



Review

Testing protocols and measurement techniques when using pressure sensors for sport and health applications: A comparative review

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ABSTRACT

Plantar pressure measurement systems are routinely used in sports and health applications to assess locomotion. The purpose of this review is to describe and critically discuss: (a) applications of the pressure measurement systems in sport and healthcare, (b) testing protocols and considerations for clinical gait analysis, (c) clinical recommendations for interpreting plantar pressure data, (d) calibration procedures and their accuracy, and (e) the future of pressure sensor data analysis. Rigid pressure platforms are typically used to measure plantar pressures for the assessment of foot function during standing and walking, particularly when barefoot, and are the most accurate for measuring plantar pressures. For reliable data, two step protocol prior to contacting the pressure plate is recommended. In-shoe systems are most suitable for measuring plantar pressures in the field during daily living or dynamic sporting movements as they are often wireless and can measure multiple steps. They are the most suitable equipment to assess the effects of footwear and orthotics on plantar pressures. However, they typically have lower spatial resolution and sampling frequency than platform systems. Users of pressure measurement systems need to consider the suitability of the calibration procedures for their chosen application when selecting and using a pressure measurement system. For some applications, a bespoke calibration procedure is required to improve validity and reliability of the pressure measurement system. The testing machines that are commonly used for dynamic calibration of pressure measurement systems frequently have loading rates of less than even those found in walking, so the development of testing protocols that truly measure the loading rates found in many sporting movements are required. There is clear potential for AI techniques to assist in the analysis and interpretation of plantar pressure data to enable the more complete use of pressure system data in clinical diagnoses and monitoring.

1. Introduction

Plantar pressure measurement systems are routinely used in sports and health applications to assess locomotion. In the clinical domain, these systems have become an integral part in helping clinicians assess a patient's gait, dynamic balance and pressure distribution to assist them in the prescription and assessment of treatment interventions including orthotics [1–11], surgery [12–16], medication [17] or rehabilitation programmes [18–21]. Within sports, practitioners, researchers and

sporting equipment designers use this technology to measure plantar pressures during sporting movements to assess the effect of factors such as footwear and terrain [22–30].

This paper follows on from our previous review of commercially available pressure sensors for sport and health applications which discussed the design requirements and the suitability, validity and reliability of commercial pressure measurement systems and future directions for the development of pressure sensors in this area [31]. The aim of this current review is to describe and critically discuss: (a)

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applications of the pressure measurement systems in sport and healthcare, (b) testing protocols and considerations for clinical gait analysis, (c) clinical recommendations for interpreting plantar pressure data, (d) calibration procedures and their accuracy, and (e) the future of pressure sensor data analysis.

2. Applications of pressure measurement systems in sport and healthcare

2.1. Pressure platforms

Rigid pressure platforms (and mats) are typically used to measure plantar pressures for the assessment of foot function during standing and walking, particularly when barefoot [32], and generally in laboratories or clinics [4,33–38]. The main uses of plantar pressure measurement in clinical gait analysis are to assist in the diagnosis and selection of treatment, to evaluate the outcome of treatment, to inform the design of orthotics and prosthetic devices, and to monitor the longitudinal progression of diseases or illness on gait [4,39]. For example, plantar pressure measurement can be used in clinical gait analysis to help prescribe and assess the effect of orthotics and other physical therapy interventions, such as taping of the foot, in redistributing or reducing plantar pressures [1–8,40,41,42]. Plantar pressures have been measured to assess the effect of surgical procedures [12,14–16,43], and medication [17] on gait characteristics whilst physical therapists have measured plantar pressure to assess the effect of rehabilitation programmes on patients' gait and balance following surgery, injury or medical conditions [18–21,44]. A further use of pressure platforms is to assess plantar pressure distribution and postural effects in patients with clinical pathologies, such as diabetes [1,45–52], Parkinson's disease [53], multiple sclerosis [54–56] and rheumatoid arthritis [57], and to monitor the progression of these pathologies. The National Institute for Health and Care Excellence (NICE) in England recommend plantar pressure assessment in their clinical guidelines to examine the biomechanical status of diabetic feet for those classified as moderate to high risk of developing a diabetic foot problem [58]. As a result of this assessment, patients may be prescribed specialist footwear and/or orthoses to redistribute areas of high pressure to minimise the risk of pressure ulcers developing [58].

