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A size-adjustable instrumented track to measure vertical ground reaction forces: a validation study

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Abstract— Force plates are widely used in sport sciences to measure ground reaction forces. However, their use in ecological conditions is limited by their restricted recording measurement area. Recently, a size-adjustable track instrumented with force sensors has been developed to measure vertical ground reaction forces (vGRF) over large perimeters. The aim of this study was to evaluate accuracy and repeatability of this instrumented track (IT). The evaluation was conducted through a two-step protocol: (i) a static protocol assessing the accuracy and repeatability of force sensors composing the IT, and (ii) an ecological protocol aiming to assess values obtained while running on both a reference force plate and a three-sensor IT configuration. Results from the static protocol demonstrated an excellent agreement between the reference force sensor and the IT sensors ($p < 0.001$, $ICC_{(3,1)} > 0.99$). Force measured from the IT sensors showed a high accuracy with an average bias of 1.27 N, corresponding to a ratio limit of agreement of 0.3%, and a repeatability error within 2 N. For the ecological protocol, there was also an excellent correlation between the vGRF running parameters measured by the reference force plate, and the IT ($p < 0.001$, $ICC_{(3,1)} > 0.98$), reinforced high accuracy results. Moreover, a ‘Minimal Detectable Changes’ analysis indicated that IT can accurately quantify all run ning patterns. This study demonstrated that force sensors integrated into the IT may be used to assess running patterns over a large area, expanding the scope of dynamic analysis in various applications.

Key words— Force sensors, Instrumented track, Ground Reaction Force, Accuracy, Repeatability

1. Introduction

In sports sciences, both kinematic and kinetic analyses are necessary to understand athletes’ performances and to quantify risk of injury. Various tools such as optoelectronic systems, inertial measurement units and markerless technologies are commonly used for kinematic analysis in both laboratory and *in situ* applications. However, for kinetic analysis, different tools may be required depending on the forces applied during the movement. For example, instrumented pedals have been developed to measure the forces applied by cyclists [1], instrumented paddles have been used for kayakers [2] and implemented holds have been designed to study climbing performance [3].

In sport involving locomotion, Ground Reaction Forces (GRF) are key metrics for understanding human movement. These force data have been widely used in clinical studies to investigate pathologies [4], [5], complex gait phenomena [6] and also in sports studies to assess performance [7], fatigue [8] and the effects of environmental parameters [9], [10], [11]. In gait analysis, the vertical component of GRF (vGRF) typically consists of a first peak corresponding to landing and a second peak during the propulsion phase [12].

Additional variables such as first impact peak, second peak or Loading Rate (LR) have been defined as critical indicators for quantifying GRF patterns [13].

GRF have usually been obtained using force plates, which are considered the gold standard devices for GRF measurement. The general objective of these force plates is to convert a mechanical stress into an electrical signal. Several methods exist to measure forces from a force plate, but the most widely used method involves strain gauge deformation [14]. Strain gauges, generally arranged in a Wheatstone bridge configuration, deform proportionally to the applied forces [15]. Force measurements are then obtained from the electrical signals transmitted by the strain gauges, which are then converted into digital signals [16].

Studying GRF during locomotion tasks like running may appear challenging due to the difficulty of measurement over a wide area. The size associated with common force plates constrains measurement to limited areas and only allows for the study of few steps. In addition, using a single force plate could also alter participant's natural locomotion due to the necessity of precisely aiming for the force plate. To enhance the recording area, some researchers have placed reference force plates side by side, allowing the measurement of multiple steps. For instance, Nagahara and colleagues used fifty force plates to record GRF over a 50-meter distance for sprint performance studies [7], [17]. However, this setup is rarely used due to the high cost of each force plate. Other studies used force plates on an athletic track in order to measure GRF at each lap and permit to quantify running mechanics changes along 800m or 5000m trials [8], [18].

Alternatively, some tools have been developed to allow GRF measurement directly in the field, such as instrumented studs for football and rugby players [19], or an instrumented treadmill for a multiple step analysis [20]. However, these devices are not adapted for the measurement of GRF in typical condition like walking and running on a flat ground. Other studies predicted GRF from embedded sensors like inertial movement units [21], [22] or pressure insoles [23], [24].

