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Use of force plates to investigate human motor performance

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ABBREVIATIONS

AP	anterior-posterior
CoP	center of pressure
Fx	mediolateral component
Fy	anterior-posterior component
Fz	vertical component
GRF	ground reaction force
ML	mediolateral

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ABSTRACT
Force plates have commonly been used to measure ground reaction forces. The acquired signals can be used to calculate several parameters for different motor tasks performed by human beings. Therefore, the goal of this tutorial is to present general information regarding the most common force plates, as well as their descriptions in terms of their structures, setup procedures, and signal acquisition, conversion, and export functions. This tutorial primarily provides information for those interested in using force plates to investigate human performances in the fields of motor behavior and biomechanics.

KEYWORDS: Kinetics | Ground reaction force | Motor tasks

INTRODUCTION

A force plate, which can also be referred to as a "force platform," basically consists of two rigid metallic structures connected by force sensors (Figure 1) that output voltage signals. These signals are proportional to the force applied to the top of the plate. Most force plates contain a sensor (either a strain gauge or piezoelectric sensor) in each corner that measures the ground reaction force (GRF) in the vertical and horizontal directions. The vertical component of the GRF is usually related to the contact force (body weight), and the two horizontal components are related to the shear forces (anterior-posterior and mediolateral). The moments can be calculated when the distance from each sensor to the center of the force plate is known for each direction. In some of the currently available force plates, the moments are calculated during data acquisition in the software provided by the manufacturer. In other cases, sufficient information is available from the manufacturer for their calculation.

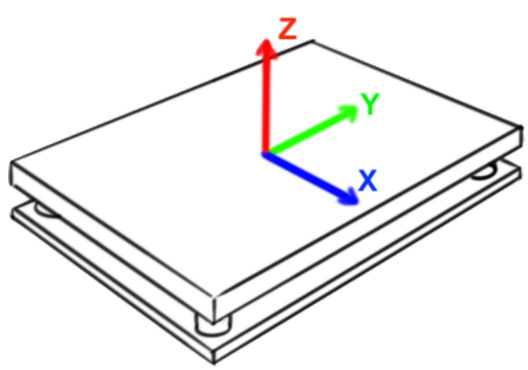

Figure 1. General representation of a force plate with a sensor in each corner between the top surface and the base that contacts the floor. The vectors representing the three force components are: vertical (Fz, red), horizontal anterior-posterior (Fy, green), and horizontal mediolateral (Fx, blue).

Force plates have been widely used to acquire GRF signals during the performance of motor tasks by different populations [1]. Among the different motor tasks, quiet stance [2,3,4], gait [5,6,7], gait initiation [8,9,10], running [11,12,13], and jumping [14,15,16] are commonly investigated by researchers to examine different aspects of human performance. In the motor behavior field, for example, researchers investigate postural control using various parameters [17] calculated from the center of pressure (CoP) [18], which is calculated from GRF signals and moments. For those interested in other motor tasks, Sarabon [19] presented a technical note related to a software development with several tests that can be conducted on force plates.

The main goal of this tutorial is to present general information regarding force plates and their use in investigating human motor behavior. More specifically, we present general aspects that should be taken into consideration when selecting a force plate, installing and acquiring data from it, and converting its electrical signal into a meaningful measurement that allows the interpretation of human performance.

SOME CRITERIA TO BE CONSIDERED RELATED TO FORCE PLATE ACQUISITION

Currently, there are different types, sizes, and manufacturers of force plates available, and detailed information regarding these aspects is not within the scope of this tutorial. However, independent of these aspects, it is important to note that to be able to acquire data from a force plate, it is necessary to obtain both hardware (the force plate itself) and software to manage the acquisition, amplification, conversion (analog to digital), and storage of signals for further processing, export, etc. Usually, the manufacturer offers software to be used in conjunction with the force plate, which is a good choice, especially for those unable to program using an interface board. The issues to be considered when selecting a force plate include the budget available for equipment acquisition, physical characteristics of the environment where the force plate will be used, experience and knowhow of the user(s), and optimization of its usage (e.g., will it be used by multiple users and for different motor tasks or for a specific motor task and location). We briefly discuss these issues in the following.