Pressure platforms have several applications in sport, and are typically used to assess plantar pressures as a measure of balance during standing sporting movements, such as during golf shots [59], air-gun shooting [60] and the body position for initiating offence in basketball [61]. Pressure platforms have also been used to measure plantar pressures during running [62–64]. However, in-shoe systems are often better for this purpose as they can measure multiple steps over a continuous effort, and can do so in the field if wireless, but they typically have lower sampling frequency and spatial resolution [31]. Pressure platforms have been used to measure plantar pressure to identify factors associated with lower limb injury risk and to screen athletes for these risk factors [6, 65–72]. For example, a prospective study of physical education students identified that those who have a more lateral centre of pressure at initial contact, more pronated foot over a prolonged period and greater pressure underneath the medial side of the foot, during running were at a greater risk of an inversion sprain [71]. Pressure platforms can also subsequently be used to assess the effect of training interventions, for example on reducing an athlete's injury risk [73].

2.2. In-shoe systems

In-shoe pressure measurement systems include discrete sensors, instrumented insoles and socks. Typically, insole systems provide a more comprehensive and valid measurement of plantar pressures than discrete sensors and socks (which contain a few discrete sensors), as the latter can miss locations of high pressure [4,74–76]. One of the main advantages of the in-shoe systems is that it is easy to record multiple

steps and, therefore, no targeting of a platform occurs, whether intended or not, and thus a more natural gait is measured [34,74,77,78]. Therefore, in-shoe pressure measurement systems are often used to assess dynamic sporting movements and are particularly suited to measuring plantar pressures during running [22,24,79–82]. They are highly suitable for assessing the effect of different types of footwear on plantar pressure [4,30,33,34,61,74,77,78,83,84–88], and can be used to measure plantar pressures inside sport specific footwear, such as during ice skating [27,89], snowboarding [90,91], and skiing [28]. Similar to pressure platforms, in-shoe pressure measurement systems can be used to help prescribe and assess the effect of orthotics in redistributing or reducing plantar pressures [9–11,40,92–94]. In-shoe systems typically have lower spatial resolution compared to platform systems due to fewer sensors [31,33,95], and wireless versions can have a thicker insole due to the incorporation of the battery and data transmitter [31]. In-shoe system sensors are more susceptible to degradation as they are subjected to bending within the shoe, as well as heat and humidity generated within footwear [31,32,77,78].

2.3. Pressure treadmills

In addition to assessing plantar pressure over multiple steps, pressure treadmills can be used for gait retraining by providing visual cues or perturbations, and then monitoring the effect of these on gait and plantar pressures [96–99]. A single session of gait training on a treadmill which provided perturbations in the form of three-dimensional tilting to the walking surface demonstrated gait improvements (increased overground walking speed and reduced gait variability) for patients with Parkinson's disease [96]. Another possible suggested application of pressure treadmills is to use the gait metrics obtained during standing and walking to estimate the Gross Motor Function Measure score in children with cerebral palsy; this is quicker than the traditional testing protocol and reduces the need for trained and specialised therapists to conduct the testing [100].

2.4. General flexible pressure sensors

Commercially available flexible pressure measurement systems can be used for sport and health applications to measure pressures between two objects in direct contact, such as prosthesis-limb interface [101–107] and joint contacts [108–111]. Stump ulcers are a common problem in amputees [112,113] and can be the result of high pressure and shear forces at the stump-prosthesis interface [114]. Therefore, specific pressure measurement systems have been developed to assist in prosthetic limb fitting, and to assess the effect of interventions to reduce prosthesis-limb interface pressures [101–107,115,116–121].