Nevertheless, these devices do not correspond to a direct measurement, representing a risk for data accuracy and repeatability. Thus, measuring GRF over a large area *in situ* remains a significant challenge for sports studies. Developing a size-adjustable force plate could be an interesting solution to measure GRF during the practice of running without limits of recording area. This innovative device could be easily transposed out of the lab to overcome the lack of ecological data support. Moreover, this disposal appears less invasive compared to other embedded sensors dedicated to motion characterization, e.g. inertial measurement units, electromyographic sensors, optoelectronic markers.

However, developing this type of innovative device requires validation studies against gold standard measurement to evaluate their accuracy and repeatability. Most studies comparing a new device disposal with a reference force plate have superimposed them [25], [26], [27]. Due to complexity of superimposing a reference force plate on an instrumented treadmill, Kluitenberg et al., (2012) compared mean GRF variables between the two devices at different paces. All these validation studies used statistical methods, such as Bland-Altman plots and intra-class correlation coefficients, to assess agreement between the devices.

The aim of this study was thus to assess validity of a size-adjustable instrumented track (IT) for measuring vGRF. Validation was conducted through a two-step protocol: (i) a static protocol to evaluate the accuracy and repeatability of the vertical sensors composing the IT, and (ii) an ecological protocol where a three-sensor configuration of IT was compared to a gold standard force plate fixed in the ground during running movements.

2. Methods

In this section, a size-adjustable IT of interest will be presented, and both the static and ecological protocols will be detailed.

2.1 Instruments

The size-adjustable IT (INSTRACK, Phyling, France) used in this study is composed of uniaxial vertical force sensors and equilateral wooden triangles with a side length of 60 cm. Sensors are mounted on a rigid structure, and the triangles are placed on each sensor at their vertices. A single sensor can support between two and six triangle vertices (Figure 1). This configuration allows for the measurement of vGRF even if the foot makes contact across two support triangles. The number of sensors and their configuration can be modified depending on the desired application.

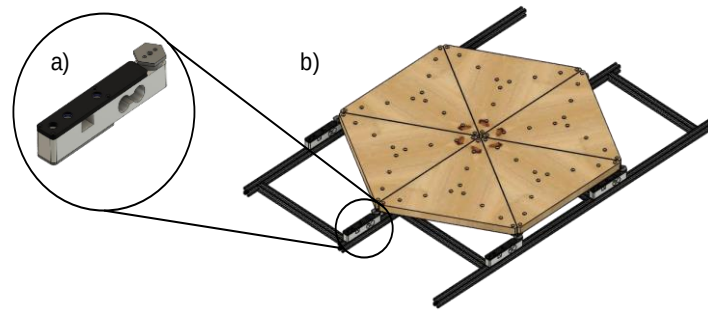


Figure 1: Size-adjustable IT illustration. a) Uniaxial vertical force sensor b) Seven-sensor configuration of the IT

Each sensor is equipped with four strain gauges arranged in full Wheatstone bridges, which convert the applied force into a voltage signal. This voltage signal is then digitized and collected by an acquisition unit (Maxi-Phyling, Palaiseau, France). Force values of each sensor are obtained by applying calibration coefficients to the raw data. These calibration coefficients are determined using a standardized calibration protocol: a calibration bench (Figure 2) is used to apply static forces ranging from 0 to 1500 N along the vertical axis. These values correspond to the range of forces measured during running activities [17]. Force is applied to both a reference sensor (SM5424, Sensel Measurement, Vincennes, France) and the uni-axial force sensor using a pressure screw. Linear regression was performed to obtain specific sensor calibration coefficients for each sensor. Total force applied on the IT is then obtained by zeroing and summing the forces recorded by all sensors.

