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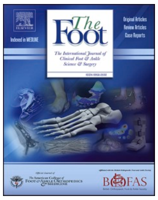

Review

Commercially available pressure sensors for sport and health applications: A comparative review

Louise Burnie[a,b,*], Nachiappan Chockalingam[c], Alex Holder[e], Tim Claypole[d], Liam Kilduff[b], Neil Bezodis[b]

[a] *Department of Sport, Exercise and Rehabilitation, Faculty of Health & Life Sciences, Northumbria University, Newcastle upon Tyne NE1 8ST, UK*
[b] *Applied Sports, Technology, Exercise and Medicine (A-STEM) Research Centre, Faculty of Science and Engineering, Swansea University, Swansea SA1 8EN, UK*
[c] *Centre for Biomechanics and Rehabilitation Technologies, Staffordshire University, Stoke on Trent ST4 2RU, UK*
[d] *Welsh Centre for Printing and Coating (WCPC), Faculty of Science and Engineering, Swansea University, Swansea SA1 8EN, UK*
[e] *A-Gas, Bristol, UK*

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ABSTRACT

Pressure measurement systems have numerous applications in healthcare and sport. The purpose of this review is to: (a) describe the brief history of the development of pressure sensors for clinical and sport applications, (b) discuss the design requirements for pressure measurement systems for different applications, (c) critique the suitability, reliability, and validity of commercial pressure measurement systems, and (d) suggest future directions for the development of pressure measurements systems in this area. Commercial pressure measurement systems generally use capacitive or resistive sensors, and typically capacitive sensors have been reported to be more valid and reliable than resistive sensors for prolonged use. It is important to acknowledge, however, that the selection of sensors is contingent upon the specific application requirements. Recent improvements in sensor and wireless technology and computational power have resulted in systems that have higher sensor density and sampling frequency with improved usability – thinner, lighter platforms, some of which are wireless, and reduced the obtrusiveness of in-shoe systems due to wireless data transmission and smaller data-logger and control units. Future developments of pressure sensors should focus on the design of systems that can measure or accurately predict shear stresses in conjunction with pressure, as it is thought the combination of both contributes to the development of pressure ulcers and diabetic plantar ulcers. The focus for the development of in-shoe pressure measurement systems is to minimise any potential interference to the patient or athlete, and to reduce power consumption of the wireless systems to improve the battery life, so these systems can be used to monitor daily activity. A potential solution to reduce the obtrusiveness of in-shoe systems include thin flexible pressure sensors which can be incorporated into socks. Although some experimental systems are available further work is needed to improve their validity and reliability.

1. Introduction

Pressure measurement systems have numerous applications in healthcare. The most common use is in clinical gait analysis to assist in the prescription and assessment of interventions such as orthotics [1–11], surgery [12–17], medication [18] or rehabilitation programmes [19–23]. They can also be used to provide biofeedback if pressure mapping data is linked to a live display [24–27], and can therefore alert patients and clinicians if patients' plantar pressures are too high, so the patient or clinician can offload the area of high pressure, reducing the risk of pressure ulcers forming [27]. Another application of pressure measurement systems is to aid the design and assessment of prosthetic limbs [28].

Pressure measurement systems also have several applications in sport. They can be used to assess the effect of footwear and terrain on plantar pressures, and the newer wireless systems can be used for athlete monitoring during running [29–37]. Also, pressure measurement systems can be used to help assess the effectiveness of sporting equipment

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* Corresponding author at: Department of Sport, Exercise and Rehabilitation, Faculty of Health & Life Sciences, Northumbria University, Newcastle upon Tyne NE1 8ST, UK.
E-mail address: louise.burnie@northumbria.ac.uk (L. Burnie).

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such as football shin guards [38] or ice-hockey helmet responses to puck impacts [39].

This review aimed to: (a) describe the brief history of the development of pressure sensors for clinical and sport applications, (b) discuss the design requirements for pressure measurement systems for different applications, (c) critique the suitability, reliability, and validity of commercial pressure measurement systems, and (d) suggest future directions for the development of pressure measurements systems in this area.