Orthopaedic surgeons and researchers often want to assess the effect of different surgical techniques on joint contact pressures and the size of the contact area; flexible pressure sensors can be used to measure these in cadavers [108–111]. Pressure measurement systems have been used during surgery to inform decisions, for example, during total knee replacement surgery to determine the position for the implant and ligament reattachments that minimise tibiofemoral contact stresses [122]. Flexible pressure sensors have also been used to assess different joint replacement devices, such as total knee arthroplasty devices [123] and different knee brace designs [124].

3. Protocols and considerations for clinical gait analysis

3.1. Pressure platforms for measuring plantar pressures

The most accurate plantar pressure readings from rigid pressure platforms are obtained from the centre of the measurement area [4,33, 78,125]. This can result in participants targeting the platform [125], particularly when a small pressure platform is used. Greenhalgh et al. (2014) found that hip and knee kinematics altered when participants

walked over a pressure platform compared to normal walking with no measurement device to target [125]. This raises questions concerning whether natural gait plantar pressures can confidently be measured with platform systems and, to reduce these effects participant familiarisation should be undertaken [4,33,78,125]. The number of steps the participant takes from gait initiation before they contact the pressure platform i.e., one, two or three-step protocols can also influence the reliability of the plantar pressures measured [126]. Bus and de Lange (2005) recommended that a two-step protocol is used to measure barefoot plantar pressures in diabetic patients, as this protocol required the least amount of trials (four trials) in order to obtain reliable estimates of peak pressure and the pressure-time integral [126]. Naemi et al. (2012) found that there were no significant differences between plantar pressures measured by a pressure platform either with or without an additional EVA walkway either side of the pressure platform to create a flush surface [127], suggesting such additional walkway panels are not necessary. However, stepping preference- whether the left or right foot contacted the pressure platform- did have a significant effect on the plantar pressures measured, and therefore needs to be considered in gait testing protocols and made consistent between trials [127]. Another factor that can influence plantar pressures is walking speed. Faster walking speeds typically result in higher plantar pressures in all regions of the foot except for the arch and lateral metatarsals [128]; this therefore needs to be monitored and controlled during testing sessions [32,128–130].

When selecting a pressure platform for assessing gait or balance, certain design specifications need to be considered for specific populations or type of assessment. When studying plantar pressures in children, higher spatial resolution pressure platforms are typically required to obtain accurate data due to their smaller feet. For posturographic assessments, pressure platforms that consist of resistive sensors are not recommended [32]. This is because they suffer from hysteresis and drift that will affect the accuracy of centre of pressure (CoP) measurements during the longer static trials required to assess balance [32].

3.2. In-shoe systems

In-shoe systems have the benefit of allowing more steps to be recorded per trial, and for this to be undertaken in a free living environment [32]. However, a common compromise of this is that the measurement accuracy of many in-shoe systems is lower than platforms [32]. Researchers have recommended that, in order to obtain reliable plantar pressure data when using in-shoe systems, a minimum of eight steps for healthy adults [131], nine steps for patients with hallux valgus [132] to 12 steps for neuropathic diabetic patients [133] are required. When using in-shoe systems the placement of the pressure insole (above or below the standard shoe insole) needs to be considered as it affects the plantar pressure measurement, with lower plantar pressures measured when the pressure insole is placed beneath the standard shoe insole [82]. Therefore, the placement of the pressure insole should be consistent and reported in research studies to allow for comparison of in-shoe plantar pressures. It has also been highlighted that it is important to use the same pressure insole for all trials for a participant, due to individual responses of a pressure insole to the same applied pressure, even for two sets of insoles of the same model and manufacturer [134–137]. Another factor that affects the plantar pressures and contact area is the type of insole material [138]. Healy et al. (2012) recommended insoles made of medium density polyurethane for patients with compromised ability to deal with pressures, as this material increased contact area and reduced the pressure-time integral compared to other materials commonly used to make orthotics for diabetic patients [138]. The choice of in-shoe system and the material of the pressure insoles can influence the pressure sensor readings [139]. For example, thicker softer insoles provide a cushioning effect and reduce the volume within the footwear which can influence the pressure readings. This also, therefore, needs to be considered when both selecting a system and interpreting the data.

