RICYDE. Revista Internacional de Ciencias del Deporte
doi: 10.5232/ricyde
Rev. Int. cienc. deporte

RICYDE. Revista Internacional de Ciencias del Deporte
Volume XVII - Year XVII
Pages: 124-139 - ISSN: 1885-3137
Issue 64 - April 2021

https://doi.org/10.5232/ricyde2021.06402

Multi-location external workload profile in U-18 soccer players
Perfil multi-ubicación de carga externa en jugadores de fútbol sub-18

Carlos David Gómez-Carmona[1], Alejandro Bastida-Castillo[2], Victor Moreno-Pérez[3],
Sergio José Ibáñez[1], & José Pino-Ortega[4]

1. Research Group in Optimization of Training and Sports Performance (GOERD). Faculty of Sports Science. University of Extremadura, Spain
2. Departamento de Actividad Física y Deporte. Universidad Isabel I. Burgos, Spain
3. Departamento de Cirugía y Patología. Universidad Miguel Hernández, Elche, Spain
4. BioVetMed & Sport Sci Research Group. Physical Activity and Sports Department. International Excellence Campus "Mare Nostrum", Sport Science Faculty, University of Murcia, Spain

Abstract

An association between accelerometer workload and injury risk has been found previously. However, any research has assessed the absorption dynamics of external workload through the measurement in different anatomical locations simultaneously. A cross-sectional study was designed to: (i) to describe the multi-joint external workload profile of youth soccer players, (ii) to identify between-participant differences related to anatomical locations, (iii) to analyze the workload dynamics at different speeds at joints and body segments, (iv) to characterize the multi-joint individual workload and the within-participant difference in each body segment. Twenty-one U-18 male players, that were part of a Youth Spanish First Division soccer team, performed an incremental running treadmill test and wore four WIMU PRO™ inertial devices in lower limb (ankle-knee) and spine (lower-upper back) locations to register cumulative tri-axial accelerometry-based workload (PlayerLoad, PL_{RT}). The main results have shown that the highest PL_{RT} was detected at the lower limb, especially at the ankle. Different dynamics of accelerometer workload have been found between lower and upper limb, being them between ankle-knee at 12-km/h and lower-upper back at 9.5-km/h (p<.05). Between-participants' differences were shown at all joints, finding the highest differences at the upper back (p<.01; d=2.17). Finally, the body segment knee-lower back reported the highest differences (%diff=34.25-to-67.28; d=2.20-to-4.77). In conclusion, a great between-participants external workload variability was found at joints and body segments, being recommended for an individualized assessment and specific training protocols.

Key words: testing; accelerometry; musculoskeletal workload; team sports.

Resumen

Una asociación entre la carga acelerometrica y el riesgo de lesión ha sido encontrada previamente. Sin embargo, no existen investigaciones que evalúen la dinámica de absorción de carga externa a través de diferentes ubicaciones anatómicas simultáneamente. Un estudio transversal fue diseñado para: (i) describir el perfil multi-ubicación de carga externa en jugadores jóvenes de fútbol, (ii) identificar diferencias entre sujetos relacionadas con las ubicaciones anatómicas, (iii) analizar la dinámica de carga a diferentes velocidades en diferentes ubicaciones anatómicas y segmentos corporales, (iv) caracterizar el perfil multi-ubicación individual y las diferencias intra-sujeto en cada segmento corporal. 21 jugadores masculinos U-18 que pertenecían a un equipo de fútbol de Primera División Nacional Juvenil realizaron un test incremental en tapiz rodante portando cuatro dispositivos inerciales WIMU PRO™ en diferentes ubicaciones del tren inferior (rodilla-tobillo) y columna (espalda alta y baja) para registrar la carga acelerométrica tri-axial acumulada (PlayerLoad, PL_{RT}). Los principales resultados muestran que el mayor PL_{RT} fue detectando en el tren inferior, especialmente en el tobillo. Diferentes dinámicas de carga acelerométrica han sido encontrados entre el tren inferior y el tren superior, siendo estas diferencias entre tobillo-rodilla a 12 km/h y entre espalda alta-baja a 9.5 km/h (p<.05). Diferencias inter-sujeto fueron encontradas en todas las ubicaciones, encontrando las mayores diferencias en la espalda alta (p<.01; d=2.17). Finalmente, el segmento corporal rodilla-espalda baja reportó las mayores diferencias (%diff=34.25-to-67.28; d=2.20-to-4.77). En conclusión, una alta variabilidad inter-sujeto en la carga externa registrada fue encontrada en todas las ubicaciones y segmentos corporales, siendo recomendable su individualización y entrenamiento específico.

Palabras clave: evaluación; acelerometría; carga musculoesquelética; deportes de equipo.

Correspondence/correspondencia: Carlos David Gómez-Carmona
Research Group in Optimization of Training and Sports Performance (GOERD). Faculty of Sports Science.
University of Extremadura, Caceres, Spain
Email: cdgomezcarmona@unex.es

Received: November 24, 2020; Accepted: January 4, 2021

Introduction

Currently, there is a great amount of interest in research into workload quantification in team sports to design specific training programs according to competing demands (Bourdon et al., 2017). Recent research has shown that the total workload supported by an athlete is composed of internal and external workload, and their quantification is important to analyze physical and physiological demands during training and competition (McLaren et al., 2018). The internal workload is considered as the biological reaction of the athlete's body, both from the physiological and psychological viewpoint (Halson, 2014). While the external workload is the mechanical and locomotor stress that an athlete suffers during the activity (Gómez-Carmona, Bastida-Castillo et al., 2020). In the last few years, research interest in external workload has increased due to a more accurate assessment of specific sport movements and skills thanks to advances in technology (Vanrenterghem et al., 2017)

The external workload can be divided into the kinematical and neuromuscular workload (Buchheit et al., 2018). The kinematical workload is related to the locomotion demands and their intensity and is recorded using different tracking technologies in outdoor (Global Navigation Satellite Systems, GNSS) (Colby et al., 2014), and indoor conditions (Ultra-Wide Band, UWB; Local Position Measurement, LPM) (Bastida-Castillo et al., 2018; Leser et al., 2014). In particular, the neuromuscular workload is defined as the force exerted by the athlete, as a result of the interaction with gravitational forces and teammates/opponents (impacts, jumps) recorded by triaxial accelerometers (Gómez-Carmona, Bastida-Castillo et al., 2020).

In this sense, new devices known as Inertial Measurement Units (IMUs) have been developed for data recording. These devices are composed of different sensors (accelerometers, gyroscopes, magnetometer, etc.) that are integrated into the same unit (Wu et al., 2007). The reliability and validity of these units to assess neuromuscular workload through event detection (impacts, shots, jumps) (Hulin et al., 2017; Jarning et al., 2015), and the instant or accumulated workload in time (Player Load, PL; Ground Reaction Forces, GRF; 3-axis acceleration) (Barrett et al., 2014; Gómez-Carmona, Bastida-Castillo, González-Custodio, et al., 2019).