2. Brief history and development of pressure sensors

Nicol and Henning (1973) developed a capacitive pressure sensor array which resulted in one of the first commercial systems (Novel GmbH) for the measurement of pressure in sport and healthcare [40]. In the 1980s, printed resistive pressure sensors were developed and patented [41,42], with the commercial Tekscan in-shoe system released in the early 1990s [43]. The first commercial pressure sensor arrays had low sampling rates (< 50 Hz) and the platforms were small and could only record one footstep at a time [44,45]. Improvements in sensor and wireless technology and computational power have resulted in systems that have higher sensor density (up to 4 sensors/cm^2) and sampling frequency (up to 400 Hz), with improved usability – thinner, lighter platforms, some of which are wireless [44] (Table A1). Also, recent technological advances have reduced the obtrusiveness of in-shoe systems due to wireless data transmission and smaller data-logger and control units (Table A2).

3. Sensor technology

There are two main types of sensors used in commercial pressure measurement systems: capacitive and resistive. Capacitive sensors comprise two electrically conducting surfaces separated by a compressive dielectric layer [4,46–49]. When pressure is applied, the dielectric layer is compressed which changes the dielectric constant of the material and reduces the distance between the plates, the combination of which alters capacitance and results in a change in voltage [4,48–51]. The dielectric layer should have good elastic recoil properties to minimise hysteresis [4,48]. One manufacturer (AMCube) uses air as the dielectric material in their capacitive pressure sensor [52]. Capacitive sensors have typically been reported to be more accurate and reliable than resistive sensors [44,47,52–56], but they tend to be thicker than resistive sensors [49]. For example, the in-shoe pressure measurement systems that use capacitive sensors range from 1.8 to 2.8 mm in thickness, whereas those that use resistive sensors range from 0.15 to 2.0 mm (Table A2). Capacitive sensors can also be sensitive to temperature, humidity, and electromagnetic interference [57].

Resistive pressure sensors change electrical resistance in response to applied pressure. Force-sensing resistors are an example of a resistive sensor; when pressure is applied to the sensor the resistance of the conductive foam, or a semi-conductive polymer sheet between two electrodes, decreases [44,50,51]. Piezoresistive sensors are a specific type of resistive sensor. They typically consist of two thin polymer sheets printed with conductive circuits, with a pressure-sensitive semi-conductive ink applied between the sheets [4,41,46,47,49,50]; commercially available examples include the Tekscan pressure measurement systems. An increase in pressure results in a decrease in the electrical resistance of the sensor. Piezoresistive sensors can achieve higher sampling rates than capacitive sensors, and their electronics and data output are relatively simple [47]. However, they have several specific disadvantages as they can exhibit non-linearity, poor durability, be affected by temperature and humidity, have a response dependent on loading history and their sensitivity can be altered after repeated use [4,46,47,52,53,56,58–68]. While degradation of the sensor over time will occur, re-equilibration and calibration can help overcome this degradation to a certain point and mean the sensor can continue to provide reliable data.

4. Design requirements for pressure sensors

When designing pressure measurement systems there are several considerations to ensure they provide sufficiently valid and reliable data, and this must be considered in the context of the desired application. Furthermore, many of these specifications are interlinked and they often need to be critically considered in combination as a desired change in one could lead to unwanted compromise in another.

Pressure measurement range: The system must have the capacity to record peak pressures created by the activity of interest without being overloaded which therefore defines the maximum pressure required [4,69]. Reports indicate that peak plantar pressures exceed 1000 kPa in some clinical pathologies such as diabetes and rheumatoid arthritis [70–72]. Also, studies have shown higher plantar pressure recordings during barefoot walking compared to the shod condition [73].

Sampling frequency: Based on previous work, a sampling frequency of 50–100 Hz is recommended for measuring plantar pressures during walking [49,69,74], with a minimum of 100 Hz for barefoot walking [71], and for higher speed activities such as running, a minimum sampling frequency of 200 Hz is recommended [49,57,69,75–78]. The maximum sampling frequency that can be achieved depends on the number of sensors in an array as this influences the electronics sampling rate, along with the quality and specification of the electronics.

Spatial resolution: The individual sensors need to be small enough to measure pressures over the area of interest, for example, the small anatomical structures of the foot, such as the metatarsal heads [4,44,49,51,69,79]. Urry (1999) recommended a minimum of 5 mm × 5 mm spatial resolution for measuring plantar pressures, as larger sensors may underestimate peak pressures [51]. Lord (1997) found that the average pressure measured by a 100 mm^2 sensor may be only 60–70% of the true peak value during barefoot standing [79]. This is particularly important when studying plantar pressure under small feet such as those of children [4,44,49,69]. For curved surfaces, the size of the individual sensors should be small relative to the interface curvature to ensure good contact with the skin, so the pressure applied to any individual sensor is homogenous [80].