The cost of a force plate with software depends on its characteristics, and attention should be paid to all the details before making a final decision, considering how the force plate will be employed on a long-term basis. For example, for users interested in acquiring additional data (e.g., kinematics and/or electromyographic signals), it is important to verify whether the selected software allows the synchronization of signals acquired from different equipment.

Currently, the most commonly employed force plate to investigate human motor performance is a multiaxial type, which is equipped with sensors that register the three GRF components (vertical, and horizontal anterior-posterior and mediolateral) and, consequently, allows the calculation of a wide range of measurements from the acquired signals. On the other hand, the simplest force plate is a uniaxial type, which is equipped with sensors that measure only the vertical force component. Although its cost is certainly lower than that of a multiaxial force plate, the data that can be calculated from this single GRF component are limited.

Some researchers have a specific location in mind for a permanent force plate installation that meets the basic requirements recommended by the manufacturer for the correct acquisition of signals. In this case, the user should decide where to install it and strictly follow all the instructions provided by a specialist and/or the manual that usually comes with the equipment. Portable models are recommended for those who intend to use the force plate in different locations or even to transport it to different places. However, both types require a firm and flat surface for installation. Figure 2 shows examples of the placements of mountable and portable force plates.

In summary, a force plate is a relatively high-cost investment. When working in a laboratory where a force plate is already installed, it is important to be aware of its characteristics and plan ahead for the possible and appropriate motor tasks to be assessed. We also hope that the main aspects presented here will be useful to those who plan to buy a force plate. Some researchers select a motor task as a means to investigate human motor performance, whereas other researchers plan to investigate the motor task itself. Thus, it is important to keep in mind your goal as a researcher and how the force plate can be used to acquire the desired and appropriate signals. If a wide range of applications using GRF signals is desired, it might be relevant to consider a more sophisticated type. Even though its cost will be higher, the investment will be worth it in the long run. On the other hand, if it is only possible to afford a uniaxial type, it is important to follow the presented guidelines and be aware that it is possible to acquire meaningful data from the vertical GRF component.

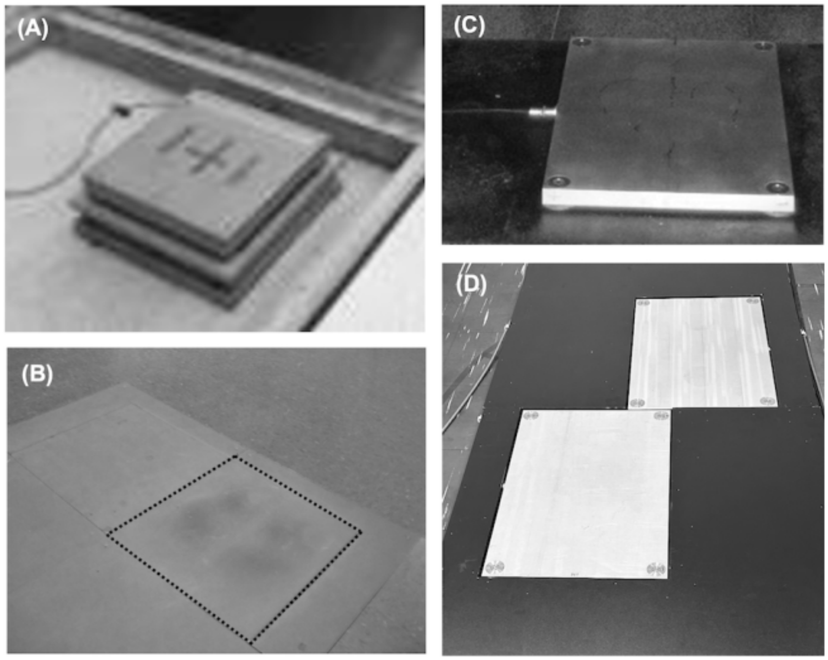

Figure 2. Illustrations of how a mountable force plate is generally installed (A) and set for data acquisition (B); and how a portable force plate can be placed either on the floor (C) or surrounded by a walkway (D).