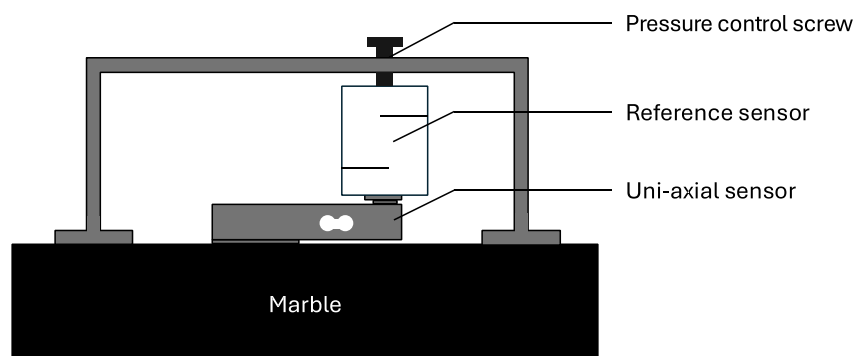


Figure 2: Calibration bench used to calibrate uni-axial sensor

To assess the validity of this size-adjustable IT, a static protocol was first conducted on each sensor separately to evaluate their accuracy and repeatability. Subsequently, an ecological approach was applied to test the IT during running movements. For this protocol, a three-sensor configuration of the IT was selected to allow straightforward comparison with a reference force plate positioned below the IT.

2.2 Static protocol

The accuracy and repeatability of the vertical force measured by the uniaxial sensors were assessed using a reference sensor (RS). The calibration setup was employed for this experiment to apply controlled forces over a wide range of values (Figure 2). Levels of forces were applied by using a pressure control screw on the vertical axis. This screw did not permit exact force values between trials. Consequently, results will be analyzed in terms of ranges of values: 0–200 N, 300–500 N, 800–1000 N, 1300–1500 N, and 1800–2000 N.

The RS was a single-axis force sensor (SM5424, Sensel Measurement, Vincennes, France). RS features a broad measurement range of up to 1000 daN with a manufacturer-stated accuracy of 0.1%. Ten uniaxial sensors were assessed five times for each range of force, typically corresponding to vGRF during running exercise [18]. The data acquisition frequency was set to 1000 Hz for both the uni-axial sensors and the RS, with 1000 data points collected for each force level. This sampling frequency is chosen to reproduce those used for measuring GRF in running activity.

Data analysis was performed using Python (3.9). Data were filtered with a low-pass Butterworth filter (40 Hz cut-off, second-order) for both uniaxial sensors and RS. Accuracy and repeatability were assessed based on the definitions provided by Bartlett et al., 2014. Accuracy was defined as the absolute measurement error, calculated by subtracting the reference value from the measurement value. Mean sensor accuracy was obtained by averaging the measurement error for the same force level (Equation 1). Repeatability reflects the device's ability to produce consistent measurements for the same input and is calculated as twice the standard deviation of the measurement data across repetitions for the same force level. Due to the inability to apply identical inputs forces, repeatability was calculated as twice the standard deviation of the measurement error for each range of forces tested. The mean sensor repeatability is determined by averaging the repeatability values at each force level (Equation 2).

$$Accuracy = \frac{1}{m} \sum_j \frac{1}{n} \sum_i |x_{ref_{i,j}} - x_{sensor_{i,j}}| \quad (1)$$

$$Repeatability = \frac{1}{n} \sum_i (2std(x_{sensor_i})) \quad (2)$$

Where n is the number of force levels, m is the number of repetitions and $x_{sensor_i} = [x_{sensor_{i,1}}, \dots, x_{sensor_{i,m}}]$ is the vector of sensor measurement data for all m repetitions at the force level i .

2.3 Ecological protocol

One participant (25 years old, 176 cm, 68 kg) was instructed to run at a self-selected velocity and to land with his right foot on the superimposed force plates over 50 steps. The variability between steps allowed for the assessment of mean differences across a broad range of values. vGRF data from IT were compared to data from a reference force plate (RFP) (AMTI OR6-6-1000, Watertown, MA, USA). A three-sensor configuration was used and mounted onto the RFP (Figure 3). Both the IT and RFP were sampled at 1000 Hz, focusing exclusively on the vertical force component.