After evaluating their validity and reliability, these variables have been widely used in team sports for workload quantification since 2010 (Gómez-Carmona, Bastida-Castillo et al., 2020). In event detection, impacts >5G range from 490-613 in soccer (Abade et al., 2014; Gómez-Carmona et al., 2018) to 895-1222 in rugby and American football (Suarez-Arrones et al., 2012; Wellman et al., 2016); and in accumulated workload through PL, values from 900-to-1500 a.u. have been registered in team sports (Gastin et al., 2019; Oliva-Lozano et al., 2020; Pino-Ortega et al., 2019). So, due to the higher values registered, numerous studies have analyzed the association between neuromuscular workload and injury risk in different team sports such as Australian football (Colby et al., 2014) or soccer (Barrett et al., 2016; Bowen et al., 2017). A previous study showed that the injury risk in youth soccer players is higher than in seniors, especially during matches (Pfirrmann et al., 2016). For this reason, it is important to analyze the total workload in youth players, but it is necessary to perform a specific assessment of the location where that workload is suffered.

Concerning the location of IMUs, it is accepted that the center of mass (COM) is a valid placement to detect whole-body movement (Barrett et al., 2014). However, in team sports, the interscapular line (upper back) is admitted as the best location for GPS signal reception (Gómez-Carmona, Bastida-Castillo et al., 2020). Nedergaard et al. (2017) subsequently found that accelerometers only record the acceleration of the body segment that they are attached. So, the measuring of whole-body acceleration is inadequate due to multi-joint complexity during sports movements. In this respect, the latest investigations suggested locating the device on the lateral malleolus to detect the ground reaction forces (Gómez-Carmona, Bastida-Castillo, González-Custodio, et al., 2019; Rojas-Valverde et al., 2019; Zhang et al., 2016).

However, the study of the accelerations in the different joints and body segments at the same time can provide useful information on the absorption dynamics of external workload that the athlete's musculoskeletal structure supports (Morris & Lawson, 2009). Therefore, the purposes of the study were to: (i) describe the multi-joint external workload profile of a U-18 soccer team during an incremental treadmill running test, (ii) identify the between-participants differences related to the anatomical location, (iii) analyze the workload dynamics at different speeds in each joint and body segment, and (iv) characterize the multi-joint individual workload and the within-participants difference in each body segment.

Methods

Participants

Twenty-one U-18 male national-level soccer players participated voluntarily in this testing (age: 17.2±0.87 years, height: 1.77±0.07 m, body mass: 73.96±4.2 kg, BMI: 21.5±1.1 kg/m^2). Although the sample was intentionally selected, all soccer players were part of a soccer team that competed in the maximum youth category in Spain (Youth Spanish First Division, Group VII). Participants had to meet the following inclusion criteria: (i) up to two years of experience at the national level in soccer, (ii) more than one year of experience with high-level monitoring both in training and competition context, and (iii) not to present any physical limitations or musculoskeletal injuries that could have affected testing.

The study was approved by the ethics committee of the University (register number 232/2019) before the start of the testing. The investigation was conducted following the ethics code of the World Medical Association by the 7th edition of the Declaration of Helsinki (Hellmann et al., 2014). Before the start of this investigation, participants were fully informed about the testing and written informed consent was obtained from both the participants and their guardians.

Equipment

Anthropometric characteristics

Each participant's height and body mass were assessed. Specifically, height was measured to the nearest 0.5 cm during a maximal inhalation using a wall-mounted stadiometer (SECA model 213, Hamburg, Germany) (Baharudin et al., 2017). Body mass was obtained with an 8-electrode segmental body composition monitor (TANITA model BC418-MA, Tokyo, Japan) (Kelly & Metcalfe, 2012). One ISAK technician with level-2 accreditation completed the anthropometrical assessment.

External workload

The variables of the players when performing the incremental running treadmill test were recorded by four inertial devices WIMUPRO^{TM} (RealTrack Systems, Almeria, Spain) (Gómez-Carmona, Bastida-Castillo, González-Custodio, et al., 2019). These devices contain four triaxial accelerometers that can detect and measure movement using a micro-electromechanical system with an adjustable sampling frequency from 10 to 1000 Hz. The full-scale output ranges are ±16 g, ±16 g, ±32 g, and ±400 g. Besides, each device has its own microprocessor, 8-GB internal memory, and high-speed USB interface, to record, store and upload data. The device is powered by an internal battery with 4-h of life, that weighs 70-g and is 81×45×16 mm in size. In the present research, the sampling frequency of the accelerometers was 100 Hz following recommendations of accuracy and reliability for sports measurement (Gómez-Carmona, Rojas-Valverde et al., 2020).

Variables

In the present research, the following independent and dependent variables were analysed:

Dependent variable

- *Player Load:* This variable is the vector sum of the four accelerometer data points in their 3 axes of movement (vertical, anteroposterior, and lateral). It is developed by RealTrack Systems and is represented in arbitrary units (a.u.). Besides, it is calculated from the following equation where PL is the player workload calculated in the current moment; X_n, Y_n, and Z_n are the values of BodyX, BodyY, and BodyZ in the current moment; and X_{n-1}, Y_{n-1}, and Z_{n-1} are the values of BodyX, BodyY, and BodyZ in the previous moment. Then, the sum of PL during the session is calculated and multiplied by 0.01 as scale factor (Gómez-Carmona, Bastida-Castillo, et al., 2020).

$$PL = \sqrt{\frac{(X_n - X_{n-1})^2 + (Y_n - Y_{n-1})^2 + (Z_n - Z_{n-1})^2}{100}}$$

$$Accumulated\ PL = \sum_{n=0}^{m} PL_{RT} \text{ x } 0.01$$

Independent variables

- *Speed:* The distance covered related to the time spent.
- *IMU placement:* This variable represented the anatomical location of the IMUs during the testing. The location made it possible to analyze two variables:
  - *Joints:* Acceleration detected by the IMU accelerometers in each anatomical location (ankle, knee, lower back, and upper back).
  - *Body segments:* Differences among anatomical locations that represent the impact absorption by the musculoskeletal structures of the human body related to gravity: (1) ankle - knee; (2) knee-lower back; (3) lower back - upper back.

Procedure

The research was conducted over 3 weeks (one testing session per week) during the pre-season phase (August 2018). All tests were conducted in the lab of the Sports Science Faculty (San Javier, Spain). In the first session, the anthropometrical measurements were recorded, and information about the testing protocol and objectives was explained. The second session consisted of familiarization with the testing procedure (treadmill running) and experimental equipment (high-level monitoring with IMUs). Finally, in the last session, participants performed the incremental treadmill running test. The starting velocity was 8 km/h. Velocity was increased every 12 seconds, by 0.1 km/h (1 km/h every 2 minutes). The test ended when the athlete could no longer maintain the effort. This protocol was used in a previous study (Gómez-Carmona, Bastida-Castillo, González-Custodio, et al., 2019) and was proposed due to it being a laboratory-controlled trial, where velocity and environmental variables can be controlled accurately (temperature: 22.1±0.2° celsius, humidity: 50±2%).

Before the testing, participants performed a standardized warm-up composed of 5 min of running at aerobic intensity (65% of maximum heart rate, HR_{MAX}). This procedure was monitored by the WIMU PRO^{TM} inertial devices that sent the data in real-time through Wi-Fi technology to a computer with the S PRO^{TM} software (RealTrack Systems, Almeria, Spain) to check that the devices were working correctly. When the testing finished, participants performed 5 min of running at recovery intensity (55% HR_{MAX}).

Prior to placement, the inertial devices were calibrated manually, according to the manufacturer's recommendations, and synchronized. This process eliminated four 3D accelerometer error sources: offset error, scaling error, non-orthogonal error, and random error (Wu et al., 2007). The accuracy and the between and within-devices reliability have obtained satisfactory results (Gómez-Carmona, Bastida-Castillo, García-Rubio, et al., 2019; Gómez-Carmona, Bastida-Castillo, González-Custodio, et al., 2020).

