# Using an Inertial Device (WIMU PRO) to Quantify Neuromuscular Load in Running: Reliability, Convergent Validity, and Influence of Type of Surface and Device Location

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## ABSTRACT

Gómez-Carmona, CD, Bastida-Castillo, A, González-Custodio, A, Olcina, G, and Pino-Ortega, J. Using an inertial device (WIMU PRO) to quantify neuromuscular load in running: reliability, convergent validity, and influence of type of surface and device location. *J Strength Cond Res* XX(X): 000–000, 2019—Currently, the use of accelerometers in sport is increasing, and thus, the devices are required to be valid and reliable. This study tested (a) the reliability and validity of WIMU PRO accelerometers to measure PlayerLoad (PL) and (b) the influence of speed, inertial device location, and type of surface where the incremental test is performed. Twenty resistance-trained men (age: 27.32 ± 6.65 years; height: 1.74 ± 0.03 m; body mass: 68.96 ± 4.37 kg; and body mass index: 22.76 ± 1.11 kg·m$^{-2}$) volunteered to participate in the study that lasted 5 weeks. Four progressive incremental tests were performed in treadmill and athletic track conditions. External load variable (PL) and physiological variables (heart rate [HR] and $SmO_2$) were recorded by 4 WIMU PRO inertial devices (scapulae, center of mass, knee, and ankle), a GARMIN HR band, and a MOXY near-infrared spectroscopy device, respectively. High reliability was found on both types of surface, showing the best values at the ankle (treadmill: intraclass correlation coefficient [ICC] = 0.99, coefficient of variation [CV] = 4.65%; track: ICC = 0.96, CV = 6.54%). A nearly perfect convergent validity was shown with $HR_{AVG}$ ($r$ = 0.99) and a moderate one with $SmO_2$ ($r$ = −0.69). Significant differences in the PL variable between surfaces were reported in all locations except the scapulae ($p$ = 0.173), and the higher values were found on the track. In the analysis per location, the ankle location reported the highest values at all speeds and on the 2 surfaces analyzed. Assessment needs to be individualized, due to the great variability of gait biomechanics among subjects. The accelerometer location should be chosen according to the purpose of the measurement, with the ankle location being recommended for neuromuscular load analysis in running.

**Key Words:** PlayerLoad, accelerometer, testing, heart rate, muscle oxygen saturation

## Introduction

The external load supported by an athlete can be considered as the total locomotor and mechanical stress produced by an activity (7). External load can provide valuable information to coaches and team staff to facilitate subsequent performance enhancement (9) and injury prevention (4,13). Notational and time motion analyses have been the most used methods to measure external load by video analysis or motion capture systems (16). Thanks to advances in applied sports technology, new instruments such as inertial movement units (IMUs) have been developed. These devices include triaxial high-resolution accelerometers (1,000 Hz) that can be used for this purpose. Nowadays, most authors analyze external load, understanding it as the acceleration of human movement in the 3 planes (x-, y-, and z-axes), using triaxial accelerometers (10,18,21) (3). In team sports, the most commonly used accelerometer-derived variable is a vector magnitude called PlayerLoad (PL) that is derived from three-dimensional measures of acceleration rate. It has been used in basketball (31,37), rugby (8,27), and soccer (9,18).

In sport science area, the most studied physiological variables for load quantification have been the heart rate (HR) and the maximum oxygen consumption, finding relationships with fatigue and overtraining (1,17). Currently, muscle oxygen saturation is beginning to be used and has a very good correlation with oxygen consumption (15). Thus, the PL variable, with the same accelerometer model (MinimaXx), has been investigated and compared with different load indicators obtaining: (a) a strong convergent validity with HR and oxygen consumption ($\dot{V}O_2$) (3), (b) a very strong concurrent validity with the force platform (24), (c) a moderate correlation with scale ratings of perceived exertion (10), (d) and a high test-retest and within-between units reliability in sports with continuous (3) and intermittent efforts (7). However, different questions about the PL applications for external load quantification have not yet been resolved.

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One of them refers to accelerometer placement. It is accepted that center of mass (COM) is the valid location to detect global whole-body movements (3,11,37). Barrett et al. (3) demonstrated strong convergent validity and high test-retest reliability when the device is placed at the COM compared with the scapulae. In team sports, scapula placement is admitted for better GPS signal reception (8,9). On the other hand, recent research conducted by Nedergaard et al. (32) reported that a body-worn accelerometer only measures the acceleration of the segment that it is attached to. Thus, it is inadequate to measure the acceleration of the whole body due to the complex multisegment motion occurring during team-sports movements. So, anatomical locations of the device different from COM or scapulae to measure PL have not been investigated in field and laboratory conditions. Also, the influence of type of surface has not been investigated either, so it could be affected by Newton's third law. Thus, accelerometry and PL vector have been extensively studied by researchers, but different influential variables have not been analyzed, and some of them remain unclear.

For these reasons, it is important to control all the variables that can influence the external load monitoring in athletes, at whole body and specific joints through a reliable and valid variable. Therefore, the aims of this research were (a) to establish the test-retest reliability of the triaxial accelerometer data depending on the type of surface and location of the inertial device during an incremental progressive running test, (b) to investigate the convergent validity of PL using heart rate ($HR_{AVG}$) and muscular oxygen saturation ($SmO_2$) as criterion measures of internal load demands, and (c) to examine the effect of accelerometer location and type of surface on PL data at different speeds and in within-between subject comparisons.