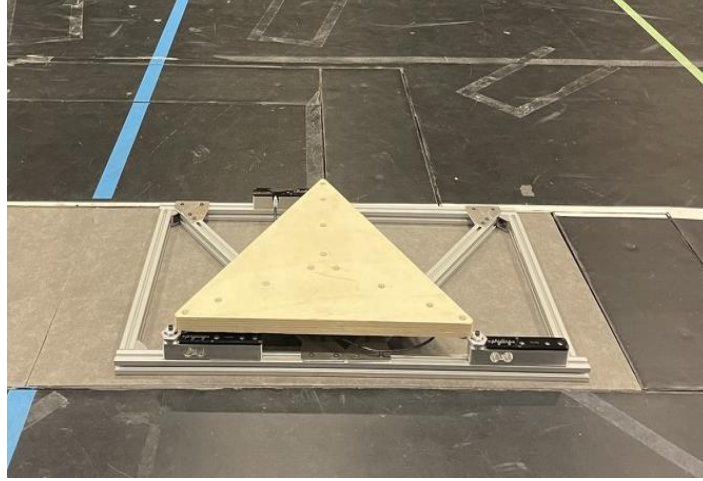


Figure 3: Instrumented Track fixed on the reference force plate during the ecological protocol.

Data analysis was performed using Python (3.9). Data were filtered with a low-pass Butterworth filter (40 Hz cut-off, second-order) for both IT and RFP. The beginning of a step was defined as the moment when the vGRF exceeded 20N [13], [29]. Running gait parameters were calculated for each step based on the description presented in Figure 4.

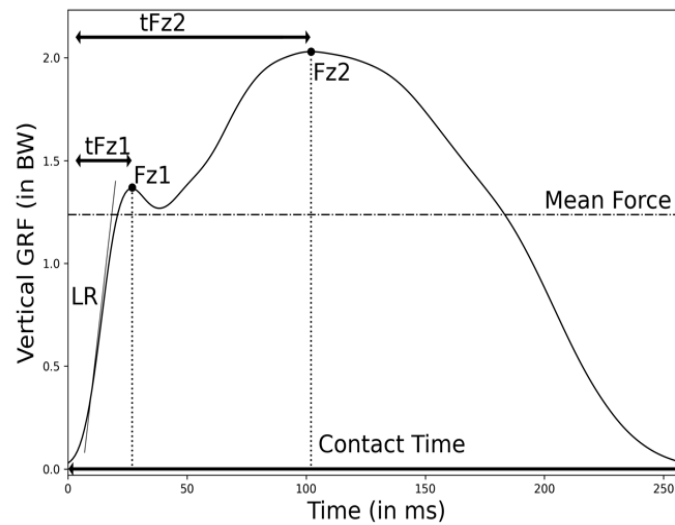


Figure 4: Biomechanical parameters extracted from a vGRF running pattern. Fz1: First peak of vGRF, in body weight (BW); tFz1: Time from footstrike to Fz1, in ms; Fz2: Second peak of vGRF, in BW; tFz2: Time from footstrike to Fz2, in ms; Mean Force: Mean force, in BW; LR: Maximal value of the derivative of GRF, in BW/s; contact time (CT): Time from footstrike to toe-off, in ms.

2.4 Statistical analysis

All data and statistical analysis were performed using Python (Python 3.9, Python Software Foundation, <https://www.python.org/>). A two-way mixed model intraclass correlation coefficient ($ICC_{(3,1)}$) and the corresponding 95% confidence interval were calculated for each parameter in this study, including force level measurements during the static protocol, and running gait parameters during the ecological protocol. ICC values were interpreted as follows: values less than 0.5 were indicative of poor reliability, values between 0.5

and 0.75 indicated moderate reliability, values between 0.75 and 0.9 indicated good reliability, and values greater than 0.90 referred to an excellent reliability [30]. Bland-Altman plots were used to assess agreement between measurement values and reference values [31]. Bias, limit of agreement (LOA), and ratio limits of agreement (RLOA) were calculated as follows: bias was determined as the mean difference between two measurements; LOA were calculated as ± 1.96 times the standard deviation of the mean difference between two measurements; and RLOA was expressed as LOA as a percentage of the mean value of the measurement [20].