Then, the devices were placed in different anatomical locations: (i) upper back, on the interscapular line (Barrett et al., 2014); (ii) lower back, at L3 near to the center of mass (McGregor et al., 2011); (iii) knee, 3-cm above the kneecap crack (Takeda et al., 2009); and (iv) ankle, 3-cm above the malleolus lateralis (Klassen et al., 2016). Both at the knee and ankle, the devices were placed on the outside of the right leg on all athletes. A specifically-designed elastic band was used to attach the devices on the participants, except on the upper back where they were placed in an anatomically designed harness (see Figure 1 for more details).

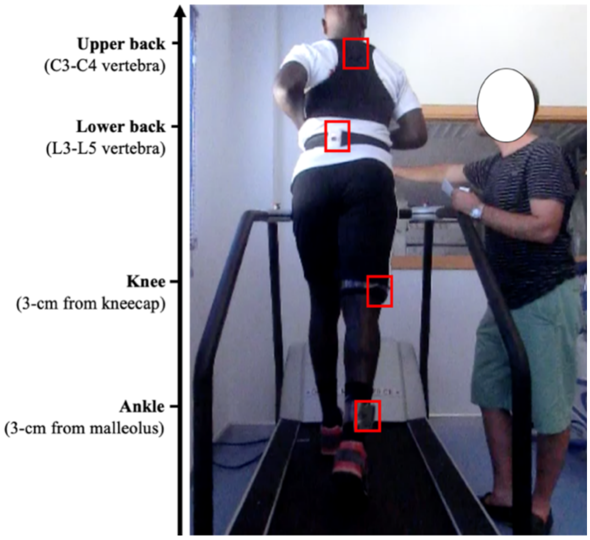

Figure 1. Anatomical placement of inertial devices during test in one of the participants.

To reduce the interference of uncontrolled variables, all the participants were instructed to maintain their habitual lifestyle and normal dietary intake before and during the study. Furthermore, the participants performed the different tests at the same time of day (i.e. 9:00 AM) to avoid the possible effects of circadian rhythms on physical performance, and with no high-intensity physical activity performed 48-hours before all tests (Spriet, 2014).

Statistical analysis

Firstly, the Shapiro-Wilk test to analyze the data distribution due to the sample size (n=21; less than 50 participants) and the Levene test to check the homoscedasticity of the sample, were performed to determine the appropriate statistical process (Field, 2013). The analysis showed a normal distribution, so parametric tests were selected. Secondly, a descriptive analysis was performed, showing data as mean (*M*) and standard deviation (*SD*).

A one-way ANOVA test was performed to identify the among-participants differences at all anatomical locations. A t-test for related samples analysed the workload dynamics concerning the speed in each joint and body segment, and also within-participants comparisons of each body segment, showing these results with the percentage of differences ($\%_{diff}$) (Vincent & Weir, 2012). The magnitude of the differences was termed unclear, being considered the observed magnitude. Thus, Cohen's d effect size (*d*) was calculated and interpreted using the following criteria: very low (0-0.2), low (0.2-0.6), moderate (0.6-1.2), high (1.2-2.0), and very high (>2.0) (Hopkins et al., 2009). The statistical analysis was performed using the *Statistical Package of Social Science* (SPSS) software (release 24; SPSS Inc., Chicago IL, USA). Besides, the plots were designed using the GraphPad Prism software (release 7; GraphPad Ltd., La Jolla CA, USA). Statistical differences were considered at the $p<.05$ value.

Results

Descriptive analysis and between-participants differences at anatomical locations

Table 1 shows the descriptive analysis and between-participant differences comparison of PL_{TM} in the different analysed locations at all speeds. The highest values were found in the lower limb (ankle=1.65±0.47; knee=1.62±0.51) in comparison with the upper limb (lower back=0.68±0.15; upper back=0.59±0.12). In the between-participants comparison, statistical differences were found at all locations ($p<.05$; *F*=13.03-56.61; *d*=1.04-to-2.17), with the greatest differences on the upper back at high speed ($p<.01$; *d*=2.49-to-4.10).

Table 1. Descriptive analysis and comparison between-participants in PL_{RT} variable in function of accelerometer location at different speeds.

Speed (km/h)	Ankle M±SD	Knee M±SD	Lower back M±SD	Upper back M±SD	Ankle *F; d*	Knee *F; d*	Lower back *F; d*	Upper back *F; d*
8.0	0.98±0.17	0.99±0.13	0.47±0.08	0.45±0.07	103.34; 2.93*	78.74; 2.56*	255.70; 4.62*	123.84; 3.21*
8.5	1.05±0.15	1.06±0.15	0.50±0.08	0.47±0.08	47.03; 1.98*	67.31; 2.37*	172.53; 3.79*	74.56; 2.49*
9.0	1.14±0.15	1.14±0.15	0.53±0.08	0.49±0.09	56.44; 2.17*	68.31; 2.39*	146.87; 3.50*	98.00; 2.86*
10.0	1.32±0.17	1.30±0.17	0.59±0.09	0.52±0.09	46.64; 1.97*	97.62; 2.85*	132.75; 3.32*	123.09; 3.21*
10.5	1.39±0.18	1.36±0.19	0.62±0.09	0.54±0.09	61.89; 2.27*	87.55; 2.70*	145.21; 3.48*	124.99; 3.23*
11.0	1.46±0.19	1.47±0.26	0.64±0.09	0.56±0.09	74.71; 2.50*	88.88; 2.72*	136.54; 3.37*	78.99; 2.55*
11.5	1.56±0.19	1.55±0.29	0.67±0.09	0.58±0.09	59.48; 2.23*	194.12; 4.02*	161.14; 3.66*	110.69; 3.04*
12.0	1.65±0.20	1.63±0.31	0.70±0.09	0.60±0.09	46.70; 1.97*	129.91; 3.29*	128.72; 3.27*	144.95; 3.46*
12.5	1.75±0.20	1.71±0.33	0.73±0.09	0.62±0.09	63.30; 2.30*	157.17; 3.62*	145.57; 3.49*	128.34; 3.27*
13.0	1.85±0.23	1.81±0.34	0.75±0.09	0.63±0.10	58.38; 2.22*	204.24; 4.13*	166.12; 3.70*	121.45; 3.18*
13.5	1.96±0.25	1.90±0.36	0.77±0.09	0.65±0.10	71.39; 2.44*	214.95; 4.23*	205.57; 4.14*	165.81; 3.68*
14.0	2.05±0.24	2.03±0.45	0.79±0.09	0.68±0.10	76.63; 2.53*	107.61; 3.00*	133.16; 3.33*	116.74; 3.12*
14.5	2.14±0.24	2.17±0.61	0.82±0.09	0.71±0.11	52.21; 2.09*	508.58; 6.51*	105.36; 2.97*	201.73; 4.10*
15.0	2.26±0.25	2.20±0.48	0.83±0.09	0.72±0.11	53.84; 2.12*	334.37; 5.28*	122.49; 3.20*	160.63; 3.64*
15.5	2.37±0.23	2.19±0.27	0.87±0.10	0.75±0.11	32.05; 1.63*	71.82; 2.45*	115.50; 3.10*	175.84; 3.86*
16.0	2.51±0.19	2.27±0.17	0.92±0.09	0.79±0.10	14.05; 1.08*	43.88; 1.91*	17.20; 1.20*	116.53; 3.68*
Total	1.65±0.47	1.62±0.51	0.68±0.15	0.60±0.13	13.03; 1.04*	24.85; 1.44*	30.51; 1.59*	56.61; 2.17*

Note. *M: Mean; SD: Standard deviation; F: F-value of ANOVA; d: Cohen's d effect size. *Statistical differences (p<.01).*

Speed influence on the external workload suffered by the joints and body segments

The external workload dynamics in each joint at all running speeds are shown in Figure 2. Higher velocity is related to a higher accelerometer workload at all anatomical locations. In addition, in the between-joint comparison, statistical differences were found in the lower limb (ankle-knee) from 12-km/h and in the upper limb (lower back – upper back) from 9.5-km/h.