## Methods

### Subjects

Twenty resistance-trained men (age: 27.32 ± 6.65 years; height: 1.74 ± 0.03 m; body mass: 68.96 ± 4.37 kg; and body mass index: 22.76 ± 1.11 $kg\cdot m^{-2}$) volunteered to participate in this study. All participants had to meet the following requirements: (a) 2 years of running experience, (b) no physical limitations or musculoskeletal injuries that could affect testing, and (c) >15 $km\cdot h^{-1}$ maximal aerobic speed (MAS: 16.26 ± 1.03 $km\cdot h^{-1}$). Height was measured to the nearest 0.5 cm during a maximal inhalation using a wall-mounted stadiometer (SECA, Hamburg, Germany). Body mass were obtained using an eight-electrode segmental body composition monitor (model BC-601; TANITA, Tokyo, Japan). The study, which was conducted according to the Declaration of Helsinki, was approved by the Bioethics Commission of the University of Murcia (Reg. Code: 2061/2018). Subjects were informed of the risks and discomforts associated with maximal testing and provided written informed consent.

### Experimental Approach to the Problem

The study lasted 5 weeks. In the first week, the familiarization session was performed to acquaint athletes with the experimental equipment and procedures. The anthropometric and physiological assessments were also performed. In the next 4 weeks, an incremental treadmill or track progressive test was administered. All tests were 7 days apart, and all sessions started at the same time to attenuate circadian variation. Participants had to meet the following requirements: (a) suppression of alcohol and caffeine intake during the previous 24 hours and (b) not to perform high-intensity physical activity during the previous 48 hours (6,39). Participants were allowed to practice moderate physical activity between tests to maintain cardiorespiratory, musculoskeletal, and neuromotor fitness (22). The athletes performed the following tests twice:

- Treadmill incremental progressive running test protocol (MASiprTM). The starting speed was 8 $km\cdot h^{-1}$, and the treadmill speed was increased by 0.1 $km\cdot h^{-1}$ every 12 seconds (equivalent to 1 $km\cdot h^{-1}$ increments every 2 minutes). The test ended when the athlete was not able to maintain the speed.
- Athletic track incremental progressive running test protocol (MASiprTF) (modified from Léger and Boucher) (29). This protocol modified the "Université de Montréal track test" (UMTT) because speed increase was progressive. To perform this test, the track was divided into 25-m sections with cones. The starting speed was 8 $km\cdot h^{-1}$. Every 2 minutes, progressive speed increments of 1 $km\cdot h^{-1}$ were applied. An acoustic signal system sounded on the track to ensure that the athletes ran at the appropriate speed. The participants had to match the sound with the passing points delimited by the cones. The protocol finished when the athlete was fatigued or did not match the pace with the sound on 2 consecutive occasions.

Before beginning the protocols, the athletes performed a standardized warm-up of 5-minute aerobic-intensity running (65% HRmax). The warm-up period was monitored in real time with S PRO software to verify the perfect functioning of the devices. When the athletes finished each protocol, they performed 5 minutes of recovery-intensity running (55% HRmax). All variable data were collected throughout the tests and averaged over 1-minute periods.

*Procedures*

***External and internal load variables: Player Load*** This is the vector sum of device accelerations in its 3 axes (vertical, anteroposterior, and lateral). This variable has been used to evaluate neuromuscular load in different athletes (14) and is calculated from the following equation:

$$\text{PlayerLoad} = \frac{\sqrt{(a_{y1} - a_{y-1})^2 + (a_{x1} - a_{x-1})^2 + (a_{z1} - a_{z-1})^2}}{100}.$$

Measurement was recorded using 4 inertial devices called WIMU PRO (RealTrack Systems, Almeria, Spain). Sensory fusion of raw data from the 4 accelerometers that composed each device was used to calculate the PL variable. The full-scale rating of the accelerometers is ±16, ±16, ±32 and ±400 g, respectively. Inertial devices have a sampling frequency of 1,000 Hz, and data were recorded on an internal memory. Data analysis was performed with S PRO software (RealTrack Systems). Devices were located on: (a) scapulae (C6 vertebra), (b) center of mass (COM, L3 vertebra), (c) knee (5 cm above kneecap crack), and (d) ankle (5 cm above lateral malleolus). At the knee and ankle, inertial devices were located on the outside of the right leg in all participants.

Figure 1 shows the protocols used to locate inertial devices on participants: (a) On the scapulae, the device was placed using a specific harness, and (b) remaining devices were placed using an adhesive elastic band. The inertial device distribution and placement in one of the participants are shown in Figure 2.



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**Figure 1.** WIMU PRO inertial devices and MOXY NIRS unit used in this research (A) before placing in the auto-calibration process, (B) scapulae device location with a specific harness and COM unit location using elastic adhesive band, and (C) ankle and knee device location using elastic adhesive band and NIRS unit location using a compression garment. COM = center of mass; NIRS = near-infrared spectroscopy.