Pressure resolution: Several studies use 10 kPa as a minimum pressure resolution for walking assessment in clinical and medical settings [57,71]. The resolution for commercially available systems for measuring plantar pressures ranges from 0.07 to 68 kPa (Table A1 and Table A2). Newly developed pressure sensors have increased sensitivity, particularly at lower pressure ranges [81].

Pressure sensor properties: Ideally, the relationship between the pressure applied to the sensor and the output signal should be linear, as this simplifies the calibration procedures and data processing within the software to convert the electrical output signal to pressure [4,47,69,75,80]. The sensors should exhibit low hysteresis [4,69] – ideally less than 5% full scale [57], low cross-talk between sensors (undesired activation of unloaded sensors when pressure is applied to neighbouring sensors) [4,69] and low drift of the sensor readings over time [75,82] – error less than 5% full scale after more than ten thousand loading-unloading cycles [57]. However, data processing algorithms can be used to compensate for the effects of hysteresis and drift in the pressure readings as long as these effects are known and consistent [83,84]. For long-term monitoring during daily living, low drift is particularly important. Ideally, the sensors should exhibit low temperature sensitivity in the range of 20–37 °C [85]. If the sensors are sensitive to change in temperature, the calibration protocol or data processing needs to account for this [82]. The frequency of the activity being measured should not exceed 60% of the natural frequency of the sensor [51], for example the frequency content of the normal force in walking is below 15 Hz [86], so the natural frequency of a pressure sensor to measure plantar pressures during walking ideally needs to be greater than 25 Hz.

Sensor thickness and flexibility: For applications where the pressure sensor needs to conform to a curved or soft surface, such as within shoes, it needs to be sufficiently flexible and thin to ensure pressure is accurately measured [47,75,82,87]. Ferguson-Pell (1980) recommended a maximum thickness of 0.5 mm for measuring body-support interface pressures, with a small sensor aspect ratio (ratio of sensor thickness to diameter) [80]. Also, when measuring pressure on or within a soft object, the pressure sensor needs to be stretchable (however whether the substrate and/or sensor itself need to be stretchable has not been specified) [47].

Usability: The pressure measuring devices need to be unobtrusive to participants, easy to use, and durable [47,57,80,82,87–89]. For example, it has been suggested that any shoe-mounted device accompanying a pressure insole must be light (less than 300 g) and small (however size was not quantified) [51,57,75,90,91]. The pressure sensors often need to be secured to prevent slippage [60,75], and need to be durable enough to withstand environmental effects, for example humidity, temperature and bending for sensors within shoes [51,57,60].

Software: For systems used in clinical settings, where limited time is typically available during appointments, the software ideally needs to provide real-time data display and visualisation for easy and quick interpretation. Real-time display is also very useful to provide biofeedback to patients or athletes for training or rehabilitation purposes. However, for other applications particularly when pressure measurement systems are used in research studies where the data will be post-processed, real-time data display is not an essential requirement.

Connectivity: Ideally, the data transmission needs to be wireless, to minimise interference to the user, and in the case of gait analysis to ensure comfortable, safe and natural gait [75,91,92]. However, wired systems have the advantages of higher sampling frequencies and sensor spatial resolution which may be necessary for certain applications.

Power supply/consumption: Wearable pressure sensors require low power consumption to minimise battery size and maximise operating time, which is a particularly important consideration for continuous monitoring during daily living [75,93,94].

The above is not an exhaustive list, and other design considerations such as the ability to synchronise with other measurement systems (e.g., video cameras, motion capture systems, EMG) and cost may need to be considered depending on the application.