Concerning the ecological protocol, Standard Error of Measurement (SEM) and Minimum Detectable Change (MDC) were also calculated as follow:

$$SEM = SD \times \sqrt{1 - ICC} \quad (3)$$

$$MDC = SEM \times 1.96 \times \sqrt{2} \quad (4)$$

SEM reflects the reliability of the IT for measuring running gait parameters [32] while MDC represents the smallest change that exceeds the SEM and indicates a “real change” in the variable that can be detected by the device [33].

3. Results

3.1 Static protocol

Force values from all uniaxial sensors showed a high correlation with RS ($p < 0.001$) and an excellent reliability ($ICC_{(3,1)} > 0.99$). Mean sensor accuracy is 1.27 N, with a maximum absolute value of 2.96N among the ten sensors tested. In relative mean, RLOA is 0.3 %, with values from -0.2 % to 0.73 %. Mean sensor repeatability is 0.96 N with all repeatability values below 1.69 N.

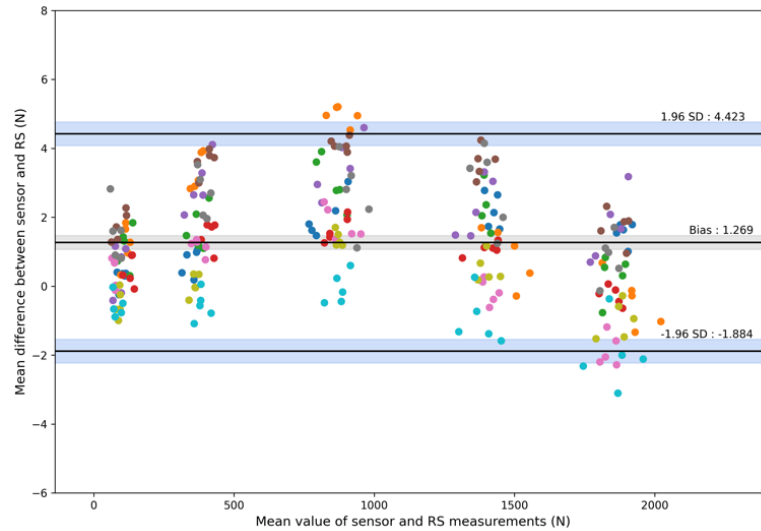


Figure 5: Bland-Altman plot with data from uni-axial force sensor and RS. Each color represents one of the ten sensors tested.

3.2 Ecological protocol

The mean results and standard deviations for both the RFP and IT are presented in Table 1, along with the $ICC_{(3,1)}$, mean bias, LOA and RLOA. The statistical analysis demonstrated excellent agreement between the

RFP and IT for all running parameters tested ($p < 0.001$; $ICC_{(3,1)} > 0.98$). Figure 5 illustrates the mean and standard deviation (SD) force pattern over fifty running steps measured by both devices for the participant.

Table 1: RFP and IT mean results with standard deviation, ICC values, mean difference with LOA and RLOA for running gait parameters.

	RFP mean $\pm$ SD	IT mean $\pm$ SD	ICC _(3,1) [CI 95%]	Mean dif. [LOA]	RLOA (%)
Fz1 (BW)	1.39 $\pm$ 0.23	1.37 $\pm$ 0.23	1.0 [1.0,1.0]	0.02 [0.01,0.03]	1.36
tFz1 (ms)	28.58 $\pm$ 3.96	29.56 $\pm$ 3.9	0.98 [0.96,0.99]	-0.98 [-2.66,0.7]	-3.34
Fz2 (BW)	2.03 $\pm$ 0.09	2.02 $\pm$ 0.09	1.0 [1.0,1.0]	0.01 [0.0,0.02]	0.53
tFz2 (ms)	123.6 $\pm$ 14.07	124.86 $\pm$ 14.04	1.0 [0.99,1.0]	-1.26 [-3.8,1.27]	-1.02
Mean (BW)	1.22 $\pm$ 0.08	1.2 $\pm$ 0.07	1.0 [1.0,1.0]	0.01 [0.0,0.02]	1.06
LR (BW/s)	84.25 $\pm$ 23.6	79.45 $\pm$ 22.14	1.0 [1.0,1.0]	4.8 [1.75,7.85]	5.92
CT (ms)	289.96 $\pm$ 23.63	292.02 $\pm$ 23.45	1.0 [1.0,1.0]	-2.06 [-4.08,-0.04]	-0.71