Before placement, the inertial devices were calibrated and synchronized. The calibration process of the devices was performed manually according to the manufacturer's recommendations. Throughout this process, static bias of the raw data between inertial devices, obtained through sensorial fusion of accelerometers, was <0.002 G (23). During this process, four 3D accelerometer error sources were eliminated: offset error, scaling error, nonorthogonal error, and random error (42). To synchronize the 4 inertial devices, they were placed in a waterproof housing and then rotated through 360°. With this system, S PRO software automatically synchronized the 4 devices for analysis.

***Heart Rate*** This variable was recorded with a GARMIN HR band (Garmin Ltd., Olathe, KS, USA), which sent data to a WIMU PRO device using Ant + technology with a sampling

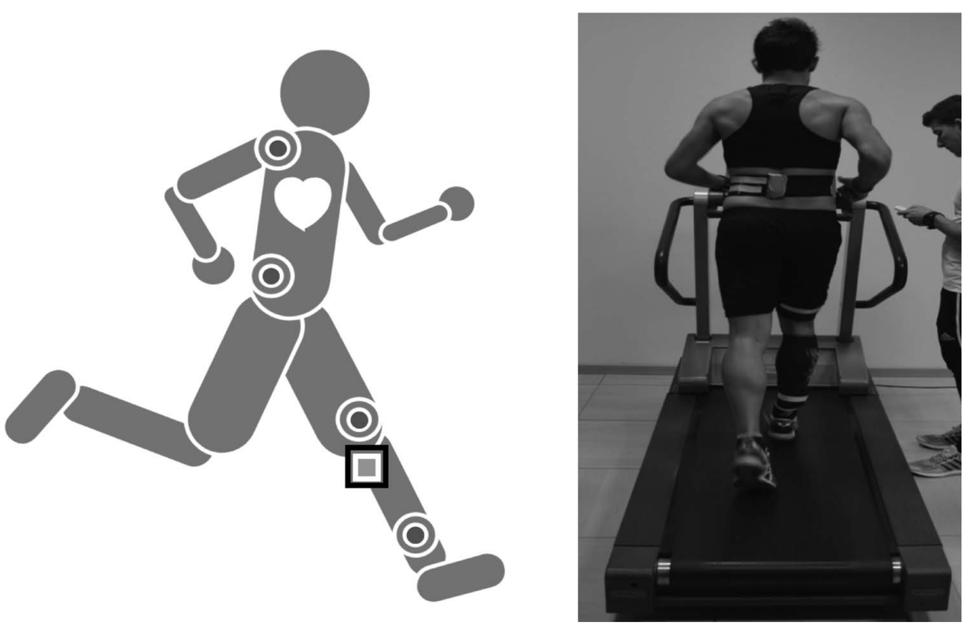

**Figure 2.** Location of WIMU PRO and MOXY NIRS devices on one of the athletes. NIRS = near-infrared spectroscopy.



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frequency of 4 Hz, a process whose validity has been analyzed and detailed previously (30).

***Muscular Oxygen Saturation ($SmO_2$)*** Gastrocnemius $SmO_2$ was measured continuously in real time using a MOXY near-infrared spectroscopy device (MOXY, Hutchinson MN, USA), which automatically calculates the relative concentration of $HbO_2$ in relation to the total amount of hemoglobin (tHb) ($SmO_2 = HbO_2/tHb$), with a sampling frequency of 4 Hz. This technology is used to monitor muscular oxygen saturation in endurance activity (35) and obtained a high reliability between sessions (38). The MOXY was placed on the gastrocnemius belly, leaving the upper edge of the device 10 cm from the popliteal space (38) (Figure 2). The area where the device was going to be located was shaved and wrapped in transparent plastic to eliminate direct contact with skin and sweat, and the device was attached using dark tape to prevent contamination due to ambient light (38,44). During measurement, data were transferred directly using Ant + technology to a WIMU PRO inertial device (5).

### *Statistical Analyses*

Test-retest reliability of PL variables on different types of surfaces at 4 different anatomical locations (scapulae, COM, knee, and ankle) was reported as the intraclass correlation coefficient (ICC; 2-way random model for absolute agreement) and the within-subject coefficient of variation (CV). Vincent's criteria (41) were adopted to interpret the ICC coefficients: $> 0.90$, high; 0.80–0.89, moderate; and $< 0.80$, questionable. Relationships between $HR_{AVG}$, $SmO_2$, and PL to convergent validity analysis and relationship between speed and PL were assessed using Pearson's product-moment correlation ($r$). The magnitude of the correlation coefficients was deemed as trivial ($r^2 < 0.1$), small ($0.1 < r^2 < 0.3$), moderate ($0.3 < r^2 < 0.5$), high ($0.5 < r^2 < 0.7$), very high ($0.7 < r^2 < 0.9$), nearly perfect ($r^2 > 0.9$), and perfect ($r^2 = 1$) (25). The Wilcoxon test was performed to check PL location placement data as a function of the type of surface at different speeds. An analysis between segments was also performed. For this, 3 segments were created to determine the difference in external load among joints: S1 (ankle–knee), S2 (knee–COM), and S3 (COM–scapulae). To complete this analysis, percentage of difference ($\%_{diff}$) and Cohen's $d$ effect size ($d$) were calculated. The following values were used to interpret Cohen's $d$ (25): 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). Finally, the cause-effect relation in PL among locations of the inertial devices was determined using linear regression. Analyses were completed using IBM SPSS Statistics (release 24.0; SPSS Inc., Armonk, NY, USA), and figures were designed using GraphPad Prism (release 7; GraphPad Software, La Jolla CA, USA). Two-tailed statistical significance was accepted as $p \leq 0.05$.