5. Parameters provided by pressure measurement systems

Pressure measurement systems provide a variety of parameters and metrics which are specific to the application. However, typically these include average and peak pressure (in the case of plantar pressures for the whole foot and in anatomical specific regions), pressure-time integral, force, impulse, contact area, contact time, centre of pressure (CoP), and length of CoP path [4,49,69,95]. Plantar pressure measurement systems can also provide spatiotemporal variables such as stride length, stride frequency, and contact times during walking and running. It is also important that researchers consider using the full time series pressure data to get a more complete understanding of a patient's or athlete's gait or movement pattern [96], rather than just reducing pressure data to discrete values (e.g. peak and average). Also, researchers need to consider using the full spatial distribution of plantar pressures; this can be done by dividing the plantar surface of the foot into anatomical regions. Burnfield et al. (2004) investigated the effect of walking speed on plantar pressures on eight anatomical regions of the foot [73]. They found faster walking speeds resulted in higher plantar pressures in all regions of the foot except for the arch and lateral metatarsals, demonstrating we cannot assume all regions of the foot respond in the same way to an intervention [73]. Pataky et al. (2008) further investigated the effects of walking speed on the spatial distribution of plantar pressures, and compared subsampling the peak pressure data into ten anatomical regions of the foot to using individual pixel data [96]. This resulted in different findings for the mid-foot, highlighting the need to use the full pressure sensor data as subsampling may obscure or reverse statistical trends [96]. Several clinically useful metrics can be derived from the plantar pressure data: peak pressure gradient [97] and peak-average pressure ratio for different plantar regions of the foot [98], which may be indicative of areas at risk of tissue breakdown.

6. Overview of commercially available pressure measurement systems

As highlighted when considering design requirements, the choice of system should be based on matching its performance profile against the requirements of the particular measurement task [51]. This section will discuss the uses and applications of different systems, the relative merits of these systems, general points to consider when using the systems, and their reported validity and reliability (refer to Table A5 for a summary of studies assessing the validity and reliability of commercially available pressure measurement systems).

6.1. Pressure platforms for measuring plantar pressures

Rigid pressure platforms (and mats) are typically used in a clinical setting to measure plantar pressures to assess gait and balance [4,48,75,94,95,99,100] and can also be used to assess plantar pressures during standing sporting movements [101–103]. Commercially available pressure platforms for measuring plantar pressures are detailed in Table A1. The advantages of these platforms are they are easy to use, measure 'true' vertical ground reaction force and can be portable [49]. However, when using pressure platforms to obtain plantar pressures during gait, the participant is required to place their foot in the centre of the measurement area to obtain accurate readings, particularly when a small pressure platform is used [4,49,75,104]. This can result in participants targeting the platform, causing them to alter their gait characteristics [104].

Sampling frequencies in the commercially available platforms range from 5 Hz to 500 Hz, sensor densities from 0.16 to 4 sensors per cm^2, and pressure measurement ranges from 0–200 kPa to 6.25–1562.5 kPa. Only approximately 40% of the platforms assessed measure plantar pressures over 1000 kPa (Table A1) and therefore, the choice of system needs to be carefully considered in the context of the patient group or application. Typically, the pressure platforms are calibrated by the manufacturer in the factory, and most systems (60%) have cabled data transmission, but some have wireless capability.

Pressure sensors for plantar pressure measurement need to be valid and reliable since they are used in biomechanics research and gait clinics to assist in patient diagnosis [105]. The i-FAB-PG consensus statement stated that there were no 'gold-standard' medical plantar pressure measurement devices available in 2012 [71]. Whilst this is an area of constant debate, the EMED pressure platform (Novel GmbH), which consists of capacitive sensors, has been shown to be the most valid and reliable pressure platform for measuring plantar pressures [52,54,55,106–109] (Table A5). However, several studies have demonstrated good reliability of the Tekscan platforms which consist of piezoresistive sensors [54,110–114] (Table A5).

Typically, the reliability of plantar pressure measurements is better for the areas of the foot (metatarsal heads and the heel) that are subjected to higher plantar pressures during walking and running [106,113,115–118]. These are the areas of the foot that researchers or clinicians are typically interested in, as high pressures can cause pain, formation of pressure ulcers, or be indicative of a disease or abnormality [4]. Therefore, many plantar pressure platforms and insole systems use automated masking algorithms within their software to divide the foot into distinct anatomical regions for plantar pressure analysis [44]. Ellis et al. (2011) investigated the accuracy of a ten-region standard masking algorithm which is based on geometric features of the footprint during static and dynamic measurements under normal feet using an EMED-X pressure platform (Novel GmbH) [119]. They found that the auto-masking algorithm accurately identified most foot regions, particularly during gait [119]. More recently, a method has been developed based on anatomical landmarks of the foot and involves integration of 3D motion capture, a plantar pressure measurement device, and a multi-segment foot model [120]. This method was as reliable and repeatable as the geometric mask and is particularly useful when there is a severe alteration in foot-ground contact pattern, such as for patients with clubfoot [120]. The software for many systems can also detect initial contact and toe-off during walking. Some of these programmes have been found to have errors of ~40 ms, but researchers have proposed new algorithms which can reduce this to as low as 10 ms [121].