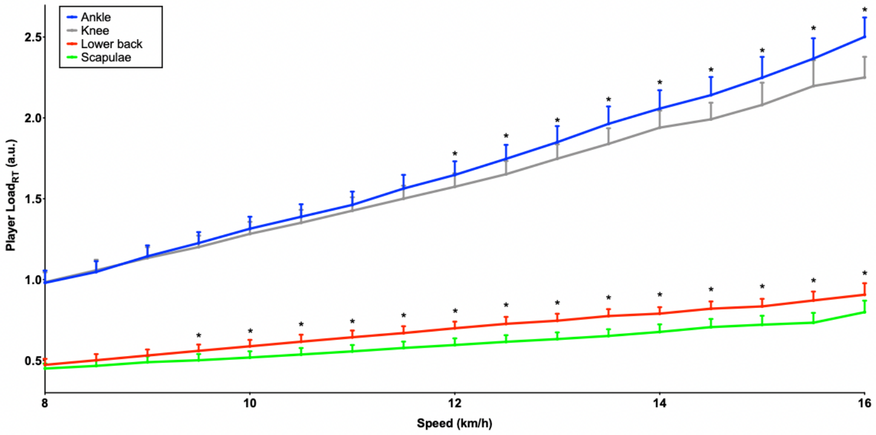

Figure 2. PLRT dynamics of all the participants in the analyzed joints between 8-16 km/h. *Statistical differences (p<.05).

Figure 3 presents the analysis of workload dynamics in relation to body segments. The greatest differences were found in segment 2 (knee – lower back), and they increased when the speed was faster. The external workload dynamics in segment 1 (ankle-knee) and segment 3 (lower back – upper back) remained constant at all speeds.

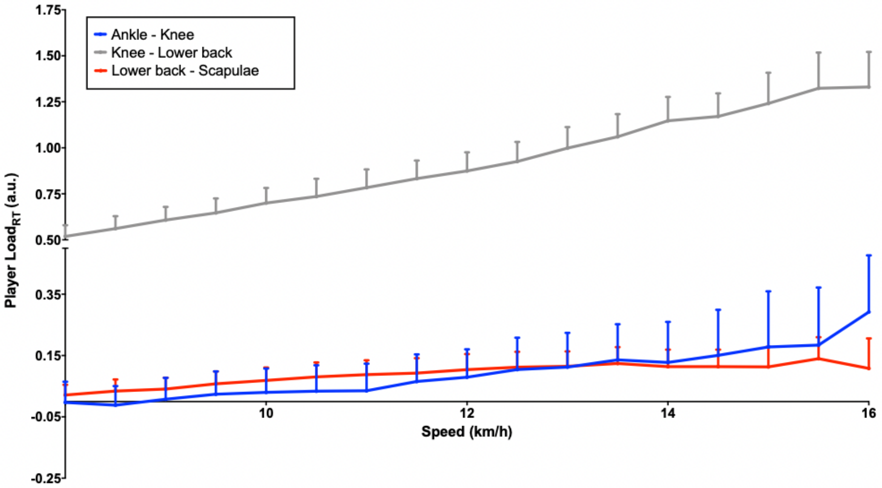

Figure 3. PLRT dynamics of all the participants in the analyzed body segments between 8-16 km/h.

Individual external workload profile and within-participant differences in body segments

Finally, the individual external workload profile and the within-participant comparison of the body segments analysed are shown in Table 2. The greatest differences were found in segment 2 (knee – lower back) with very high effect size, showing all soccer players had a higher PLRT at the knee in comparison with the lower back ($\%_{diff}$= 34.25-to-67.28; *d*= 2.20-to-4.77). Conversely, in segment 1, 23.81% of the participants (6, 8, 9, 12, and 13) supported a higher workload at the knee than the ankle ($\%_{diff}$= -2.77 to -65.98), and in segment 3, 23.81% of the participants (5, 8, 12, 13 and 14) suffered a higher workload in the upper back than the lower back ($\%_{diff}$= -2.79 to -16.43). Besides, greater between-participant variability was found in the external workload profile in all body segments.

Table 2. Within-participant differences of related samples. Percentage of differences, p-value, ranges and Cohen's d effect size on PL_{RT} dynamics in relation to body segments during the incremental treadmill running test.

N	Ankle	Knee	Lower back	Upper back	Segment 1 Knee - Ankle		Segment 2 Lower back - Knee		Segment 3 Upper back – Lower Back	
	M±SD	*M±SD*	*M±SD*	*M±SD*	*%$_{diff}$; d*	Ranges (a-k-d)	*%$_{diff}$; d*	Ranges (k-lb-d)	*%$_{diff}$; d*	Ranges (lb-ub-d)
1	1.49±0.40	1.47±0.46	0.65±0.13	0.47±0.08	1.94; 0.05*	55-19-3	54.11; 2.53*	77-0-0	27.74; 1.71*	77-0-0
2	1.30±0.38	1.26±0.23	0.82±0.09	0.58±0.07	-0.50; 0.03	24-34-1	34.25; 2.61*	59-0-0	29.50; 3.01*	59-0-0
3	1.38±0.33	2.40±1.08	0.73±0.11	0.62±0.13	-65.98; -1.23*	0-72-0	64.68; 2.29*	72-0-0	15.21; 0.91*	67-4-1
4	1.77±0.34	1.79±0.36	0.75±0.11	0.62±0.09	-0.84; -0.06	25-35-10	57.67; 4.07*	70-0-0	17.49; 1.31	70-0-0
5	1.77±0.55	1.51±0.31	0.50±0.05	0.60±0.05	11.47; 0.60*	50-12-1	58.41; 4.77*	25-0-0	-12.40; -2.00	0-25-0
6	1.58±0.47	1.77±0.41	0.68±0.13	0.51±0.11	-14.44; -0.43*	4-77-1	61.43; 3.73*	82-0-0	24.85; 1.42	82-0-0
7	1.65±0.43	1.53±0.21	0.84±0.17	0.58±0.06	3.73; 0.37*	46-36-1	45.92; 3.65*	83-0-0	28.83; 2.12	83-0-0
8	1.80±0.38	2.00±0.52	0.65±0.10	0.75±0.07	-10.45; -0.43*	0-74-1	66.65; 3.78*	75-0-0	-16.43; -1.18	0-75-0
9	1.45±0.34	1.50±0.41	0.56±0.09	0.47±0.05	-2.77; -0.13*	24-53-3	61.79; 3.32*	80-0-0	14.33; 1.27	80-0-0
10	1.71±0.51	1.49±0.35	0.71±0.20	0.63±0.11	11.02; 0.51*	74-9-0	52.96; 2.81*	83-0-0	7.03; 0.51	64-18-1
11	1.93±0.48	1.84±0.52	0.70±0.14	0.55±0.07	4.87; 0.18*	56-19-4	61.11; 3.13*	79-0-0	20.34; 1.40	79-0-0
12	1.44±0.45	1.59±0.41	0.51±0.11	0.53±0.10	-12.07; -0.35*	5-75-1	67.28; 3.76*	81-0-0	-4.05; -0.19	12-57-12
13	1.52±0.47	1.67±0.42	0.58±0.13	0.59±0.13	-11.83; -0.34*	11-71-0	64.85; 3.65*	82-0-0	-2.79; -0.08	17-57-8
14	1.85±0.47	1.46±0.32	0.70±0.10	0.80±0.11	19.93; 0.99*	81-0-0	51.63; 3.34*	81-0-0	-15.58; -0.95	0-81-0
15	1.91±0.60	1.43±0.43	0.64±0.15	0.55±0.13	24.58; 0.93*	85-0-0	54.33; 2.55*	85-0-0	12.87; 0.65	83-1-1
16	1.63±0.49	1.20±0.25	0.69±0.11	0.58±0.06	9.50; 1.14*	50-7-1	47.05; 2.73*	58-0-0	15.67; 1.28	58-0-0
17	1.47±0.29	1.45±0.27	0.72±0.11	0.65±0.06	1.05; 0.07*	42-22-6	50.31; 3.67*	70-0-0	8.16; 0.81	55-10-5
18	1.47±0.33	1.28±0.25	0.75±0.11	0.62±0.09	12.43; 0.66*	79-0-0	40.76; 2.84*	79-0-0	16.45; 1.31	79-0-0
19	1.59±0.35	1.38±0.34	0.56±0.14	0.46±0.09	13.65; 0.61*	76-0-0	59.02; 3.27*	76-0-0	16.99; 0.87	73-3-0
20	1.82±0.48	1.63±0.43	0.70±0.16	0.70±0.19	10.81; 0.42*	86-0-0	56.70; 2.98*	86-0-0	0.01; 0.00	36-47-3
21	1.49±0.27	1.41±0.23	0.63±0.11	0.48±0.04	4.49; 0.32*	54-7-1	55.89; 4.46*	62-0-0	22.31; 1.88	62-0-0
Total	1.61±0.46	1.60±0.51	0.68±0.15	0.59±0.13	-0.11; 0.02*	927-622-34	55.84; 2.55*	1545-0-0	-0.56; 0.64	1164-378-31