FROM INSTALLATION OF A FORCE PLATE TO ITS SIGNAL ACQUISITION

The rule of thumb is to read and follow the instructions found in the manufacturer's manual that comes with the purchased equipment. As previously mentioned, the force plate should be placed on a firm and flat surface that is as free as possible from vibration. For this reason, it is recommended to check for any external source of noise before deciding on the final mounting or placement in the designated environment. It is usually recommended to mount the force plate on the same level as its surroundings to make it even with the ground and safe, which will prevent tripping and falling (Figures 2B and 2D). No part of the force plate should contact its surroundings. In addition, depending on the motor task to be performed and the aims of the investigation, the floor covering on the top of the force plate could be similar to that of the surrounding area to prevent the performer from being aware of the force plate's position, which could influence the task performance. For example, if the performer can see or is aware of the force plate's position along a pathway in experiments involving gait, he/she could either avoid or deliberately hit the force plate by adjusting the steps during the performance, depending on the instructions provided by the experimenter or aims of the investigation [20,21].

A mounting frame plate (Figures 2A and B) is desirable when there is available space for a permanently mounted installation, especially if the motor task to be performed is a vigorous one (e.g., jumping or running) that requires a secure connection between the force plate and the surface where it will be placed. Regardless of its installation, it is imperative that the force plate be level and not able to move at all to gather accurate signals.

It is important to note that force plates operate on the principle that no matter how many or what body part contacts any spot along its top surface, the resultant GRF signals for each component will be the main outcome measurements, which will be numerically and physically equivalent to all the applied forces. Thus, to acquire signals from a force plate, a specific body part (e.g., one foot or both feet) must be solely in contact with the top surface of the force plate. Otherwise, the signals must be discarded.

Another important issue is regarding the orientation of the force plate in relation to the performer. The user is free to define the force plate's coordinate system in terms of movement direction (i.e., positive and negative signals indicating backward, forward, left, right). However, attention should be paid to this issue either before acquiring the signals (by configuring the acquisition software) or during data processing (by indicating the correct movement direction in relation to the force plate orientation), to ensure data accuracy.

Before any assessment using a force plate, it is strongly recommended that the force plate be turned on for a minimum of 30 min to reach its thermal stability, which will enable the acquisition of accurate signals, with no drift. Likewise, it is necessary to check specific parameters in the software to be used, such as the gain levels, sampling frequency, and duration of the signal acquisition based on the motor task under consideration. Depending on the software, most of these parameters can be saved and used in further assessments that require the same configuration.

In general, regarding the gain levels, the output signals are fed to a charge amplifier unit that includes selectable gain levels for each channel that determine the exact values for the scale factors of the vertical and horizontal GRF components. It is recommended to select the minimum range possible to take full advantage of the maximum output voltage, which will keep the noise and other errors as small as possible. However, attention should be paid to the selected task to avoid signal saturation. For example, the gain level for the vertical component during the acquisition of walking is lower than that for the acquisition of vertical jumping. If the user did not increase the gain level, he/she would not acquire the maximum signal magnitude and, consequently, the data should be discarded. The user should consult the manual to determine whether the range for the gain levels is set automatically or manually, as this depends on the manufacturer.

Regarding the sampling frequency, the band limit at the frequency of Nyquist frequency (*f*) signals should be at least twice *f* [22]. A sampling frequency lower than *f* will distort the signals regarding the motor task under investigation [23]. For example, when standing still, walking, and running, the minimum sampling frequencies should be 50 Hz, 200 Hz, and 1000 Hz, respectively.

Last but not least, each force plate has its own "identity" in terms of sensitivity. Thus, all the signals should be calibrated to allow the user to convert the electrical signals (in V) recorded during the acquisition into a force unit (usually Newtons), which is more meaningful to the users. The manufacturer should provide either software configured with the correct values or a calibration certificate with the results of sensitivity measurements according to the range level. Usually, the calibration procedure is only conducted once, and the information is never modified (unless the user modifies it). Attention should be paid to the specifications of the selected force plate.

After following the procedures described in this tutorial, it is time for data acquisition. However, it is important to be familiar with all the procedures. Thus, we suggest practicing with some volunteers (e.g., teammates, laboratory members), simulating the real experiment before the recruitment of the participants that will take part of the study. In this way, the investigator(s) will avoid wasting potential participants from the required sample to be investigated. After data acquisition, it might be possible to calculate the pre-selected parameters using the same software and then export the values (e.g., to an ASCII file). It might also be possible to export the raw data and process them using a specific program such as Matlab (MathWorks, Inc.), Python (Phyton Software Foundation), Octave (Free Software Foundation), Excel (Microsoft Office, Inc.), etc.