6.2. In-shoe systems

The commercially available in-shoe pressure measurement systems (Table A2) include insoles, discrete sensors, and socks. One of the main advantages of in-shoe systems is that it is easy to record multiple steps without the likelihood of platform targeting, and therefore participants are more likely to adopt natural gait [46,49,51,95]. In-shoe systems are thus often used to assess dynamic sporting movements, and are particularly suited to measuring plantar pressures during running [29,31,122–125]. As these systems fit within the shoe, they are very suitable for applications such as assessing the effect of different types of footwear on plantar pressure [4,46,49,51,75,95,103,126–132], measuring plantar pressures inside sport-specific footwear [34,35,62,133,134] and helping to prescribe and assess the effect of orthotics in redistributing or reducing plantar pressures [9–11,135–138].

Some in-shoe pressure measurement systems have a data-logger and transmitter attached to a belt around the waist with wires running the length of the leg to connect the pressure insoles to the data recording unit, whilst others have the data recorder attached to the lower leg or shoe (Table A2). The wires, data-logger and transmitter have the potential to interfere with the participant when they are performing a movement. Kong and De Heer (2009) found that an in-shoe system, which had a data-logger on the waist and associated cables from the insoles strapped to the legs, increased participants' stride frequency and decreased their stride length during running [139]. Manufacturers have therefore focused on wireless data transmission and reducing the size and mass of the data-logger/control unit [92], leading to fully wireless systems with a small data-logger attached to the shoe or even incorporated within the insoles themselves (Table A2). However, as highlighted earlier, these can lead to compromises in other specifications such as lower sampling rates and a smaller number of sensors [92]. Some of the completely wireless systems can often be thicker than the wired systems, as the power supply (battery) and data transmitter are incorporated within the insoles (Table A2). This has the potential to influence plantar pressures and may cause discomfort to the participant due to the addition of a thicker, stiffer insole [78]. The in-shoe pressure measurement systems typically have a battery life in the range from 1.5 to 8 h which is primarily influenced by battery size and sampling frequency (Table A2). The in-shoe systems typically have lower spatial resolution compared to platform systems due to fewer sensors [75,78] (Table A1, Table A2), and these sensors are more susceptible to degradation as they are subjected to bending within the shoe, as well as heat and humidity generated within footwear [44,46,49]. Another consideration is that data quality is affected by the slippage of the sole of the foot relative to the insoles [57]. Most of the insole systems are provided in set shoe sizes, however, the F-Scan insoles (Tekscan) can be cut to size, so researchers and clinicians do not need a full set of different sized insoles - although they are typically single use (Table A2).

The systems which have data-logger or wireless capability have the advantage of allowing data to be collected outside the laboratory when participants are performing their daily tasks or sporting movement. Diverse examples range from monitoring the effect of disease progression on gait [57] to measuring plantar pressures during trail running [29], skateboarding [30], and sports (e.g. running, tennis, soccer) on different court surfaces [31–33]. Several of the newer wireless in-shoe systems link to a smartphone app (Table A2), which means the users, clinicians or coaches can obtain real-time monitoring with visual or auditory feedback which can be used in attempts to alter behaviour and/or alert them to a potential issue [25,27,94,140–146].

In-shoe systems measure force normal to the plane of the insole, so this is not a 'true' vertical ground reaction force, as it is not a totally flat surface and the foot and shoe bend during ground contact [49]. However, researchers have often assessed the validity of various in-shoe pressure measurement systems by comparing the normal force measured by the insoles when a participant walks or runs to the vertical ground reaction force simultaneously measured by a force plate and therefore caution must therefore be applied when interpreting these comparisons [60–62,64,67,77,83,117,121,140,141,147–160].