## Results

### *Descriptive and Reliability Analysis*

A descriptive analysis of PL variable as a function of speed, anatomical location and type of surface is shown in Table 1. With respect to the device location, the highest values were found at the ankle and the lowest values at the scapulae locations. With regard to type of surface, higher values were found on the track in all unit placements. PL showed high reliability between treadmill and track trials at all anatomical locations, but questionable reliability of PL was demonstrated between treadmill and track conditions (Table 2).

**Table 1**

**Mean ± *SD* and 95% CIs (in parentheses) in PlayerLoad variable in function of location placement of triaxial accelerometer and between treadmill and athletic track conditions at 8–16 km·h$^{-1}$ in all participants.***

| | PlayerLoad | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Speed (km·h$^{-1}$) | Treadmill | | | | Athletic track | | | |
| | Ankle | Knee | COM | Scapulae | Ankle | Knee | COM | Scapulae |
| 8 | 7.95 ± 0.68 (6.85–8.95) | 7.66 ± 0.94 (6.04–8.43) | 4.61 ± 0.98 (3.46–5.85) | 4.34 ± 0.45 (3.81–4.84) | 8.71 ± 0.68 (7.81–9.65) | 8.04 ± 0.83 (7.14–9.67) | 5.05 ± 0.58 (4.26–6.21) | 4.34 ± 0.53 (3.67–5.20) |
| 9 | 9.28 ± 0.74 (8.08–10.37) | 8.63 ± 0.96 (7.39–9.74) | 5.13 ± 1.03 (3.93–6.49) | 4.84 ± 0.55 (4.25–5.50) | 10.43 ± 0.83 (9.25–11.53) | 9.30 ± 0.90 (8.48–10.86) | 5.60 ± 0.70 (4.76–6.90) | 4.98 ± 0.63 (4.11–5.85) |
| 10 | 10.43 ± 0.87 (9.13–11.72) | 9.97 ± 0.98 (8.44–11.07) | 5.64 ± 1.05 (4.41–6.96) | 5.26 ± 0.52 (4.68–5.95) | 12.15 ± 0.95 (10.75–13.46) | 10.61 ± 1.15 (9.52–12.55) | 6.21 ± 0.82 (5.26–7.54) | 5.43 ± 0.65 (4.56–6.35) |
| 11 | 11.44 ± 0.96 (10.03–12.91) | 10.93 ± 1.13 (9.27–12.28) | 6.03 ± 1.10 (4.72–7.27) | 5.57 ± 0.53 (4.89–6.31) | 14.12 ± 1.03 (12.68–15.52) | 12.28 ± 1.25 (10.96–14.18) | 6.97 ± 1.01 (5.75–8.32) | 5.89 ± 0.68 (4.92–6.75) |
| 12 | 12.86 ± 0.99 (11.41–14.33) | 12.08 ± 1.25 (10.33–13.66) | 6.37 ± 1.12 (5.09–7.61) | 5.78 ± 0.58 (5.09–6.56) | 16.27 ± 1.13 (14.31–17.91) | 13.66 ± 1.50 (12.10–15.97) | 7.64 ± 1.18 (6.16–9.06) | 6.20 ± 0.73 (5.21–7.19) |
| 13 | 14.21 ± 1.09 (12.53–15.92) | 13.09 ± 1.38 (10.98–14.79) | 6.79 ± 1.15 (5.41–8.01) | 6.19 ± 0.60 (5.46–6.91) | 18.29 ± 1.20 (16.53–19.98) | 14.99 ± 1.63 (13.34–17.36) | 8.23 ± 1.38 (6.60–9.93) | 6.52 ± 0.74 (5.55–7.59) |
| 14 | 15.52 ± 1.21 (13.54–17.37) | 14.22 ± 1.53 (11.59–16.16) | 7.03 ± 1.09 (5.77–8.55) | 6.54 ± 0.61 (5.88–7.22) | 20.12 ± 1.25 (18.22–22.16) | 16.43 ± 1.83 (14.53–19.15) | 8.95 ± 1.53 (7.05–10.62) | 7.02 ± 0.76 (5.95–8.17) |
| 15 | 17.27 ± 1.24 (15.31–19.11) | 15.45 ± 1.60 (12.63–17.54) | 7.55 ± 1.08 (6.30–9.00) | 7.06 ± 0.63 (6.30–7.77) | 22.14 ± 1.41 (20.19–24.09) | 18.06 ± 2.08 (15.87–21.03) | 9.66 ± 1.68 (7.59–11.45) | 7.45 ± 0.80 (6.35–8.58) |
| 16 | 18.45 ± 1.37 (16.36–20.09) | 16.57 ± 1.66 (13.99–18.57) | 7.98 ± 1.12 (6.61–9.48) | 7.42 ± 0.67 (6.62–8.43) | 24.12 ± 1.56 (21.87–26.33) | 19.22 ± 2.23 (16.49–22.55) | 10.17 ± 1.78 (8.14–12.33) | 7.86 ± 0.83 (6.64–9.48) |
| Total | 117.23 ± 8.05 (106.23–127.86) | 108.52 ± 6.26 (102.10–115.74) | 56.71 ± 4.57 (51.75–61.43) | 52.54 ± 3.01 (48.99–8.95) | 146.26 ± 9.13 (135.87–157.81) | 122.42 ± 7.49 (113.33–132.91) | 68.32 ± 5.18 (62.65–73.77) | 55.42 ± 3.70 (51.80–59.23) |

*CI = confidence interval; COM = center of mass.