REPRESENTATION OF DATA ACQUIRED WITH FORCE PLATES WHILE STANDING STILL AND WALKING

Before concluding this tutorial, we would like to illustrate samples of data acquired with force plates for two common motor tasks: standing still and walking. These data are from different studies conducted by our research group. Some general characteristics of two non-disabled individuals who performed the tasks are presented in Table 1.

Table 1 – General characteristics of the two non-disabled individuals for which data from the force plates are presented in this tutorial.

Individual	*Motor task*	*Sex*	*Age (yrs.)*	*Mass (kg)*	*Height (m)*
#1	Standing still	Male	33	76.7	1.76
#2	Walking	Male	34	85.1	1.77

For the standing still task, the non-disabled male maintained an upright position ("as still as possible") on a force plate (Kistler, model 9286BA, Figure 2C) for 30 s, with parallel feet (shoulder width), arms hanging at his side, and eyes closed. Figures 3A and B show time series profiles of the three GRF components. Because the individual was instructed to stay as still as possible, only the vertical component (Fz) presents a high magnitude value that corresponds to his body weight, either full (Figure 3A) or normalized by body weight (Figure 3B). The horizontal components (Fy and Fx) are close to zero because the accelerations in those directions had minimum values during this task. Figure 3C shows the time series profile of the CoP displacements in both the mediolateral (ML) and anterior-posterior (AP) directions, and Figure 3D shows a common representation of the CoP values in both directions, from which we can calculate, for example, the area of CoP oscillation. Figures 3C and D show a higher range of oscillation in the AP direction (-1.25 to +0.75 cm, approximately) compared to the ML direction (<-0.25 to <+0.25 cm). This is due to the experimental condition (i.e., parallel feet). In contrast, if the individual were in a tandem stance position, for example, we would observe a higher range of CoP oscillation in the ML direction than in the AP direction.

For the walking task, the non-disabled individual was instructed to walk at a comfortable self-selected speed (his average speed was 1.3 m/s) while wearing walking shoes on a 10-m walkway. This walkway contained two embedded force plates (Kistler, model 9286BA, Figure 2D) covered with a thin rubber carpet. Figures 4A and B show time series profiles of the three GRF components for the right and left legs, representing the full body weight (Figure 4A) and values normalized by his body weight (Figure 4B). A typical pattern can be observed for the three components. Specifically, the vertical component (Fz) represents the force applied downward against the ground, and it is the main contributor to the resultant GRF during walking. We can observe two distinct peaks in this component, with a greater magnitude than the body weight and a valley between the two peaks, which was lower than the body weight (Figure 4C). The first peak occurs when the leg is receiving the body weight right after the foot contacts the ground. The valley occurs midstance (with the foot flat on the ground), and the second peak occurs close to the end of the foot contact.

The anterior-posterior component (Fy) provides information regarding the forward and backward forces applied to the ground, and corresponds to the breaking (deceleration impulse) and propulsion (acceleration impulse) of the forward motion (Figure 4D). The first and second force peaks of this component almost coincide temporally with the two peaks of the vertical component. The mediolateral component (Fx) is less consistent than the Fz and Fy components among individuals, which makes it difficult to interpret it. However, it often presents an initial peak in the lateral direction, which results from an inward foot movement as it touches the ground. For the remaining part of the foot contact with the ground, Fx represents the foot placement, which can be either an inward (adduction) or outward (abduction) foot placement during the stance.

It is important to note that there is a peak (not always evident in walking) in the first 50 ms of foot contact, which is associated with the impact force. The magnitude of this impact might be influenced by factors such as the walking speed and type of shoes worn (or if the individual is walking with bare feet).

Based on the presented data (standing still and walking), several parameters can be calculated and analyzed to investigate different issues related to human motor performance. It is not within the scope of this tutorial to present these parameters and how to calculate them. Nevertheless, there are a variety of published studies that can be examined according to the motor task to be investigated.