The Pedar insole system (Novel GmbH), which consists of capacitive sensors, has been shown to be the most valid and reliable in-shoe system for measuring plantar pressures in published research studies [53,56,78,83,84,95,151,161–165] (Table A5). A recent study has also demonstrated good reliability and validity of the X4 insoles (XSENSOR Technologies) [166]. Price et al. (2016) found the Pedar system was more valid and reliable than two other commercially available systems which comprised resistive sensors [53], but it must be remembered that other systems may be more suited for certain applications due to the wired nature and relative cost of the Pedar system. Furthermore, for some systems (e.g. F-Scan in-shoe system, Tekscan) several researchers have demonstrated that the validity and reliability can be further improved by using alternative calibration procedures [56,58,95,163]. A recent DELPHI-derived consensus provides guidance on use of the F-Scan system and appropriate measurement protocols to reduce potential systematic error and highlight system limitations [167]. In a recent study, the reliability of F-Scan insoles in predicting 3D ground reaction forces (GRFs) during walking was evaluated using recurrent neural networks [168]. Additionally, the accuracy of predicted GRFs was compared between walking and jogging, considering the increased shear and bending loads on the sensors during jogging [168]. The study utilised long short-term memory (LSTM) networks, which effectively capture the time-dependent patterns of pressure and force data [168]. The results demonstrated a high level of accuracy in predicting 3D GRFs [168]. These findings suggest that the integration of more advanced models and neural networks into plantar pressure systems can enable the real-time monitoring and analysis of forces, and wearable plantar pressure insoles could therefore become cost effective alternative to force plates for real-time reflection of GRFs.

There are some wireless insoles that contain discrete sensors (range 8–37) which can provide real-time feedback (Table A2). As these insoles contain discrete sensors, and not a full pressure sensor array covering the whole insole, they do not provide comparable data to pressure platforms. Nagahara and Morin (2018) found poor agreement in vertical ground reaction forces, support time and flight time during sprint running between a force plate system and wireless insoles sampling at 50 Hz [77]. As the support time during maximal sprint running is approximately 0.1 s [77], wireless in-shoe pressure systems require higher sampling frequencies to be suitable for such applications with short contact times and rapid rate of force development [77,78]. An example of the new wireless insoles is the SurroSense Rx intelligent insole system (previous model of the Orpyx SI insole; Orpyx Medical Technologies) which was designed for monitoring and providing feedback to patients with diabetes. The insole contains eight sensors linked to a smartwatch which can give the wearer a warning of high plantar pressure in a specified location and will continue to give alerts until the area is offloaded. This system was used by Abbott et al. (2019) in patients with diabetes, peripheral neuropathy and a recent history of plantar foot ulceration, with the intelligent insoles resulting in a 71% reduction in ulcer incidence compared to a control group [27].

A further, recent development is smart socks which incorporate textile pressure sensors into socks to measure plantar pressures. These can be used to calculate temporal gait parameters such as stance and stride duration, step frequency, and to classify foot strike (i.e., heel, mid or forefoot) [78,169,170]. There is one commercially available smart sock, the Sensoria Sock 2.0 (Sensoria Inc.) (Table A2). The sock contains three textile pressure sensors integrated into the plantar surface and has a removable inertial measurement unit (IMU) attached at ankle level, so the socks can be washed. The Sensoria Sock has been found to measure similar static CoP path length to a pressure platform [171]. The price of in-shoe systems vary depending on the product specifications and intended use. For systems to be adopted for everyday large scale use, such as patient monitoring of in-shoe pressures, affordability is a key consideration [78], and this likely means a considered compromise in other specifications.

6.3. *Pressure treadmills*

Typically, pressure treadmills are used for gait retraining by providing visual cues or perturbations, and then monitoring the effect of these on gait and plantar pressures [172–175]. The commercially available pressure treadmill systems are detailed in Table A3. Of the four pressure treadmills manufactured, only the FDM-T treadmill (Zebris GmbH) has been assessed for reliability [116,165,176,177] (Table A5). The FDM-T treadmill, which consists of capacitive sensors, has demonstrated moderate to excellent within- and between-session reliability for peak forces and pressures and spatiotemporal gait parameters during walking and running [116,176]. However, it is important to be cautious when comparing pressure data obtained from overground walking to that of treadmill walking, as previous research has consistently shown variations in gait patterns between the two modes of locomotion [178,179].

6.4. *General flexible pressure sensors*

The commercially available flexible pressure measurement systems that have been used for sport and health applications include general flexible pressure sensor arrays for measuring pressures between two objects in direct contact, such as measuring prosthesis-limb interface pressures and measuring bone joint contact pressures (Table A4). There are a couple of systems specifically designed for measuring prosthesis-limb interface pressures (Table A4), although none of the current versions of these systems have been assessed for validity.