Note. *%$_{diff}$: Percentage of differences; p: p-value; Ranges (a: ankle, k: knee, lb: lower back, ub: upper back, d: draws); d: Cohen's d effect size. *Statistical differences ($p<0.01$).*

Discussion

Different investigations have analysed the influence of external workload on sports injuries (Bowen et al., 2017; Kiernan et al., 2018). However, a lack of research has been found about investigating the body segment differences (absorption dynamics of external workload in the whole body) through measurement at different anatomical locations simultaneously. Therefore, the main goal of the present research was to describe the multi-joint external workload profile of a U-18 soccer team related to speed and device location on joints and body segments and its comparison within- and between-participants. The main results showed that a lower distance to the ground-to-ground contact and a faster speed provoked higher external workloads. In addition, great between-participant variability was found both in joints and body segments in the accelerometer workload profile.

Multi-joint external workload profile

The results of the present study showed a greater external workload on the lower limb (ankle = 1.65 ± 0.47; knee = 1.62 ± 0.51) than the upper limb (lower back = 0.68 ± 0.15; upper back = 0.59 ± 0.12). Besides, each group obtained different external workload dynamics. Regarding the workload dynamics of the upper limb, Barrett et al. (2014) and Simons & Bradshaw (2016) found a greater external workload at the lumbar region than the scapulae in an incremental treadmill running test and in a specific jump assessment, respectively. Regarding the workload dynamics of the lower limb, Zhang et al. (2016) analyzed the difference in external workload between the ankle and the tibia, finding higher impacts on the ankle than the tibia, determining that the ankle is the most valid location to detect ground reaction forces (GRF).

Finally, only one investigation carried out by Nedergaard et al. (2017) has evaluated peak acceleration at different upper limb and lower limb joints simultaneously. The referred study found a greater acceleration peak at the tibia in comparison with the trunk, the center of mass, the pelvis and the scapulae at all speeds (2-5 m/s), both in linear locomotion and in 45º-to-90º changes of direction, the external workload being smaller as the distance to the ground increases. The highest external workload was recorded at the ankle and knee, and a recent review by Lopes et al. (2012) found that most sports injuries in runners were in both structures with an incidence rate between 22.7% and 9.1%, specifically Achilles and patellar tendinopathy and tibial stress fractures for every 1000 hours of practice. Therefore, a smaller distance to the ground contact during running will cause a higher external workload and a greater probability of injury, which is reduced as the distance to the ground increases. Besides, there are different workload dynamics between the lower and upper body.

Speed influence

Another interesting finding in our study was that a higher speed caused an increase in external workload at all anatomical locations, showing significant differences between ankle and knee from 12 km/h and between the lower back and upper back from 9.5 km/h. In this line of research, Barrett et al. (2014) and Nedergaard et al. (2017) found that a higher speed provoked higher PlayerLoad^{TM} and peak triaxial acceleration in an incremental treadmill test from 8-to-16 km/h at the center of mass and scapulae and during specific movements from 2-to-5 m/s at the tibia, trunk, center of mass, trunk and back, respectively. Specifically, Barrett et al. (2014) found significant differences at all speeds in the PL of the anteroposterior axis, not finding differences in the PL of the vertical axis and mediolateral axis at high speeds (> 11 km/h), results which contrasted with those found in the present investigation. Conversely, Nedergaard et al. (2017) obtained significant differences in all locations at all speeds, in contrast to the present investigation where a speed higher than 12.5 km/h had to be reached to obtain significant differences between the ankle and knee. Therefore, speed directly influences the external workload that the evaluated joints support, being its influence more important in the lower limb in comparison with the upper limb regarding the nearer distance to the ground contact (Gómez-Carmona, Bastida-Castillo, González-Custodio, et al., 2019; Nedergaard et al., 2017). In this respect, a comparative analysis of the external workload supported at each speed by a healthy athlete could be performed and considered in the return-to-play processes to program the specific progress in running speed, especially in lower limb injuries.

Anatomical location comparison

Significant differences were shown in the between-participant comparison in all joints and at all speeds. The differences with the smallest effect size were obtained specifically at the ankle. These differences were greater the higher the unit location and the highest was found in the upper back. The smallest differences were found in the ankle as it is in the closest contact with the ground concerning Newton's third law. The ankle impact is influenced by the athlete’s weight (Derrick et al., 2002), the muscle mass and fat mass of the lower limb (Liu and Nigg, 2000), the impact surface (Dixon et al., 2000), the type of footwear (Hardin et al., 2004), and the flight time between steps related to the stride rate (Heiderscheit et al., 2011). In this study, only the weight of the participants (*SD*=4.2 kg), the ratio of muscle mass and fat mass on the lower limb, and the flight time could influence the results. The type of footwear and the impact surface (treadmill) were not modified.

The differences in the rest of the joints increased when there was a greater distance from the ground so that the results obtained could be explained in relationship with different specific running biomechanics (Cochrum et al., 2017; Nigg, 2001), or an individualized absorption of the external workload by the musculoskeletal structures. In summary, because the players had similar anthropometric and physiological characteristics, the difference in the external workload at the ankle is the least variable among participants. In the rest of the anatomical locations, due to musculoskeletal characteristics and individual gait biomechanics, the variability of the external workload increased the higher the location in the body. Therefore, individual analysis of the external workload at all anatomical locations and at the specific intensities of locomotion that will be performed during the competition is recommended.