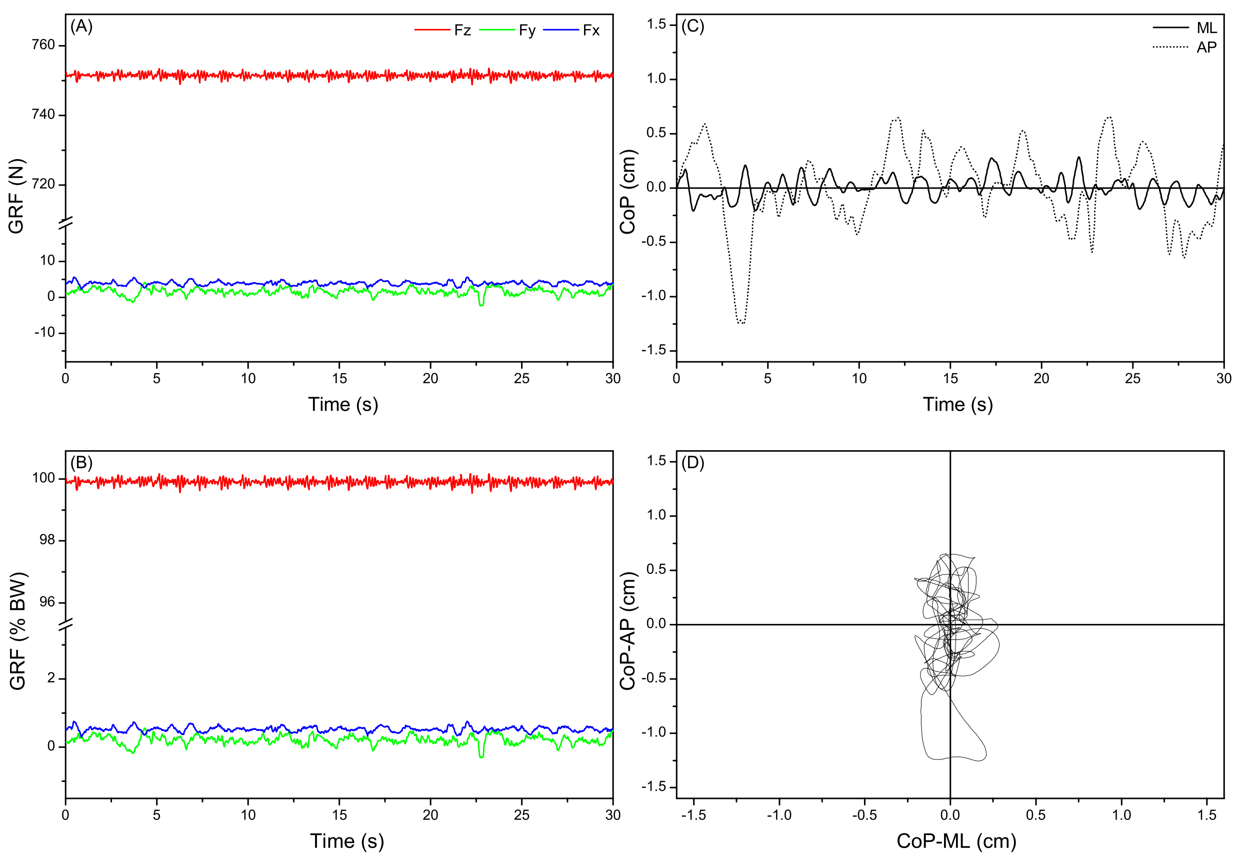

Figure 3. Time series profile of ground reaction force (GRF) of the vertical (Fz), and horizontal anterior-posterior (Fy) and mediolateral (Fx) components with the full body weight (A) and normalized by it (B); time series profile (C) and a stabilogram (D) of the center of pressure (CoP) displacement for the mediolateral (ML) and anterior-posterior (AP) directions.

