The Foot 59 (2024) 102094

Contents lists available at ScienceDirect

The Foot

journal homepage: www.elsevier.com/locate/foot

Review

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

Louise Burnie [a,b,*], Nachiappan Chockalingam [c], Alex Holder [d], Tim Claypole [e], 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] A-Gas, Bristol, UK
[e] Welsh Centre for Printing and Coating (WCPC), Faculty of Science and Engineering, Swansea University, Swansea SA1 8EN, UK

ARTICLE INFO

Keywords:
Health monitoring
Gait assessment
Plantar pressure
Pressure measurement
Sensors
Sports technology

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)

* 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).

https://doi.org/10.1016/j.foot.2024.102094
Received 16 February 2024; Accepted 24 March 2024
Available online 28 March 2024

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 by 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 encourage 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.

Acknowledgements

This research was funded by the European Regional Development Fund - Application of Functionalised Micro and Nano Materials (AFM^2) - scale up to volume production, under the SMARTExpertise programme (#2018/COL/014).

References

[1] Bus SA, Waaijman R, Arts M, de Haart M, Busch-Westbroek T, van Baal J, et al. Effect of custom-made footwear on foot ulcer recurrence in diabetes: a multicenter randomized controlled trial. Diabetes Care 2013;36:4109–16.
[2] Castro MP, Soares D, Mendes E, Machado L. The influence of different in-shoe inserts on the plantar pressure during the gait of healthy elderly people. Gait Posture 2012;36:S16.
[3] Dixon SJ, McNally K. Influence of orthotic devices prescribed using pressure data on lower extremity kinematics and pressures beneath the shoe during running. Clin Biomech 2008;23:593–600.
[4] Rosenbaum D, Becker HP. Plantar pressure distribution measurements. Technical background and clinical applications. Foot Ankle Surg 1997;3:1–14.
[5] Franklyn-Miller A, Wilson C, Bilzon J, McCrory P. Foot orthoses in the prevention of injury in initial military training: a randomized controlled trial. Am J Sports Med 2011;39:30–7.
[6] Wilssens J. Can the RSscan footscan system predict and reduce injuries? Footwear Sci 2009;1:87–8.
[7] Hsieh CJ, Kuo FL, Yang SW, Hsieh LF. Effect of Functional Knee Brace and Lateral Wedge Insole in Management of Patients with Osteoarthritic Knee. J Biomech 2007;40:S449.
[8] Windle CM, Gregory SM, Dixon SJ. The shock attenuation characteristics of four different insoles when worn in a military boot during running and marching. Gait Posture 1999;9:31–7.
[9] Zhang X, Li B. Influence of in-shoe heel lifts on plantar pressure and center of pressure in the medial-lateral direction during walking. Gait Posture 2014;39:1012–6.
[10] Kearney RS, Lamb SE, Achten J, Parsons NR, Costa ML. In-shoe plantar pressures within ankle-foot orthoses: implications for the management of Achilles tendon ruptures. Am J Sport Med 2011;39:2679–85.
[11] Tang UH, Zügner R, Lisovskaja V, Karlsson J, Hagberg K, Tranberg R. Comparison of plantar pressure in three types of insole given to patients with diabetes at risk of developing foot ulcers - a two-year, randomized trial. J Clin Transl Endocrinol 2014;1:121–32.
[12] Lorei TJ, Kinast C, Klärner H, Rosenbaum D. Pedographic, clinical, and functional outcome after scarf osteotomy. Clin Orthop Relat Res 2006;451:161–6.
[13] Wetke E, Zerahn B, Kofoed H. Prospective analysis of a first MTP total joint replacement. Evaluation by bone mineral densitometry, pedobarography, and visual analogue score for pain. J Foot Ankle Surg 2012;18:136–40.
[14] Morasiewicz P. Pedobarographic evaluation of body weight distribution on the lower limbs and balance after derotation corticotomies using the Ilizarov method. Acta Bioeng Biomech 2013;15:91–6.
[15] Tulchin K, Jeans KA, Karol LA, Crawford L. Plantar pressures and ankle kinematics following anterior tibialis tendon transfers in children with clubfoot. J Foot Ankle Res 2012;5:O32.
[16] Kamenaga T, Nakano N, Takayama K, Tsubosaka M, Takashima Y, Kikuchi K, et al. Comparison of plantar pressure distribution during walking and lower limb alignment between modified kinematically and mechanically aligned total knee arthroplasty. J Biomech 2021;120:110379. https://doi.org/10.1016/j.jbiomech.2021.110379.
[17] Holl B, Wewerka G, Bartsch H, Malisa M, Illhardt C, Pilz G, et al. Extensive semi-automated gait analysis by Zebris FDM during treatment of multiple sclerosis associated gait disturbances with PR-fampridine. J Neurol Sci 2013;333:e390. https://doi.org/10.1016/j.jns.2013.07.1415.
[18] Druzbicki M, Rusek W, Szczepanik M, Dudek J, Snela S. Assessment of the impact of orthotic gait training on balance in children with cerebral palsy. Acta Bioeng Biomech 2010;12:53–8.
[19] Suciu O, Onofrei RR, Totorean AD, Suciu SC, Amaricai EC. Gait analysis and functional outcomes after twelve-week rehabilitation in patients with surgically treated ankle fractures. Gait Posture 2016;49:184–9.
[20] Taniguchi M, Sawano S, Kugo M, Maegawa S, Kawasaki T, Ichihashi N. Physical activity promotes gait improvement in patients with total knee arthroplasty. J Arthroplast 2016;31:984–8.
[21] Krauss I, Steinhilber B, Haupt G, Miller R, Grau S, Janssen P. Efficacy of conservative treatment regimes for hip osteoarthritis-Evaluation of the therapeutic exercise regime" Hip School": A protocol for a randomised, controlled trial. 2011 BMC Musculoskelet Disord 2011;12:270. https://doi.org/10.1186/1471-2474-12-270.
[22] Björklund G, Swarén M, Born D, Stöggl TL. Biomechanical adaptations and performance indicators in short trail running. Front Physiol 2019;10:506. https://doi.org/10.3389/fphys.2019.00506.
[23] Leuchanka A, Ewen J, Cooper B. Bipedal in-shoe kinetics of skateboarding - the ollie. Footwear Sci 2017;9:S122–4.
[24] Tessutti V, Ribeiro AP, Trombini-Souza F, Sacco IC. Attenuation of foot pressure during running on four different surfaces: asphalt, concrete, rubber, and natural grass. J Sport Sci 2012;30:1545–50.
[25] Damm L, Starbuck C, Stocker N, Clarke J, Carré M, Dixon S. Shoe-surface friction in tennis: influence on plantar pressure and implications for injury. Footwear Sci 2014;6:155–64.
[26] Eils E, Streyl M, Linnenbecker S, Thorwesten L, Völker K, Rosenbaum D. Characteristic plantar pressure distribution patterns during soccer-specific movements. Am J Sport Med 2004;32:140–5.
[27] Buckeridge E, LeVangie MC, Stetter B, Nigg SR, Nigg BM. An on-ice measurement approach to analyse the biomechanics of ice hockey skating. PLoS One 2015;10:e0127324. https://doi.org/10.1371/journal.pone.0127324.