Body segment comparison

Regarding body segment comparison, the highest external workload absorption was found in the segment between the knee and the lower back in all the participants, where the change in external workload dynamics occurs between the lower limb and the upper limb ($\%_{diff}$ = 34.25 to 67.28; d = 2.20 to 4.77). In addition, it was found that the differences in segment 1 (ankle-knee) ($\%_{diff}$ =-0.11; d= 0.02) and segment 3 (upper back – lower back) ($\%_{diff}$ = -0.56; d= 0.64) remained stable throughout all speeds, while segment 2 (knee–lower back) increased as the speed got faster. This aspect is important, because the majority of muscle injuries in team sports, and specifically in soccer, are produced in segment 2 (knee-lower back) both in the anterior and posterior part of the thigh (Ekstrand et al., 2011). Maybe this phenomenon could be considered as a factor of the injury risk. Also, the same as at each joint, there is a large between-participants variability of the external workload among the body segments. This finding confirms the results presented in the comparison between joints, showing that gait biomechanics (Cochrum et al., 2017), and the musculoskeletal characteristics of the athletes are determinants in the absorption of the external workload.

Finally, different participants were found (8/21, 38.09%) who presented an atypical pattern of impact absorption as a higher impact was recorded in a location that was further from the ground compared to a location that was nearer to the ground. This atypical profile was divided into three groups: (a) an abnormal profile of the lower limb, with a higher workload at the knee than the ankle ($\%_{diff}$= -2.77 to -65.98) that was found in three soccer players (3, 6, and 9; 14.28%); (b) an abnormal profile of the upper limb, with a higher workload at the upper back than the lower back recorded in two players (5 and 14; 9.52%) ($\%_{diff}$= -2.79 to -16.43) and (c) an abnormal profile in the upper and lower limb of three players (8, 12 and 13; 14.028%) that presented a higher accelerometer workload at the knee and upper back than the ankle and lower back, respectively. This atypical pattern of impact absorption could be due to different causes such as gait biomechanics (Cochrum et al., 2017), sex and maturation development (Sigward et al., 2012), and previous sports learning (Rugg et al., 2018). The last variable is very important because early sport-specialized athletes in basketball, soccer and volleyball demonstrated altered lower extremity coordination that may lead to less stable landings and increased injury risk (DiCesare et al., 2019). This aspect was confirmed in elite-level basketball players where multisport participants during their sport formation were less likely to sustain a major injury risk during their career and had a longer active time (Rugg et al., 2018). Therefore, individualized analysis of the difference in the accelerometer workload between joints is very important to identify the impact absorption profile of each participant (Gómez-Carmona, Pino-Ortega, & Ibáñez, 2020; Gómez-Carmona, Bastida-Castillo et al., 2020).

Limitations and future research

While the results of this study have provided information regarding a new protocol to assess the multi-joint external workload profile of youth soccer players through simultaneously joint evaluation (ankle, knee, lower back, and upper back) with inertial measurement units (IMUs), some limitations to the study must be acknowledged. One of the limitations concerns the sample studied; it would be interesting to extend this study to include more athletes, levels, categories, and sport disciplines, to characterize the specific profiles and compare these profiles among groups. Besides, only one inertial device model with a specific variable was used in the present research, in this sense, users can compare the results if this specific formula is applied to the data raw provided by their inertial device models. In addition, it would also be interesting for futures studies to analyze the same parameters on sport-specific locomotion and skills in training and competition contexts.

Conclusions and practical applications

From the results obtained in the present study, five conclusions concerning the study purposes can be mentioned:

1. The highest external workload is suffered at ankle location as a consequence of a nearer distance to the ground contact, decreasing the impact when is ascend in the human body.
2. A faster speed caused a greater neuromuscular workload, being the highest increase in the lower limb locations (ankle and knee).
3. A different external workload dynamic was found between lower limb (ankle-knee) and upper limb (lower back – upper back). For this reason, related to speed, these differences are shown before in upper limb locations (9 km/h) respect to lower limb (12.5 km/h).
4. The segment 2 (knee – lower back) presented the greatest differences on external workload, showing an increase of these when the speed was faster. Instead, no differences in segment 1 and segment 3 were found related to a faster speed.
5. A great between-subject external workload variability was found at joints and body segments. For this reason, an individualized assessment is recommended.

The standardized protocol performed in the present research is proposed to evaluate the external workload suffered by the joints and body segments at all speeds during linear locomotion. It implies a direct practical application, since knowledge of the absorption capacity of the external workload in each athlete will make it possible to establish individualized training protocols to avoid injury risk, and the referential values obtained will be able to help the return-to-play process.

Acknowledgments

“This study has been developed by the Research Group in Optimization of Training and Sports Performance (GOERD) of the Sports Science Faculty of the University of Extremadura. The author Carlos D. Gómez Carmona was supported by a grant from the Spanish Ministry of Science, Innovation and Universities (FPU17/00407). This study has been partially subsidized by the Aid for Research Groups (GR18170) from the Regional Government of Extremadura (Department of Employment, Companies, and Innovation), with a contribution from the European Union from the European Funds for Regional Development.

References

Abade, E. A.; Gonçalves, B. V.; Leite, N. M., & Sampaio, J. E. (2014). Time-motion and physiological profile of football training sessions performed by under-15, under-17, and under-19 elite portuguese players. *International Journal of Sports Physiology and Performance*, *9*(3), 463–470. https://doi.org/10.1123/ijspp.2013-0120

Baharudin, A.; Ahmad, M. H.; Naidu, B. M.; Hamzah, N. R.; Zaki, N. A. M.; Zainuddin, A. A., & Nor, N. S. M. (2017). Reliability, technical error of measurement and validity of height measurement using portable stadiometer. *Pertanika Journal of Science & Technology*, *25*(3), 675-686.

Barrett, S.; Midgley, A.; Reeves, M.; Joel, T.; Franklin, E.; Heyworth, R.; Garret, A., & Lovell, R. (2016). The within-match patterns of locomotor efficiency during professional soccer match play: implications for injury risk? *Journal of Science and Medicine in Sport*, *19*(10), 810–815. https://doi.org/10.1016/j.jsams.2015.12.514

Barrett, S.; Midgley, A., & Lovell, R. (2014). PlayerLoad^{TM}: reliability, convergent validity, and influence of unit position during treadmill running. *International Journal of Sports Physiology and Performance*, *9*(6), 945–952. https://doi.org/10.1123/ijspp.2013-0418

Bastida-Castillo, A.; Gómez-Carmona, C. D.; De la Cruz Sánchez, E., & Pino-Ortega, J. (2018). Accuracy, intra- and inter-unit reliability, and comparison between GPS and UWB-based position-tracking systems used for time–motion analyses in soccer. *European Journal of Sport Science*, *18*(4), 450–457. https://doi.org/10.1080/17461391.2018.1427796

Bourdon, P. C.; Cardinale, M.; Murray, A.; Gastin, P.; Kellmann, M.; Varley, M. C.; Gabbett, T. J.; Coutts, A. J.; Burgess, D. J.; Gregson, W., & Cable, N. T. (2017). Monitoring athlete training loads: consensus statement. *International Journal of Sports Physiology and Performance*, *12*(Suppl 2), S2-161-S2-170. https://doi.org/10.1123/IJSPP.2017-0208