In-shoe pressure measurement systems that consist of discrete sensors attached to anatomical locations on the foot may miss information if the locations of high pressure occurs away from the sensors and total normal force cannot be obtained [4,74–76]. Nevertheless, a minimum of nine sensors has been shown to be sufficient for accurately calculating CoP during walking and running [140]. However, care needs to be taken when choosing the sensor layout as different sensor layouts have been found to affect the strength of the correlation of the CoP with that measured by a force plate [75]. Another important consideration is to ensure the discrete sensors are placed in the same location for each session to ensure reliable pressure sensor data [74,77]. Using inked mats and the palpation of bony landmarks can assist this process [77]. There are several other important considerations when using discrete sensors: the sensors may migrate during a trial due to shear stresses, so need to be firmly secured to the sole of the foot using tape [75,77,141]; the sensors can act as a foreign body in the shoe, acting as an irritant to the participant [77], and the difference between the material of the pressure sensor and the skin can cause an edge effect leading to falsely elevated pressure values [78].

Recently, guidelines for the use of the commercially available pressure measurement system (F-Scan, Tekscan) was published based on a DELPHI-derived consensus by clinicians involved in managing plantar ulcers [142]. Whilst these provide a valuable framework and highlight some important concepts that users must consider, some remain quite broad and users will need to critically interpret and apply them in the context of their own specific uses.

3.3. Environmental factors

Environmental factors such as heat, humidity and dust within the testing environment can influence pressure sensor measurement [77, 143,144]. Piezoresistive sensors can be particularly sensitive to changes in temperature and humidity [77,137,143,145–148]. In-shoe pressure sensors are more susceptible to degradation than platform systems as they are subjected to bending within the shoe, and the heat and humidity generated within footwear can also damage the sensors [32,77, 78]. For example, it has been shown during a 7 km run that the temperature of the shoe midsole may increase by as much as 15C and for many devices this may have an important effect on device sensitivity [77,149]. Many manufacturers specify an operating temperature range for which the calibration is valid. The sensors will also degrade quicker when subjected to higher forces, so their life-span will be shortened if they are used for measuring relatively high force activities, such as running and jumping compared to walking, and creases, bends or other degradation of the insole can result in measurement artefacts [74,77, 150,151].

4. Clinical recommendations for data interpretation

Clinicians typically compare the pattern of plantar pressures measured for their patient to normative plantar pressure data collected from healthy individuals. If atypical plantar pressure distributions are observed, clinicians will then often prescribe interventions to adjust plantar pressures to the normal range [78]. Plantar pressure assessment can be used to identify abnormal biomechanical loading for those with osteoarthritis to identify if they require an orthotic [152] and by podiatrists to assess those with rheumatoid arthritis and foot problems [153].

One of the key areas of the clinical application of plantar pressure assessment is in the management of diabetic foot and its complications. The International Diabetes Federation and International Working Group on the Diabetic Foot along with many national healthcare systems provide guidelines for clinical care of the diabetic foot [154]. For example, NICE (England) recommend moderate to high risk diabetic feet be biomechanically assessed which can include measuring plantar pressure during standing and walking [58]. As a result of this assessment

patients may be prescribed specialist footwear and/or orthoses to redistribute areas of high pressure with the aim of minimising the risk of pressure ulcers developing [58]. For diabetic patients, a mean peak pressure of 200 kPa has been proposed as a potential threshold to reduce risk in a previously ulcerated foot affected by diabetes [47,155,156]. However, the thresholds discussed in various reports and guidelines disregards the effect of plantar shear stresses, which often occur at different locations to peak pressure [157] and are an important consideration in the formation of diabetic ulcers [77,78,158,159–161]. In addition, there are differences in absolute values between technologies such as capacitive and resistive sensor based systems and the type of system used either in-shoe or platform [162]. The amount of cushioning effect introduced by the systems themselves also needs to be considered. Hence, it is important that one does not take absolute values from one type of system and compare it against another system. Whilst plantar pressure assessment has a pivotal role to play in the management of the foot at risk, it is important to understand that the assessment cannot be reduced to single number and the pressure distribution seen on the screen is combination of a variety of interlinked biomechanical factors.