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**Table 2**
**Test-retest reliability statistics through ICC with 95% CI (in parentheses) and percentage of CV for triaxial accelerometer data collected at ankle, knee, COM, and scapulae during incremental treadmill and track conditions running test at speeds between 8 and 16 km·h$^{-1}$.***

| | Anatomical location | Treadmill (T1 vs. T2) | Athletic track (T1 vs. T2) | Treadmill vs. athletic track (T1 + T2 vs. T1 + T2) |
|---|---|---|---|---|
| ICC | Ankle | 0.99 (1.00–0.98) | 0.96 (0.98–0.95) | 0.75 (0.80–0.65) |
| | Knee | 0.98 (0.99–0.97) | 0.93 (0.96–0.91) | 0.70 (0.76–0.64) |
| | COM | 0.97 (0.99–0.95) | 0.90 (0.93–0.87) | 0.22 (0.35–0.12) |
| | Scapulae | 0.93 (0.96–0.91) | 0.88 (0.91–0.85) | 0.66 (0.72–0.60) |
| CV (%) | Ankle | 4.65 | 6.54 | 13.69 |
| | Knee | 4.92 | 7.01 | 14.07 |
| | COM | 5.37 | 8.12 | 21.21 |
| | Scapulae | 3.52 | 6.57 | 9.70 |

*ICC = intraclass correlation coefficient; CI = confidence interval; CV = coefficient of variation; COM = center of mass; T1 = trial 1; T2 = trial 2.

### Convergent Validity

The within-subject and between-subject relationships as a function of inertial device location and type of surface among internal load ($HR_{AVG}$ and $SmO_2$) and external load variables (PL) are shown in Table 3. The strongest correlations were found at the ankle between $HR_{AVG}$ and $SmO_2$. If the accelerometer location was higher, the correlation between physiological and kinematic variables decreased. Better relations were reported on the treadmill than the track. Finally, between-subject internal and external load variable relationships were weaker than the within-subject relationships, at all anatomical locations and type of surface.

### Type of Surface

Statistical differences in PL variables were reported between treadmill and track trials at all anatomical locations except the scapulae ($p = 0.173$) (Figure 3). Treadmill PL was lower than track at all anatomical locations. Besides, significant differences across the whole range of speeds were only found at the ankle location in between-surface comparison. At all other locations, statistical differences were obtained at higher speeds.

### Location of Accelerometer

A Spearman correlation was performed between PL variables at all anatomical locations and types of surface in relation to speed. A directly proportional relationship was obtained ($p < 0.001$) on the treadmill (ankle: $r = 0.86$; knee: $r = 0.75$; COM: $r = 0.43$; and scapulae: $r = 0.64$) and on the athletic track (ankle: $r = 0.91$; knee: $r = 0.77$; COM: $r = 0.57$; and scapulae: $r = 0.61$).

Figure 4 presents the differences between anatomical locations in treadmill and track conditions. As a function of device placement, 3 segments were created to determine the difference in impact between joints: (S1) ankle–knee, (S2) knee–COM, and (S3) COM–scapulae. The highest differences were obtained on both surfaces in S2 (treadmill: $\%_{diff} = 47.30\%$, $d = 1.18$ and track: $\%_{diff} = 43.94\%$, $d = 2.24$; $p < 0.001$). In the rest of the segments analyzed (S1 and S3), differences were greater on the track (S1: $\%_{diff} = 15.81\%$, $d = 0.97$ and S3: $\%_{diff} = 18.53\%$, $d = 0.73$; $p < 0.001$) than the treadmill (S1: $\%_{diff} = 7.19\%$, $d = 0.25$ and S3: $\%_{diff} = 7.49\%$, $d = 0.27$; $p < 0.001$). Besides, a large *SD* in the percentage of difference was shown. Finally, differences were found in between-surface comparison in each segment in S1 ($d = 0.75$; $p < 0.001$) and S3 ($d = 0.57$; $p < 0.001$), but no differences were found in S2 ($d = 0.08$; $p = 0.498$).

### Relationship Between Inertial Device Location Accelerations

A between-subject and within-subject linear regression in PlayerLoad was performed at different anatomical locations on the treadmill and track (Table 4). In between-subject regression, a moderate relationship was found among anatomical locations in treadmill ($r = 0.45$–$0.77$; $p < 0.001$) and track conditions ($r = 0.23$–$0.77$; $p < 0.001$). On the other hand, there was a nearly perfect correlation between all anatomical locations in within-subject comparison ($r > 0.990$; $p < 0.001$). Besides, a high correlation between scapulae and COM (upper body movement) and a very high correlation between ankle and knee (lower body movement) were reported on both types of surface.