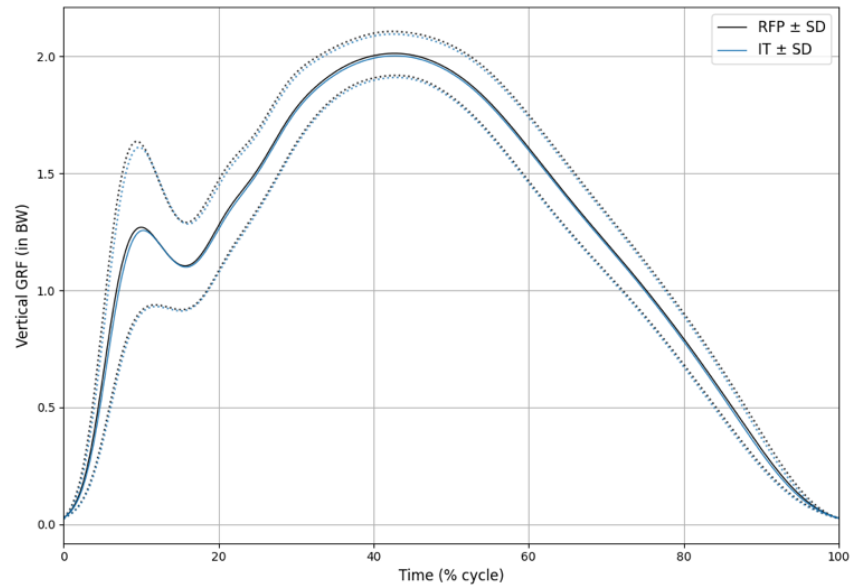


Figure 6: Mean $\pm$ SD of vertical ground force reaction (vGRF) measured by IT (blue line) and RFP (black line) over 50 running steps.

Results of SEM and MDC are presented in Table 2. There was a quasi-null MDC for Fz1, Fz2, and mean force values. MDC is 0.36 ms and 0.22 ms for tFz1 and tFz2 respectively, 0.19 BW/s for LR and 0.08 ms for CT.

Table 2 : SEM and MDC for running gait parameters

	<i>SEM</i>	<i>MDC</i>
Fz1 (BW)	1.3e-04	3.6e-04
tFz1 (ms)	0.13	0.37
Fz2 (BW)	9.4e-05	2.5e-04
tFz2 (ms)	0.08	0.23
Mean (BW)	2.3e-04	6.4e-04
LR (BW/s)	0.07	0.21
CT (ms)	0.03	0.09

4. Discussion

The aim of this study was to evaluate the accuracy and repeatability of a size-adjustable IT by assessing properties of associated uniaxial sensors during a static protocol with a RS. Additionally, a multiple-sensor configuration of the IT has been compared to a gold standard force plate while a participant was running on both devices.

Firstly, in regard to the static protocol, all tested sensors demonstrated excellent agreement between uniaxial sensors and the RS. These findings confirm that the sensors used in this study are reliable tools for measuring vertical forces, achieving an average accuracy of 1.27 N, or approximately 0.3% relative to the applied force. All of the ten sensors tested demonstrated an accuracy below or equal to 0.73%. This level of accuracy is in line with reference force sensors, such as AMTI force plates (0.5% of accuracy, Bartlett et al., 2014). Bland-Altman plot in Fig. 5 show that all sensors have same behavior with a maximal difference between devices around 1000 N. Other studies compared field-based force sensors to a reference signal using the normalized Root Mean Squared Error, reporting approximately 3% differences between devices [34], [35].