5. Calibration procedures

Calibration of pressure sensor systems is essential to ensure accuracy of measurement. Some systems are calibrated by the manufacturer whilst others require the user to perform a calibration prior to each testing session [150]. Pressure platforms certified as medical devices must have their technical performance checked in the factory and certified [32]. The calibration procedure should simulate the conditions at the interfaces being measured [163] and will typically include static and dynamic calibration tests. Pressure sensors that have a linear response simplify the process of static calibration [74]. However, most pressure sensors will be used to measure pressures during dynamic conditions and, therefore, a dynamic calibration should also be performed [164]. Dynamic calibrations should also be performed to assess and account for any time-dependent effects such as hysteresis and drift [74,165,166]. A dynamic calibration requires the sensor to be subjected to loading-unloading cycles within a specific time interval – both the time and load should be representative of the loading conditions likely to be encountered during the activity of interest, and these will differ between activities such as walking, running, sprinting, jumping and many others [164]. However, the testing machines that are commonly used for dynamic calibration have loading rates that are frequently less than even those found in walking, so the development of testing protocols that truly measure the loading rates found in many sporting movements are required [74,164]. These testing and calibration protocols should include impulse loading with a force of appropriate magnitude but very short duration (average braking time < 0.03 s for male sprinters over the first 50 m [167]), as this gives an indication of a sensor's ability to respond to rapid loading rates [74]. Where array systems are used, it is recommended that each cell is calibrated individually, as individual cells can, and do, have different calibration characteristics and using one calibration for all cells can introduce large errors [77].

A popular calibration method is to apply several known uniform pressures over the pressure sensor using a compressed-air filled rubber bladder. This system allows the sensors to be uniformly loaded and permits the generation of a calibration matrix for each sensor or group of sensors [78]. An example of such a system is the trublu® calibration device (Novel), which allows the user to check and calibrate their devices at any time. Giacomozzi et al. (2009) developed a specialist pneumatic test device for pressure sensor assessment that is relatively light, easily transportable, and adaptable to pressure sensors and platforms of different technologies and size [168]. It can apply pressure in the range 0–700 kPa under static and dynamic conditions over a small square area, in the frequency range 0.5–1 Hz [168]. However, this device still cannot load at the rates required for many sporting movements,

such as running and jumping. In clinical settings, a simple check of the validity of the calibration of a pressure platform or insoles is a single stance body weight test (BWT) which should be done before assessing a patient [32]. The patient's mass is measured and then the patient stands on one leg for a few seconds on at least five different areas of the platform surface [32]. If the root mean squared error is greater than 10% of the expected value then the platform may require maintenance or re-calibration and should not be used [32].

Often the effects of the temperature, humidity, and electromagnetic fields in the testing environment can be compensated by taking into account measurement values at zero pressure at the start of each testing session [166]. The effects of hysteresis and drift of pressure sensors can be compensated by using algorithms; these include both deconvolution-based algorithms and custom-made drift correction algorithms [166,169–172]. Different base materials under the pressure sensor have also been shown to influence its response [134,135,173]. Therefore, the calibration and validation of the sensors needs to be performed under the same loading and environmental conditions as the sensor will be used.