## Discussion

To the best of our knowledge, this is the first investigation to measure PL on 2 different types of surface with external load

**Table 3**
**Between- and within-subject Spearman correlation coefficients for PlayerLoad and $HR_{AVG}$ and PlayerLoad and $SmO_2$ recorded during an incremental progressive running test in treadmill and athletic track conditions at speeds between 8 and 16 km·h$^{-1}$.***

| | | Between-subject correlation | | Within-subject correlation | |
|---|---|---|---|---|---|
| Type of surface | Accelerometer placement | $HR_{AVG}$ | $SmO_2$ | $HR_{AVG}$ | $SmO_2$ |
| Athletic track | Ankle | 0.73† | −0.04 | 0.99† | −0.60† |
| | Knee | 0.57† | −0.21† | 0.99† | −0.61† |
| | COM | 0.39† | −0.30† | 0.99† | −0.60† |
| | Scapulae | 0.29† | −0.23† | 0.99† | −0.59† |
| Treadmill | Ankle | 0.57† | −0.16 | 0.99† | −0.77† |
| | Knee | 0.55† | −0.06 | 0.99† | −0.79† |
| | COM | 0.18 | −0.28† | 0.99† | −0.77† |
| | Scapulae | 0.39 | −0.08 | 0.99† | −0.77† |

*COM = center of mass; $HR_{AVG}$ = heart rate average; $SmO_2$ = muscle oxygen saturation.
†Significant correlations ($p < 0.05$).



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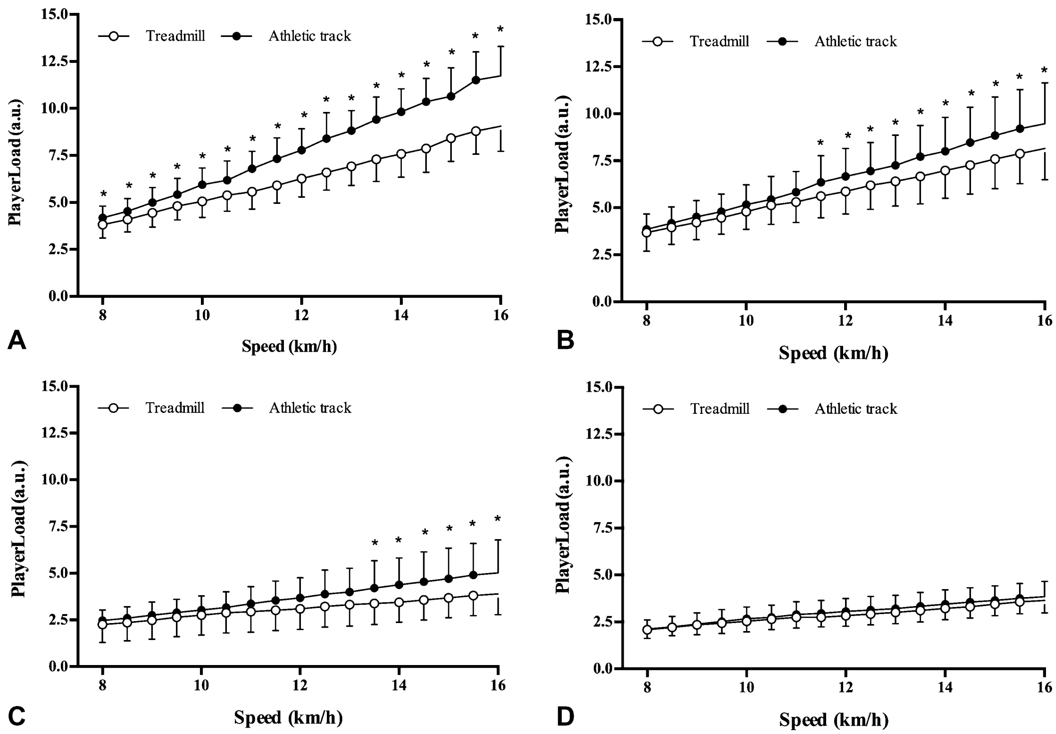


**Figure 3.** Dispersion plot with *SD*s and difference of means between treadmill and track conditions in PlayerLoad at 8–16 km·h$^{-1}$ as a function of anatomical location of accelerometers: (A) ankle, (B) knee, (C) center of mass, and (D) scapulae. *Significant differences between treadmill and track ($p < 0.05$).

monitoring using inertial device accelerometers at different anatomical locations (ankle, knee, COM, and scapulae) and internal load monitoring by physiological variables ($HR_{AVG}$ and $SmO_2$) during an incremental progressive test. The objectives of this research were (a) to check the convergent validity of PL vector at different locations for measuring external load, (b) to evaluate the test-retest and within-between unit reliability, and (c) to analyze the differences according to anatomical location and type of surface where the incremental running tests were performed.