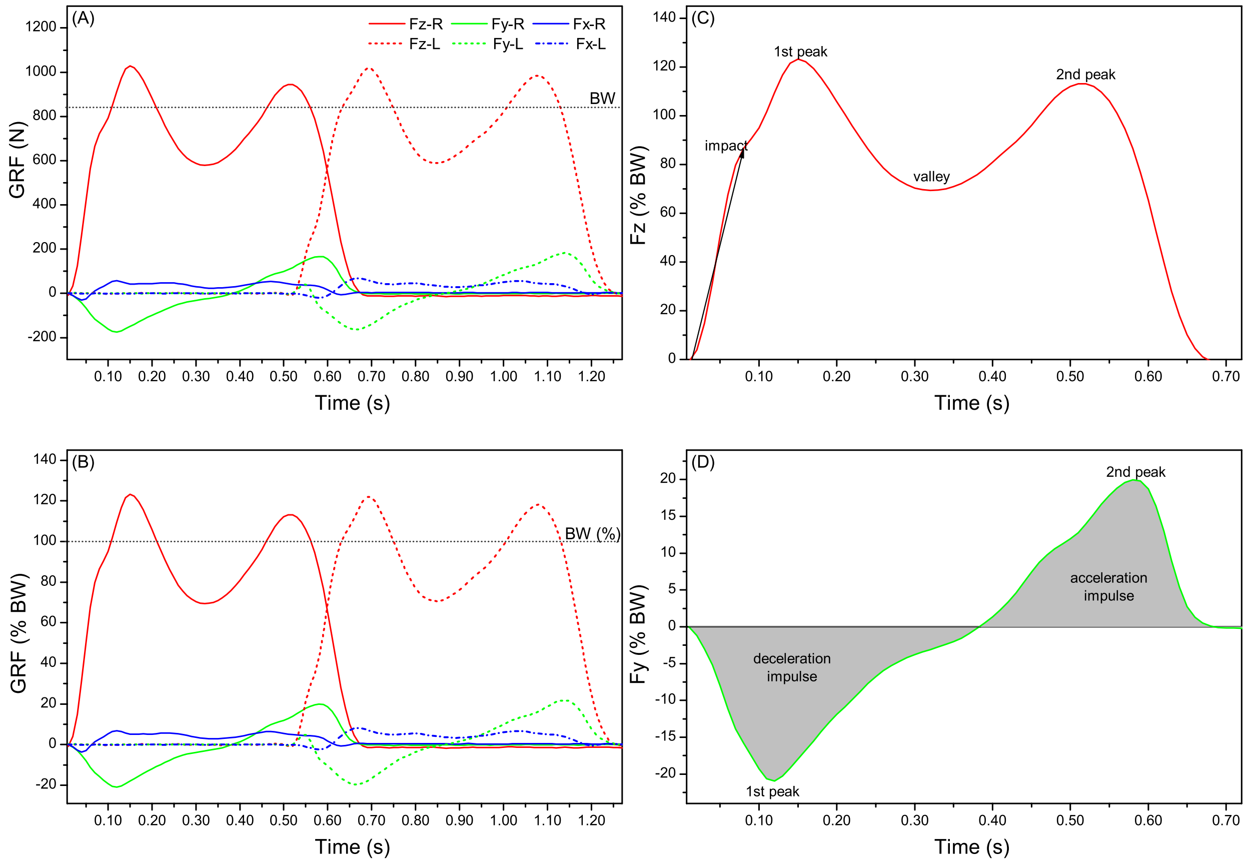

Figure 4. Time series profile of ground reaction force (GRF) of the vertical (Fz), and horizontal anterior-posterior (Fy) and mediolateral (Fx) components for the right (R) and left (L) legs, with the full body weight (BW) (A) and normalized by the BW (B); illustration of the vertical GRF component (C), with the two peaks, the valley, and the impact peak, and the anterior-posterior component (D) with the two peaks and the deceleration and acceleration regions (shaded areas). Note: an estimation of the impact force's rate can be obtained by calculating the slope of the line (black arrow) in approximately the first 50 ms (i.e., until the impact peak) through least-squares adjustments.

FINAL CONSIDERATIONS

This tutorial aimed to describe the main aspects of force plates. Considering the numerous applications of force plates, one of the first steps before using them is to be aware of some basic and fundamental issues. Thus, we hope this tutorial provides guidance for anyone unfamiliar with this equipment.

For those who intend to employ force plates in future studies, this tutorial could be used as a basic guide and starting point when planning the settings, configurations, data acquisition and storage, and so on. Regarding the possible and appropriate parameters to be considered in a further analysis, the readers should search for previous published studies related to the specific motor task they plan to investigate.

Finally, it is important to note that this was a first attempt to present practical information regarding force plates. We apologize if any reader feels that something is missing. We hope that this tutorial will be useful to those who plan to adopt force plate(s) in their future investigations.

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