[28] Matsumura S, Ohta K, Yamamoto S, Koike Y, Kimura T. Convenient method for detecting ski-turn features with inertial and plantar pressure sensors. Proceedings 2020;49:24. https://doi.org/10.3390/proceedings2020049024.
[29] Perttunen J, Kyrolainen H, Komi PV, Heinonen A. Biomechanical loading in the triple jump. J Sport Sci 2000;18:363–70.
[30] Worsfold P, Smith NA, Dyson RJ. Kinetic assessment of golf shoe outer sole design features. J Sport Sci Med 2009;8:607–15.
[31] Burnie, L.; Chockalingam, N.; Holder, A.; Claypole, T.; Kilduff, L.; Bezodis, N. Commercially available pressure sensors for sport and health applications: A comparative review. 2023;102046. https://doi.org/10.1016/j.foot.2023.102046.
[32] Giacomozzi C, Healy A, Chockalingam N. Chapter 4: Gait analysis – kinetics. In: Chockalingam N, editor. Technologies and techniques in gait analysis, e-book. The Institution of Engineering and Technology; 2022. p. 85–107.
[33] Razak A, Hadi A, Zayegh A, Begg RK, Wahab Y. Foot plantar pressure measurement system: A review. Sensors 2012;12:9884–912.
[34] Guo Y, Wang L. Recent advance in plantar pressure measurement systems. Sens Transducers 2012;145:96–105.
[35] Deepashini H, Omar B, Paungmali A, Amaramalar N, Ohnmar H, Leonard J. An insight into the plantar pressure distribution of the foot in clinical practice: Narrative review. Pol Ann Med 2014;21:51–6.
[36] Nigg BM. Pressure distribution. In: Nigg BM, Herzog W, editors. Biomechanics of the musculo-skeletal system. Chichester: Wiley; 2007. p. 225–36.
[37] Ramirez-Bautista JA, Huerta-Ruelas JA, Chaparro-Cárdenas SL, Hernández-Zavala A. A review in detection and monitoring gait disorders using in-shoe plantar measurement systems. IEEE Rev Biomed Eng 2017;10:299–309.
[38] Alexander IJ, Chao EYS, Johnson KA. The assessment of dynamic foot-to-ground contact forces and plantar pressure distribution: a review of the evolution of current techniques and clinical applications. Foot Ankle 1990;11:152–67.
[39] Brand RA. Assessment of musculoskeletal disorders by locomotion analysis: a critical historical and epistemological review. In: Capozzo A, Marchetti M, Tosi V, editors. Biolocomotion: A Century of Research Using Moving Pictures. Roma, Italy: Promograph; 1992. p. 227–42.
[40] Pawelka S, Kopf A, Zwick E, Bhm T, Kranzl A. Comparison of two insole materials using subjective parameters and pedobarography (pedar-system). Clin Biomech 1997;12:S6–7.
[41] Carter K, Chockalingam N. An assessment of strapping techniques commonly used for pronated foot deformities. J Am Podiatr Med Assoc 2009;99:391–8.
[42] Newell T, Simon J, Docherty CL. Arch-taping techniques for altering navicular height and plantar pressures during activity. J Athl Train 2015;50:825–32.
[43] Becker HP, Rosenbaum D, Kriese T, Gerngross H, Claes L. Gait asymmetry following successful surgical treatment of ankle fractures in young adults. Clin Orthop Relat Res 1995;311:262–9.
[44] Tomanova M, Lippert-Grüner M, Lhotska L. Specific rehabilitation exercise for the treatment of patients with chronic low back pain. J Phys Ther Sci 2015;27:2413–7.
[45] Cavanagh PR, Ulbrecht JS. Clinical plantar pressure measurement in diabetes: rationale and methodology. Foot 1994;4:123–35.
[46] Cavanagh PR, Lipsky BA, Bradbury AW, Botek G. Treatment for diabetic foot ulcers. Lancet 2005;366:1725–35.