Thus, the mean intra-sensor repeatability of 0.96 N obtained in the current study was found to be comparable to, if not exceeding, that of commercial devices [28], indicating high repeatability across force levels. Thus, each uniaxial vertical force sensor can be considered highly accurate and repeatable for measuring vertical forces in the range of 0 to 2000 N.

Regarding the ecological protocol, results indicated that IT was highly accurate for assessing running gait parameters. All parameters measured by IT and RFP were significantly correlated ($p < 0.05$), with excellent ICC. According to current results, the IT device was able to accurately measure a peak force value like Fz1 (1.36 %), a mean force value (0.53 %), a derivative force value like LR (5.92 %) and a time to peak force as tFz1 and tFz2 (around 1ms) regardless of the executed task. Compared to previous validation studies, current findings related to force values (Fz1, Fz2, and mean force) and derivative values (LR) align with prior accuracy reports [20], [36]. Other studies have validated similar devices by superimposing force sensors in jump tasks to analyze peak force and time-to-peak, yielding comparable results [26], [27]. However, it has to be noted that sampling frequency may have an influence on the measurement of ground reaction force variables, especially for LR [37].

Concerning temporal parameters (tFz1, tFz2 and CT), a 1 ms difference at a 1000 Hz frequency corresponds to a one-frame variation. Observed differences in temporal peak parameters are therefore one-frame accurate, indicating IT is also accurate for vGRF temporal parameters. Concerning CT, results showed a difference of

2 ms, indicating a two-frame accuracy. This difference may come from the fact that both devices, i.e. IT and RFP, were not synchronized, so the difference may be due to a frame-error on each side of the running step when segmenting running cycles. More generally, this short temporal difference appears below the step-to-step variation typically found between devices when analyzing human activity, e.g. gait analysis, thus supporting the temporal accuracy of the IT.

Running biomechanics analysis is usually approached by focusing on vGRF parameters. For instance, studies by Bazuelo-Ruiz et al., 2018 quantified significant changes in vGRF parameters to assess the effects of fatigue and gender, while Logan et al., 2010 focused on the effects of running shoes. All significant differences reported in these studies might have been detected using IT. Indeed, the MDC derived from ICC indicated that IT can reliably measure all significant changes in running gait across parameters. Therefore, IT could be effectively used to assess the effects of various conditions in running biomechanics.

Linearity and hysteresis were not analyzed during the static protocol, although it has been conducted in other studies aiming to validate experimental force plates [39]. This limitation is related to the fact that the calibration bench did not allow for repeated application of input forces, thus preventing the study of loading and unloading hysteresis, as well as the application of forces across the full range of sensor values.

We assumed that a limitation of the setup could be related to the superimposed force plates, as forces applied on IT might not be well transmitted to RFP positioned below. Indeed, it may explain differences observed in impact-related peaks (LR, Fz1, tFz1) and second peak parameters (Fz2, tFz2). Nevertheless, based on the current results, the setup had probably a minimal effect on accuracy.

During the ecological protocol, the accuracy of the size-adjustable IT was only evaluated using a single configuration. This three-sensor configuration was selected as a straightforward setup to allow comparison through force plate superimposition. In the next future, an extended configuration of the IT that allows for a multi-step analysis will be tested. Indeed, this configuration might permit running analysis *in situ*. Indeed, obtaining GRF data directly in the field could enable the quantification of kinetic changes according to exercise, such as fatigue. This approach might be relevant to measure a running-related injury risk on-line. [8].

Using this innovative device *in-situ* requires embedding it on a flat track to enhance ecological validity. Additionally, we recommend periodically calibrating the sensors to ensure accuracy and adjusting the range of calibration forces if the track is used for activities other than running.

5. Conclusion

This study aimed to evaluate accuracy and repeatability of a size-adjustable IT which measured vGRF during a static protocol and ecological situations. Results demonstrated that both the sensors taken individually, and the IT, were highly accurate and repeatable for force measurement, particularly during running movements. This innovative, size-adjustable device may facilitate extensive kinetic studies across various *in situ* situations, providing new insights for understanding sport biomechanics in the field.

Appendix

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