The main highlight of this study is the strong and moderate within-subject correlation between PL and $HR_{AVG}$ ($r = 0.99$) and $SmO_2$ ($r = -0.69$), respectively. It suggests that the PL vector is an acceptable index for monitoring external load during linear running. These results agree with those of Barrett et al. (3) who reported a strong relationship with $HR_{AVG}$ ($r = 0.980$; $p < 0.01$) and $\dot{V}O_2max$ ($r = 0.960$; $p < 0.01$) in within-subject comparison. However, when a between-subject analysis was performed, only the ankle and knee reported moderate correlations with $HR_{AVG}$ (ankle: $r = 0.546$; knee: $r = 0.732$) and low ones with $SmO_2$ (ankle: $r = -0.044$; knee: $r = -0.296$). The correlation differences between internal load variables and PL in between- and within-subject comparisons could be due to individual running kinematics (which affects PL) (12,33), athletes' running economy/efficiency (which affects internal load) (28,34), and physical conditioning (40). For this reason, the within-subject method of establishing the convergent validity of PL is more appropriate, and PL can only be used in between-subject comparisons for external load quantification. Between-subject relationships among physiological variables ($HR_{AVG}$ and $SmO_2$) and PL also confirmed athlete variability.

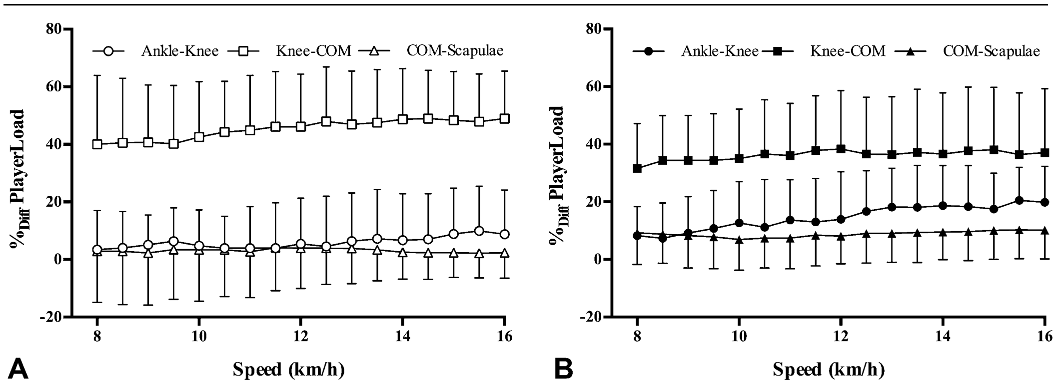


**Figure 4.** Dispersion plot with *SD*s in percentage of difference in PlayerLoad variable between joints at 8–16 km·h$^{-1}$ in the 2 types of surface analyzed: (A) treadmill and (B) athletic track.



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**Table 4**

**Between- and within-subject linear regression in function of accelerometer location for PlayerLoad.***

| | PlayerLoad | | |
|---|---|---|---|
| | Scapulae | COM | Knee |
| Between-subject regression | | | |
| Athletic track | | | |
| Scapulae | | | |
| COM | 0.66 | | |
| Knee | 0.58 | 0.23 | |
| Ankle | 0.51 | 0.34 | 0.77 |
| Treadmill | | | |
| Scapulae | | | |
| COM | 0.53 | | |
| Knee | 0.64 | 0.45 | |
| Ankle | 0.75 | 0.50 | 0.77 |
| Within-subject regression | | | |
| Athletic track | | | |
| Scapulae | | | |
| COM | 0.95 | | |
| Knee | 0.96 | 0.98 | |
| Ankle | 0.96 | 0.97 | 0.98 |
| Treadmill | | | |
| Scapulae | | | |
| COM | 0.97 | | |
| Knee | 0.98 | 0.98 | |
| Ankle | 0.97 | 0.96 | 0.99 |

*COM = center of mass.

PL vector magnitude reported high test-retest reliability at all accelerometer placements on the treadmill (ICC = 0.93–0.99; CV = 3.52–5.37%), moderate to high reliability on the track (ICC = 0.88–0.96; CV = 6.54–8.12%), and questionable reliability between treadmill and athletic track (ICC = 0.22–0.75; CV = 9.70–21.21%). In terms of reliability, the data obtained in this study corroborate high reliability, which was also found in other studies in laboratory contexts (3,32), and in practical sport contexts (2,7). Although the within-unit reliability was high in treadmill tests (3), the between-unit reliability has only been studied under highly controlled laboratory conditions (7). In this investigation, for the first time, a moderate-to-high between-unit reliability was verified in both laboratory and field conditions. This reliability is enough to measure acceleration in team sports and suggests that calibration of device sensors before the assessment may allow each player to use a different device. But, the data between types of surfaces cannot be extrapolated because a modification in gait biomechanics is produced (43). For this reason, conditioning coaches must be caution to interpret the external load profile obtained by the present protocol between different types of surfaces.

In relation to the reliability results, the highest ICC (0.93–0.98) was at the ankle, but the scapulae recorded the lowest CV (3.52–9.68%). Raper et al. (36) found that the tibia is a valid and reliable location for the external load monitoring of the lower limb. Conversely, Zhang et al. (45) compared the acceleration recorded in the tibia and ankle. The results revealed that the ankle location obtained better correlations than the tibia to measure ground reaction forces. Thus, the ankle location could be the more suitable option for external load monitoring by accelerometers during running, showing greater reliability and better sensitivity in relation to COM or the scapulae, due to the distance from the ground-to-ground contact.

