored yet, and therefore, it remains to be determined how both *Knee Load* and *Hip Load* contribute to performance optimization in real practice.

In the current study biomechanical load indicators were obtained using a cross-sectional design and standardized tests. To further demonstrate the practical relevance of these load indicators future studies might assess biomechanical load during standardized match simulations or during the return to sport process where training is progressively built up towards performance.

5 Conclusions

The results confirm discriminative ability of angular acceleration-based biomechanical load indicator *Knee Load* during jumping and kicking, but discriminative ability of *Knee Load* during sprinting and *Hip Load* in general is not confirmed. Although significant relationships with performance were observed, the magnitude ranged from trivial to large. This suggests that the angular acceleration-based indicators *Knee Load* and *Hip Load* only explain the difference in performance to a limited extent and other factors should be explored, such as task execution. The results provide further understanding of how to use angular acceleration-based training load indicators derived from a lower extremity inertial sensor setup for sport performance evaluations. Furthermore, this study provided reference values of angular acceleration-based biomechanical load indicators for the lower extremities and performance during soccer-specific field tests. These values can be used by coaches, trainers, and staff to evaluate player performance.

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Data availability The data is available upon reasonable request.

References

1. Smith DJ (2003) A framework for understanding the training process leading to elite performance. Sports Med 33(15):1103–1126
2. Vanrenterghem J et al (2017) Training load monitoring in team sports: a novel framework separating physiological and biomechanical load-adaptation pathways. Sports Med 47(11):2135–2142
3. Akenhead R, Nassis GP (2016) training load and player monitoring in high-level football: current practice and perceptions. Int J Sports Physiol Perform 11(5):587–593
4. Stevens TGA et al (2014) Measuring acceleration and deceleration in soccer-specific movements using a local position measurement (LPM) system. Int J Sports Physiol Perform 9(3):446–456
5. Boyd LJ, Ball K, Aughey RJ (2011) The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. Int J Sports Physiol Perform 6(3):311–321
6. Naito K, Fukui Y, Maruyama T (2010) Multijoint kinetic chain analysis of knee extension during the soccer instep kick. Hum Mov Sci 29(2):259–276
7. Verheul J et al (2020) Measuring biomechanical loads in team sports – from lab to field. Sci Med Football 4(3):246–252
8. Kalkhoven JT et al (2021) Training Load and Injury: causal pathways and future directions. Sports Med 51(6):1137–1150
9. Bastiaansen BJC et al (2020) An inertial measurement unit based method to estimate Hip and Knee Joint Kinematics in Team Sport Athletes on the Field. J Visual Exp. https://doi.org/10.3791/60857-v
10. Wilmes E et al (2020) inertial sensor-based motion tracking in football with movement intensity quantification. Sensors (Basel). https://doi.org/10.3390/s20092527
11. Zajac FE, Gordon ME (1989) Determining muscle's force and action in multi-articular movement. Exerc Sport Sci Rev 17:187–230
12. Pandy MG, Zajac FE (1991) Optimal muscular coordination strategies for jumping. J Biomech 24(1):1–10

13. Huang L et al (2013) Segment-interaction and its relevance to the control of movement during sprinting. J Biomech 46(12):2018–2023
14. Bastiaansen BJC et al (2022) Biomechanical load quantification using a lower extremity inertial sensor setup during football specific activities. Sports Biomech. https://doi.org/10.1080/14763141.2022.2051596
15. Impellizzeri FM et al (2022) The 'training load' construct: why it is appropriate and scientific. J Sci Med Sport 25(5):445–448
16. Wilmes E, Bastiaansen BJ, de Ruiter CJ, Vegter RJ, Brink MS, Weersma H, Goedhart EA, Lemmink KA, Savelsbergh GJ (2023) Construct Validity and Test–Retest Reliability of Hip Load Compared With Playerload During Football-Specific Running, Kicking, and Jumping Tasks. Int J Sports Physiol Perform 18(1):3–10.https://doi.org/10.1123/ijspp.2022-0194
17. Haugen TA, Tonnessen E, Seiler S (2013) Anaerobic performance testing of professional soccer players 1995–2010. Int J Sports Physiol Perform 8(2):148–156
18. Boyne M et al (2021) 2021 It's not all about power: a systematic review and meta-analysis comparing sex-based differences in kicking biomechanics in soccer. Spor Biomech. https://doi.org/10.1080/147631411981426
19. Altmann S et al (2019) Validity and reliability of speed tests used in soccer: a systematic review. PLoS ONE 14(8):e0220982
20. Impellizzeri FM, Marcora SM (2009) Test validation in sport physiology: lessons learned from clinimetrics. Int J Sports Physiol Perform 4(2):269–277
21. de Ruiter CJ, van Dieën JH (2019) Stride and step length obtained with inertial measurement units during maximal sprint acceleration. Sports 7(9):202
22. Frencken WG, Lemmink KA, Delleman NJ (2010) Soccer-specific accuracy and validity of the local position measurement (LPM) system. J Sci Med Sport 13(6):641–645
23. Markovic G et al (2004) Reliability and factorial validity of squat and countermovement jump tests. J Strength Cond Res 18(3):551–555
24. Vanezis A, Lees A (2005) A biomechanical analysis of good and poor performers of the vertical jump. Ergonomics 48(11–14):1594–1603
25. Markovic G, Dizdar D, Jaric S (2006) Evaluation of tests of maximum kicking performance. J Sports Med Phys Fitness 46(2):215–220
26. Sinclair J et al (2014) Three-dimensional kinematic correlates of ball velocity during maximal instep soccer kicking in males. Eur J Sport Sci 14(8):799–805
27. Madgwick SOH, Harrison AJL, Vaidyanathan R (2011) Estimation of IMU and MARG orientation using a gradient descent algorithm. IEEE International Conference on Rehabilitation Robotics, Zurich, Switzerland, pp 1–7,https://doi.org/10.1109/ICORR.2011.5975346
28. Bosco C, Luhtanen P, Komi PV (1983) A simple method for measurement of mechanical power in jumping. Eur J Appl Physiol 50(2):273–282
29. Rantalainen T, Finni T, Walker S (2020) Jump height from inertial recordings: a tutorial for a sports scientist. Scand J Med Sci Sports 30(1):38–45
30. Hopkins WG et al (2009) Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc 41(1):3–13
31. Dowling JJ, Vamos L (1993) Identification of kinetic and temporal factors related to vertical jump performance. J Appl Biomech 9(2):95–110
32. Lees A, Vanrenterghem J, De Clercq D (2004) The maximal and submaximal vertical jump: implications for strength and conditioning. J Strength Cond Res 18(4):787–791
33. Bobbert MF, van Soest AJ (2001) Why do people jump the way they do? Exerc Sport Sci Rev 29(3):95–102
34. Dorge HC et al (2002) Biomechanical differences in soccer kicking with the preferred and the non-preferred leg. J Sports Sci 20(4):293–299
35. Morin JB et al (2012) Mechanical determinants of 100-m sprint running performance. Eur J Appl Physiol 112(11):3921–3930
36. Dorn TW, Schache AG, Pandy MG (2012) Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance. J Exp Biol 215(Pt 11):1944–1956
37. Steijlen A et al (2021) Smart sensor tights: movement tracking of the lower limbs in football. Wear Technol 2:e17