Bowen, L.; Gross, A. S.; Gimpel, M., & Li, F.-X. (2017). Accumulated workloads and the acute:chronic workload ratio relate to injury risk in elite youth football players. *British Journal of Sports Medicine*, *51*(5), 452–459. https://doi.org/10.1136/bjsports-2015-095820

Buchheit, M.; Lacome, M.; Cholley, Y., & Simpson, B. M. (2018). Neuromuscular responses to conditioned soccer sessions assessed via GPS-embedded accelerometers: insights into tactical periodization. *International Journal of Sports Physiology and Performance*, *13*(5), 577–583. https://doi.org/10.1123/ijspp.2017-0045

Cochrum, R. G.; Connors, R. T.; Coons, J. M.; Fuller, D. K.; Morgan, D. W., & Caputo, J. L. (2017). Comparison of running economy values while wearing no shoes, minimal shoes, and normal running shoes. *Journal of Strength and Conditioning Research*, *31*(3), 595–601. https://doi.org/10.1519/JSC.0000000000000892

Colby, M. J.; Dawson, B.; Heasman, J.; Rogalski, B., & Gabbett, T. J. (2014). Accelerometer and GPS-derived running loads and injury risk in elite australian footballers. *Journal of Strength and Conditioning Research*, *28*(8), 2244–2252. https://doi.org/10.1519/JSC.0000000000000362

Derrick, T. R.; Dereu, D., & Mclean, S. P. (2002). Impacts and kinematic adjustments during an exhaustive run. *Medicine & Science in Sports & Exercise*, *34*(6), 998–1002. https://doi.org/10.1097/00005768-200206000-00015

DiCesare, C. A.; Montalvo, A.; Foss, K. D. B.; Thomas, S. M.; Hewett, T. E.; Jayanthi, N. A., & Myer, G. D. (2019). Sport specialization and coordination differences in multisport adolescent female basketball, soccer, and volleyball athletes. *Journal of Athletic Training*, *54*(10), 1105–1114. https://doi.org/10.4085/1062-6050-407-18

Dixon, S. J.; Collop, A. C., & Batt, M. E. (2000). Surface effects on ground reaction forces and lower extremity kinematics in running. *Medicine & Science in Sports & Exercise*, *32*(11), 1919–1926. https://doi.org/10.1097/00005768-200011000-00016

Ekstrand, J.; Hagglund, M., & Walden, M. (2011). Epidemiology of muscle injuries in professional football (soccer). *The American Journal of Sports Medicine, 39*(6), 1226–1232. https://doi.org/10.1177/0363546510395879

Field, A. (2013). *Discovering Statistics Using IBM SPSS Statistics* (4th ed.). London, UK: SAGE.

Gastin, P. B.; Hunkin, S. L.; Fahrner, B., & Robertson, S. (2019). Deceleration, acceleration, and impacts are strong contributors to muscle damage in professional australian football. *Journal of Strength and Conditioning Research*, *33*(12), 3374-3383. https://doi.org/10.1519/JSC.0000000000003023

Gómez-Carmona, C.D.; Gamonales, J.; Pino-Ortega, J., & Ibáñez, S.J. (2018). Comparative analysis of load profile between small-sided games and official matches in youth soccer players. *Sports*, *6*(4), 173. https://doi.org/10.3390/sports6040173

Gómez-Carmona, C.D.; Rojas-Valverde, D.; Rico-González, M.; Ibáñez, S. J., & Pino-Ortega, J. (2020). What is the most suitable sampling frequency to register accelerometry-based workload? A case study in soccer. *Proceedings of the Institution of Mechanical Engineers Part P Journal of Sports Engineering and Technology*, *Epub: Ahead of Print*. https://doi.org/10.1177/1754337120972516

Gómez-Carmona, C.D.; Bastida-Castillo, A.; García-Rubio, J.; Ibáñez, S. J., & Pino-Ortega, J. (2019). Static and dynamic reliability of WIMU PRO^{TM} accelerometers according to anatomical placement. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *233*(2), 238–248. https://doi.org/10.1177/1754337118816922

Gómez-Carmona, C.D.; Bastida-Castillo, A.; González-Custodio, A.; Olcina, G., & Pino-Ortega, J. (2019). Using an inertial device (WIMU PRO^{TM}) to quantify neuromuscular load in running. reliability, convergent validity and influence of type of surface and device location. *Journal of Strength and Conditioning Research*, *34*(2), 365-373. https://doi.org/10.1519/jsc.0000000000003106

Gómez-Carmona, C.D.; Bastida-Castillo, A.; Ibáñez, S. J., & Pino-Ortega, J. (2020). Accelerometry as a method for external workload monitoring in invasion team sports. A systematic review. *PLoS ONE*, *15*(8), e0236643. https://doi.org/10.1371/journal.pone.0236643

Gómez-Carmona, C.D.; Pino-Ortega, J., & Ibáñez, S. J. (2020). Design and validity of a field test battery for assessing multi-location external load profile in invasion team sports. *E-Balonmano.com: Journal of Sport Science*, *16*(1), 23–48.

Halson, S. L. (2014). Monitoring training load to understand fatigue in athletes. *Sports Medicine*, *44*(S2), 139–147. https://doi.org/10.1007/s40279-014-0253-z

Hardin, E. C.; Van Den Bogert, A. J., & Hamill, J. (2004). Kinematic adaptations during running: effects of footwear, surface, and duration. *Medicine & Science in Sports & Exercise*, *36*(5), 838–844. https://doi.org/10.1249/01.MSS.0000126605.65966.40

Heiderscheit, B. C.; Chumanov, E. S.; Michalski, M. P.; Wille, C. M., & Ryan, M. B. (2011). Effects of step rate manipulation on joint mechanics during running. *Medicine & Science in Sports & Exercise*, *43*(2), 296–302. https://doi.org/10.1249/MSS.0b013e3181ebedf4

Hellmann, F.; Verdi, M.; Schlemper Junior, B. R., & Caponi, S. (2014). 50th anniversary of the declaration of helsinki: the double standard was introduced. *Archives of Medical Research*, *45*(7), 600–601. https://doi.org/10.1016/j.arcmed.2014.10.005

Hopkins, W. G.; Marshall, S. W.; Batterham, A. M., & Hanin, J. (2009). progressive statistics for studies in sports medicine and exercise science. *Medicine & Science in Sports & Exercise*, *41*(1), 3–13. https://doi.org/10.1249/MSS.0b013e31818cb278

Hulin, B. T.; Gabbett, T. J.; Johnston, R. D., & Jenkins, D. G. (2017). Wearable microtechnology can accurately identify collision events during professional rugby league match-play. *Journal of Science and Medicine in Sport*, *20*(7), 638–642. https://doi.org/10.1016/j.jsams.2016.11.006

Jarning, J. M.; Mok, K.-M.; Hansen, B. H., & Bahr, R. (2015). Application of a tri-axial accelerometer to estimate jump frequency in volleyball. *Sports Biomechanics*, *14*(1), 95–105. https://doi.org/10.1080/14763141.2015.1027950

Kelly, J. S., & Metcalfe, J. (2012). Validity and Reliability of Body Composition Analysis Using the Tanita BC418-MA. *Journal of Exercise Physiology*, *15*(6), 74–83.