Orthopaedic surgeons, biomedical engineers and researchers often want to measure bone joint contact pressures and size of contact area to assess the effect of different surgical techniques [180–183], inform surgical decisions and assess joint replacement devices [184]. Several of the flexible sensors detailed in Table A4 can be used for measuring joint pressures and contact areas and have been found to be more accurate than the film pressure measuring systems which were used previously for measuring contact forces, pressures and areas between articulating bones [184–188], and they have the further advantage of providing real-time measurements [184,185] (Table A5). However, some of the systems have been found to suffer drift, so the time point at which the measurements are taken should be standardised, and the calibration procedure should use the same time interval from load applied to the sensor as the testing protocol [185]. Another consideration when measuring bone contact pressures is the location of the sensors, as pressure readings are affected by the mounting surface (on top of the cartilage or directly on the bone), and also whether they are cemented in place [186–188].

7. Limitations of current pressure measurement systems

When choosing a pressure measurement system, the user clearly needs to decide on their priorities. Currently there is no small, in-shoe wireless system with a large number of sensors, high sampling rate and long battery life and therefore appropriate compromises must be made based on what is important for the particular application. One main current limitation of commercial pressure measurement systems is they cannot measure shear stress in conjunction with pressure, but the recent advances in the application of neural networks to predict 3D ground reaction forces from pressure data demonstrate great potential in this application [168]. Also, the effect of concurrent shear stress on the accuracy of pressure sensor measurements has not been reported in the literature or by the manufacturers, and it is likely that various devices will respond differently [46]. Accordingly, validation studies should assess the effects of concurrent shear stress and pressure on the accuracy of the perpendicular pressure sensor readings.

Thin, flexible pressure sensors exhibit greater hysteresis (typically greater than 5%) and drift compared to rigid pressure sensors [47]. These are inherent properties of the polymer materials required to achieve a flexible sensor and result in higher inaccuracy compared to conventional inflexible sensors [47]. Therefore, the challenge for manufacturers and designers of thin flexible sensors is to minimise these effects on the pressure readings. Another issue with pressure measurement systems is they can experience drift in pressure sensor readings when used continuously [52,53,58,61,63–66,83,84,162,185,189–191], with even some of the more valid and reliable sensors suffering drift of up to 17% after 3 h, and 34% after 7 h [83,189]. It is suggested that correction factors can be applied to the measured pressure sensor values to account for the effects of drift [84,185,189,190], and this can reduce the errors in the force and CoP measurements by 50% [190].

8. Future directions and challenges for the development of new pressure measurement systems

The focus for future development of in-shoe pressure measurement systems is to continue to reduce sensor thickness to minimise any potential interference to the patient or athlete, and to reduce power consumption of the wireless systems to improve the battery life, so these systems can be used to monitor daily activity [57,75,92,94,192]. Developers are trying to increase the sensor density and sampling frequency of these wireless systems, so they can provide research quality data outside of the laboratory. Several of the new in-shoe systems include other sensors such as IMUs which provide additional information which can be useful for characterising gait, and temperature sensors which can be used to assess the risk of a diabetic patient developing plantar ulcers [57,193–196]. The continued developments in flexible electronics, miniaturisation of electronics, battery free power, and data processing and classification algorithms will support the continued advancement of in-field measurement of plantar pressures [57,78].

New improved tools for giving feedback are continually being developed, an example being the tool developed by Turner et al. (2021) to visualise the real-time pressures at prosthetic socket–residuum interface to give clinicians and prosthetists feedback to help with prosthetic socket fitting [197]. This system is wireless and the software provides a colour map across the surface of a 3D prosthetic socket model, so clinicians can identify the locations of high pressure which may result in skin breakdown [197–199]. The smartphone apps that link to pressure sensors will continue to be developed further, incorporating more advanced data processing algorithms to provide more detailed feedback to the users, clinicians, and coaches.

Several researchers have demonstrated the potential of using the data obtained from pressure measurement devices to predict ground reaction forces, joint kinetics or classify patients' posture or gait [70,168,200–206]. For example, the information from pressure insoles can be used to predict ground reaction forces in walking and running [168,200–202], whilst data from landing from horizontal jumps suggests that pressure insoles can be used to predict kinetic knee asymmetry and therefore potentially screen athletes following anterior cruciate ligament reconstruction surgery [203]. In addition to the promising work of neural networks to predict 3D GRFs, other applications of neural networks and machine learning include classification of the existence of a variety of different conditions/pathologies based on pressure sensor readings which has potential for healthcare monitoring and diagnosis [57,94,207,208].