In the type of surface comparison, significantly higher values have been reported in PL at all anatomical locations when the athlete performed the test on a track compared with on a treadmill, except at the scapulae ($p = 0.173$). For both conditions, to be compared fairly, the treadmill was maintained with a 1% incline during the test (26). The largest and statistically significant differences in an analysis every 0.5 $km \cdot h^{-1}$ were observed when the device was located at the ankle. As the reliability results showed previously, the accelerometer signal will have greater sensitivity to detect these changes in this location. Besides, the highest correlations between speed and PL were found at the ankle location in both surfaces (treadmill: $r = 0.858$; track: $r = 0.910$). Thus, the type of surface (19) and modified gait biomechanics (43) provoked differences in external load (PL), with the ankle being considered as the most valid option to detect them. Accordingly, from the results obtained, treadmill running is recommended as a one of the first steps in return-to-play process due to the lesser impact than the track.

In relation to the external load measured in the different segments, an analysis was performed to detect differences between locations and to observe the external load absorption dynamics of the human body's musculoskeletal structure during the activity (Figure 4). The S2 (knee–COM) obtained the highest percentage of difference on the treadmill and track. Besides, segment 1 (ankle–knee) and segment 3 (COM–scapulae) showed a higher percentage of difference on the athletic track than the treadmill with a moderate effect size (S1: $d = 0.75$; S3: $d = 0.57$; $p < 0.001$). To the best of our knowledge, this analysis has not yet been performed in the sport science area, and the comparison of the present results is difficult. In reference to the difference between knee and COM impact, we could suppose that it is produced by lower limb and trunk musculature work. Thus, if 90% of muscular injuries in soccer occur in the knee-COM segment (20), the high absorption or incorrect absorption of impacts could be considered as one of their causes. Finally, the greater PL percentage of difference and effect size in segments 1 and 3 on the track maybe is produced by a harder surface and a difference in gait biomechanics. Research on the absorption dynamics of external forces by the musculoskeletal structure during running could provide very important information to strength and conditioning trainers in the readaptation and injury prevention process, opening up a new research area for sport science investigators.

Finally, moderate correlations in between-subject analysis were obtained in treadmill and track conditions ($r^2 = 0.23–0.77$). By contrast, the intrasubject relationship at all accelerometer locations showed very high correlations ($r^2 > 0.99$; $p < 0.001$), identified by an individualize pattern of gait biomechanics. This fact has only been analyzed in the research by Nedergaard et al. (32), where a between-subject analysis focusing on the relation of the acceleration of the COM with the rest of the body segments was performed showing a low correlation. Thus, this research concluded that it is complex to measure the acceleration of the whole body by multisegment movements during sports actions, unlike the cyclic movement pattern during running analyzed in this study.

Although the results of this study have provided information regarding validity and reliability of PL to monitoring external load and the influence of surface and anatomical location, some limitations of this study should be considered when interpreting the findings. Firstly, the number of participants is small ($n = 20$), so that could influence the statistical power of results. Secondly, we must bear in mind that these statements can only be extrapolated to the performance of the cyclical exercise of running and not to sports actions in competition. Finally, only 4 IMUs at a specific sampling rate were tested. Both the sensor components within the IMU, the calibration of the sensors, and the sampling rate could have an effect on the results. All processes were performed following the manufacturer's recommendations.



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In conclusion, PL was confirmed to be a valid method for external load monitoring due to the high correlations with internal load indicators (HR and $SmO_2$). Very good interunit reliability and moderate-to-high test-retest reliability of PL vector seem to be confirmed in field and laboratory conditions, but PL data cannot be extrapolated between surfaces. In addition, the findings showed that a closer distance from the device to ground contact, a harder surface and a faster displacement speed provoked higher PL values. Finally, the greatest differences between locations in PL were found in segment 2 (knee-COM), where a change of lower limb and trunk musculature work was observed.

## Practical Applications

For conditioning coach, movement demands in athletes should be regularly monitored, as they may significantly relate to player injury risk. The specific considerations analyzed in this study provide initial guidelines for the use of PL in external load monitoring. In relation to the advice that the accelerometer must be placed according to the measuring aim, it is recommended to locate it at the ankle as seems to be the location most suitable to detect impact forces, type of surface, gait biomechanics, and work load of the lower body in running, due to the lesser distance from the ground-to-ground contact. On the other hand, to understand load analysis through PL, within-subject analysis is recommended due to the great between-subject variability reported, produced by an individualize movement pattern.

Future researches could use the designed protocol in the present research to identify the musculoskeletal absorption dynamics of external load in the participants, at joints and body segments, and use this information to design specific strength and conditioning programs to improve sport performance and reduce injury risk.

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The last author of this article is a Sport Science advisor in the company that develops the inertial device mentioned. To guarantee the objectivity of the results, this author has no contributed to data analysis and results section. This author participated significantly in the other parts of the article without having access to the data set or data analysis. This article is original and not previously published, nor is it being considered elsewhere until a decision is made as to its acceptability by the JSCR Editorial Review Board.

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