Kiernan, D.; Hawkins, D. A.; Manoukian, M. A. C.; McKallip, M.; Oelsner, L.; Caskey, C. F., & Coolbaugh, C. L. (2018). Accelerometer-based prediction of running injury in National Collegiate Athletic Association track athletes. *Journal of Biomechanics*, *73*, 201–209. https://doi.org/10.1016/j.jbiomech.2018.04.001

Klassen, T. D.; Simpson, L. A.; Lim, S. B.; Louie, D. R.; Parappilly, B.; Sakakibara, B. M.; Zbogar, D., & Eng, J. J. (2016). "Stepping up" activity poststroke: ankle-positioned accelerometer can accurately record steps during slow walking. *Physical Therapy*, *96*(3), 355–360. https://doi.org/10.2522/ptj.20140611

Leser, R.; Schleindlhuber, A.; Lyons, K., & Baca, A. (2014). Accuracy of an UWB-based position tracking system used for time-motion analyses in game sports. *European Journal of Sport Science*, *14*(7), 635–642. https://doi.org/10.1080/17461391.2014.884167

Liu, W., & Nigg, B. M. (2000). A mechanical model to determine the influence of masses and mass distribution on the impact force during running. *Journal of Biomechanics*, *33*(2), 219-224. https://doi.org/10.1016/s0021-9290(99)00151-7

Lopes, A. D.; Junior, L. C. H.; Yeung, S. S., & Costa, L. O. P. (2012). What are the main running-related musculoskeletal injuries? *Sports Medicine*, *42*(10), 891-905. https://doi.org/10.1007/bf03262301

McGregor, S. J.; Armstrong, W. J.; Yaggie, J. A.; Parshad, R. D., & Bollt, E. M. (2011). Fatiguing exercise increases complexity of postural control: control entropy of high-resolution accelerometry. *Medicine & Science in Sports & Exercise*, *43*(Suppl 1), 526. https://doi.org/10.1249/01.MSS.0000401451.63095.d3

McLaren, S. J.; Macpherson, T. W.; Coutts, A. J.; Hurst, C.; Spears, I. R., & Weston, M. (2018). The relationships between internal and external measures of training load and intensity in team sports: a meta-analysis. *Sports Medicine*, *48*(3), 641–658. https://doi.org/10.1007/s40279-017-0830-z

Morris, R. G., & Lawson, S. E. M. (2009). A review and evaluation of available gait analysis technologies, and their potential for the measurement of impact transmission. *Newcastle University, UK*, 15.

Nedergaard, N. J.; Robinson, M. A.; Eusterwiemann, E.; Drust, B.; Lisboa, P. J., & Vanrenterghem, J. (2017). The relationship between whole-body external loading and body-worn accelerometry during team-sport movements. *International Journal of Sports Physiology and Performance*, *12*(1), 18–26. https://doi.org/10.1123/ijspp.2015-0712

Nigg, B. M. (2001). The role of impact forces and foot pronation: A new paradigm. *Clinical Journal of Sport Medicine: Official Journal of the Canadian Academy of Sport Medicine*, *11*(1), 2–9.

Oliva-Lozano, J. M.; Rojas-Valverde, D.; Gómez-Carmona, C. D.; Fortes, V., & Pino-Ortega, J. (2020). Impact of contextual variables on the representative external load profile of spanish professional soccer match-play: a full season study. *European Journal of Sport Science*, *Epub: Ahead of Print*, 1–22. https://doi.org/10.1080/17461391.2020.1751305

Pfirrmann, D.; Herbst, M.; Ingelfinger, P.; Simon, P., & Tug, S. (2016). Analysis of injury incidences in male professional adult and elite youth soccer players: a systematic review. *Journal of Athletic Training*, *51*(5), 410–424. https://doi.org/10.4085/1062-6050-51.6.03

Pino-Ortega, J.; Rojas-Valverde, D.; Gómez-Carmona, C. D.; Bastida-Castillo, A.; Hernández-Belmonte, A.; García-Rubio, J.; Nakamura, F. Y., & Ibáñez, S. J. (2019). Impact of contextual factors on external load during a congested-fixture tournament in elite u’18 basketball players. *Frontiers in Psychology*, *10*, 1100. https://doi.org/10.3389/fpsyg.2019.01100

Rojas-Valverde, D.; Sánchez-Ureña, B.; Pino-Ortega, J.; Gómez-Carmona, C.D.; Gutiérrez-Vargas, R.; Timón, R., & Olcina, G. (2019). External workload indicators of muscle and kidney mechanical injury in endurance trail running. *International Journal of Environmental Research and Public Health*, *16*(20), 1–13. https://doi.org/10.3390/ijerph16203909

Rugg, C.; Kadoor, A.; Feeley, B. T., & Pandya, N. K. (2018). The effects of playing multiple high school sports on national basketball association players’ propensity for injury and athletic performance. *The American Journal of Sports Medicine*, *46*(2), 402–408. https://doi.org/10.1177/0363546517738736

Sigward, S. M.; Pollard, C. D.; Havens, K. L., & Powers, C. M. (2012). Influence of sex and maturation on knee mechanics during side-step cutting. *Medicine & Science in Sports & Exercise*, *44*(8), 1497–1503. https://doi.org/10.1249/MSS.0b013e31824e8813

Simons, C., & Bradshaw, E. J. (2016). Reliability of accelerometry to assess impact loads of jumping and landing tasks. *Sports Biomechanics*, *15*(1), 1–10. https://doi.org/10.1080/14763141.2015.1091032

Spriet, L. L. (2014). Exercise and Sport Performance with Low Doses of Caffeine. *Sports Medicine*, *44*(S2), 175–184. https://doi.org/10.1007/s40279-014-0257-8

Suarez-Arrones, L. J.; Nuñez, F. J.; Portillo, J., & Mendez-Villanueva, A. (2012). Running demands and heart rate responses in men rugby sevens. *Journal of Strength and Conditioning Research*, *26*(11), 3155–3159. https://doi.org/10.1519/JSC.0b013e318243fff7

Takeda, R.; Tadano, S.; Todoh, M.; Morikawa, M.; Nakayasu, M., & Yoshinari, S. (2009). Gait analysis using gravitational acceleration measured by wearable sensors. *Journal of Biomechanics*, *42*(3), 223–233. https://doi.org/10.1016/j.jbiomech.2008.10.027

Vanrenterghem, J.; Nedergaard, N. J.; Robinson, M. A., & Drust, B. (2017). Training load monitoring in team sports: a novel framework separating physiological and biomechanical load-adaptation pathways. *Sports Medicine*, *47*(11), 2135–2142. https://doi.org/10.1007/s40279-017-0714-2

Vincent, W. J., & Weir, J. P. (2012). *Statistics in Kinesiology* (4th ed.). Champaign, USA: Human Kinetics.

Wellman, A. D., Coad, S. C., Goulet, G. C., & McLellan, C. P. (2017). Quantification of accelerometer derived impacts associated with competitive games in National Collegiate Athletic Association Division I college football players. *The Journal of Strength & Conditioning Research, 31*(2), 330-338. https://doi.org/10.1519/JSC.0000000000001506

Wu, F.; Zhang, K.; Zhu, M.; Mackintosh, C.; Rice, T.; Gore, C.; Hahn, A., & Holthous, S. (2007). An investigation of an integrated low-cost GPS, INS and magnetometer system for sport applications. In *Proceedings of the 20th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2007)*, pp. 113-120.

Zhang, J. H.; An, W. W.; Au, I. P. H.; Chen, T. L., & Cheung, R. T. H. (2016). Comparison of the correlations between impact loading rates and peak accelerations measured at two different body sites: Intra- and inter-subject analysis. *Gait & Posture*, *46*, 53–56. https://doi.org/10.1016/j.gaitpost.2016.02.002