There is a need to develop pressure measurement systems that can measure shear stresses in conjunction with pressure, as it is thought the combination of both contributes to the development of pressure ulcers and diabetic plantar ulcers [46,49,193,209–211]. However, a recent demonstration that these can be predicted from pressure sensor data using neural networks is promising [168]. The simultaneous measurement of pressure and shear stresses has been demonstrated in some research papers [210,212–220]. However, these systems are difficult to use and not suitable for clinical use, as they often use pressure sensitive film that requires post analysis to obtain pressure and shear stresses, or the systems involve pressure and shear stress being measured in separate trials.

There has been development in textile pressure sensors which can be used for measuring plantar pressures and seat pressures, for breath and activity monitoring and as tactile sensors [75,78,133,169,221–226]. Some of these textile pressure sensors have incorporated nanomaterials such as graphene [224]. However, textile pressure sensors are often characterised by high hysteresis and non-linearity [78,223]. A recent development is smart socks (such as the aforementioned Sensoria smart sock) which incorporate textile pressure sensors into socks to measure plantar pressures which can be used to calculate temporal gait parameters [78,169–171,227,228]. The Sensoria socks have been demonstrated to accurately measure step number and velocity, but further developments are required to enable them to determine other metrics such as cadence before they can be used for daily monitoring for health and sport applications [227]. A further potential application of smart socks could be to measure the pressures between the upper of the shoe and the foot, which could be important for diabetic patients, as currently there is only the Pedar pad (Novel GmbH) that can measure pressure at this interface.

Flexible pressure sensors for wearable applications and devices are currently receiving considerable research and engineering interest due to potential applications for medical diagnostics and health and fitness wearables, such as for the monitoring of pulse, blood-pressure and heart rate [93,229,230]. These include flexible pressure sensors for electronic skin (e-skin) applications, such as in intelligent robotics, human-machine interactions and biomimetic prostheses [93,230–232]. Recently, near transparent skin-like pressure sensors have been developed which present new opportunities for wearable sensors [93,231]. There has been a significant improvement in properties of these sensors, so they are lightweight, highly flexible, foldable, low cost, have a quick response time (< 100 ms) and have portable data processing and reduced power consumption which are required for wearable health monitoring devices [93,229]. The development in flexible pressure sensors has corresponded with the advances in flexible stretchable electronics which are required to fabricate large-area, low-cost pressure sensors [93,94]. These new pressure sensor devices are often multifunctional, for example, they can measure temperature as well as pressure which is useful for healthcare monitoring [93]. Researchers are currently investigating if it is possible to develop self-powered pressure sensors for wearables which would be ideal for long-term monitoring as the batteries would not need to be replaced or recharged [93].

9. Conclusions

To summarise this comparative review of pressure sensors for sport and health applications:

- Commercial pressure measurement systems generally use capacitive or resistive sensors, and typically capacitive sensors have been reported to be more valid and reliable than resistive sensors.
- Improvements in sensor and wireless technology and computational power have resulted in systems that have higher sensor density and sampling frequency with improved usability – thinner, lighter platforms, some of which are wireless, and reduced the obtrusiveness of in-shoe systems due to wireless data transmission and smaller datalogger and control units.
- When designing or selecting pressure measurement systems for a specific application, considerations include pressure measurement range, sampling frequency, spatial resolution, pressure resolution, pressure sensor properties, sensor thickness and flexibility, usability, software, connectivity, and power supply/consumption. Many of these specifications are interlinked, so must be appraised in the context of the desired application.
- There is a need to develop commercial pressure measurement systems that can measure shear stresses in conjunction with pressure, as it is thought the combination of both contributes to the development of pressure ulcers and diabetic plantar ulcers.
- Future developments of thin flexible pressure sensors including textile sensors need to focus on reducing the effects of hysteresis and drift on the pressure sensor readings to improve their validity and reliability.

In addition to sensor selection, ensuring the use of proper protocols for data collection and sensor calibration is extremely crucial. Most systems provide the option to calibrate sensors, but it is essential to consider the material properties of the surface being measured or used for calibration, as they can impact the sensor results significantly. In our follow-up article we will discuss the importance of appropriate calibration procedures and data collection protocols to ensure reliable and valid pressure data is collected with pressure measurement systems. It is important to exercise caution when interpreting previous papers and results as inadequate calibration practices may have influenced their findings. We will also discuss the analysis and interpretation of pressure data in clinical gait analysis as this is a key stage to ensure appropriate treatment options are selected by the clinician. Artificial intelligence offers the potential to assist clinicians in the analysis and interpretation of pressure data.

Declaration of Competing Interest

None.

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Appendix A. Supporting information

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