Several researchers have proposed new calibration methods and techniques in an attempt to improve the validity and reliability of pressure sensor measurements [174–179]. These include using a compressed-air filled rubber bladder [174,175] or mechanical loading materials testing machine [177–179] to apply standardised loading ramp with each load held for a period before being increased to the next load followed a similar unloading sequence to generate a calibration equation to convert raw electrical signal to force/pressure instead of the single point loading method typically recommended by the manufacturers. Also, some researchers have used different algorithms to create the calibration equation instead of using the standard linear relationship [178,179]. Users of pressure measurement systems need to consider the suitability of the calibration procedures for their chosen application when selecting and using a pressure measurement system.

6. Future directions for data analysis

Pressure measurement systems can generate a large amount of data. For example, a single walking trial which lasts for 8 s, with plantar pressures measured by 100 sensors per insole at 200 Hz generates 320,000 data points per trial. Multiple trials and participants obviously increases the quantity of data but this is then typically reduced to discrete values such as average and peak pressure. Pataky et al. (2008) demonstrated the benefits of analysing pixel level plantar pressure data, using statistical parametric mapping to compare the effects of walking speeds on the spatial distribution of plantar pressures, with different findings for pixel level data compared to average plantar pressure data when assessing the midfoot region [130]. This highlights the potential importance of methods that analyse the pressure data at higher spatial resolutions to ensure that more valid conclusions can be drawn from the data when necessary. Artificial intelligence (AI) techniques have provided promising innovations in medical imaging, and impacted how radiologists work, helping them to speed up scan time, make more accurate diagnoses, and ease their workload [180–182]. Given that medical images made up of pixels are fundamentally similar to pressure sensor data, some AI methods such as deep learning models have recently been applied to plantar pressure sensor data [76,183–189]. Mun and Choi (2022) demonstrated that deep learning models (such as long short-term memory; LSTM) can be used to predict pressure distribution of the whole foot based on pressure data from a small number of pressure sensors in an insole [187]. These types of algorithm therefore have the potential for applications to data obtained from low-cost portable smart insole systems in order to facilitate the monitoring of plantar pressures across the whole foot in daily living in clinical populations [187]. Deep learning models have also been successfully applied to plantar pressure images to assess the risk of foot ulcers, which has the potential to transform diabetic patient monitoring [184]. In the

future, AI clearly has the potential to assist in the analysis and interpretation of plantar pressure data to assist in clinical diagnoses and monitoring, and researchers working in this space are encouraged to collaborate with AI experts to explore the transfer of existing and new techniques to the analysis of pressure sensor data.

7. Conclusions

This comparative review of testing protocols and measurement techniques when using pressure sensors for sport and health applications highlights that:

- Rigid pressure platforms are typically used to measure plantar pressures for the assessment of foot function during standing and walking, particularly when barefoot, and are the most accurate for measuring plantar pressures. For reliable data - two steps before contacting the pressure plate are recommended (two-step protocol).
- In-shoe systems are most suitable for measuring plantar pressures in the field during daily living or dynamic sporting movements as they are often wireless and can measure multiple steps. They are the most suitable equipment to assess the effects of footwear and orthotics on plantar pressures. However, they typically have lower spatial resolution and sampling frequency than platform systems.
- Users of pressure measurement systems need to consider the suitability of the calibration procedures for their chosen application when selecting and using a pressure measurement system. For some applications a bespoke calibration procedure is required to improve validity and reliability of the pressure measurement system.
- The testing machines that are commonly used for dynamic calibration of pressure measurement systems frequently have loading rates of less than even those found in walking, so the development of testing protocols that truly measure the loading rates found in many sporting movements are required.
- There is clear potential for AI techniques to assist in the analysis and interpretation of plantar pressure data to enable the full use of pressure system data collected during a movement to assist in clinical diagnoses and monitoring.

CRediT authorship contribution statement

Nachiappan Chockalingam: Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. **Louise Burnie:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Tim Claypole:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision. **Alex Holder:** Conceptualization, Data curation, Investigation, Methodology, Project administration. **Neil Bezodis:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Liam Kilduff:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision.

Declaration of Competing Interest

None.

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