[47] Owings TM, Apelqvist J, Stenström A, Becker M, Bus SA, Kalpen A, et al. Plantar pressures in diabetic patients with foot ulcers which have remained healed. Diabet Med 2009;26:1141–6.
[48] Al-Angari HM, Khandoker AH, Lee S, Almahmeed W, Al Safar HS, Jelinek HF, et al. Novel dynamic peak and distribution plantar pressure measures on diabetic patients during walking. Gait Posture 2017;51:261–7.
[49] Giacomozzi C, Martelli F. Peak pressure curve: an effective parameter for early detection of foot functional impairments in diabetic patients. Gait Posture 2006;23:464–70.
[50] Solano MP, Prieto LM, Varon JC, Moreno M, Boulton A. Ethnic differences in plantar pressures in diabetic patients with peripheral neuropathy. Diabet Med 2008;25:505–7.
[51] Yavuz M, Erdemir A, Botek G, Hirschman G. Peak Plantar Pressure and Shear Locations: Relevance to diabetic patients. Diabetes Care 2007;30:2643–5. https://doi.org/10.2337/dc07-0862.
[52] Chatwin KE, Abbott CA, Boulton AJ, Bowling FL, Reeves ND. The role of foot pressure measurement in the prediction and prevention of diabetic foot ulceration—A comprehensive review. Diabetes Metab Res 2020;36:e3258. https://doi.org/10.1002/dmrr.3258.
[53] Okada Y, Fukumoto T, Takatori K, Nagino K, Hiraoka K. Abnormalities of the first three steps of gait initiation in patients with Parkinson's disease with freezing of gait. Park Dis 2011;2011. https://doi.org/10.4061/2011/202937.
[54] Rusu L, Neamtu MC, Rosulescu E, Cosma G, Dragomir M, Marin MI. Analysis of foot and ankle disorders and prediction of gait in multiple sclerosis rehabilitation. Eur J Med Res 2014;19. https://doi.org/10.1186/s40001-014-0073-5.
[55] Kalron A, Givon U, Frid L, Dolev M, Achiron A. Static posturography and falls according to pyramidal, sensory and cerebellar functional systems in people with multiple sclerosis. PLoS One 2016;11:e0164467. https://doi.org/10.1371/journal.pone.0164467.
[56] Kalron A. Symmetry in vertical ground reaction force is not related to walking and balance difficulties in people with multiple sclerosis. Gait Posture 2016;47:48–50.
[5] Giacomozzi C, Martelli F, Nagel A, Schmiegel A, Rosenbaum D. Cluster analysis to classify gait alterations in rheumatoid arthritis using peak pressure curves. Gait Posture 2009;29:220–4.
[58] NICE Diabetic foot problems: prevention and management (NG19); 2015; ⟨https://www.nice.org.uk/guidance/ng19/resources/diabetic-foot-problems-prevention-and-management-pdf-1837279828933⟩.
[59] MacDonald DJ. A Pilot Study Investigating the Impact of a Pressure Mat Intervention on the Performance of Novice Golfers. Int J Golf Sci 2016;5:152–62.
[60] Radivoj V, Irina VA. Mechanism of pose regulation and distribution characteristics under feet in air-gun shooters. Footwear Sci 2009;1:67–9.
[61] Rubin P, Vasiljev R, Vasiljev I, Milosavljevic S. Comparing the foot loading characteristics of female basketball players when initiating offence. Footwear Sci 2011;3:S138–40.
[62] Willems TM, De Ridder R, Roosen P. The effect of a long-distance run on plantar pressure distribution during running. Gait Posture 2012;35:405–9.
[63] Breine B, Malcolm P, Frederick EC, DeClercq D. Initial foot contact patterns during steady state shod running. Footwear Sci 2013;5:S81–2.
[64] Askari Z, Esmaeili H. Effect of trunk muscles fatigue on plantar pressure distribution in novice runners. J Biomech 2021. https://doi.org/10.1016/j.jbiomech.2021.110487.
[65] Nunns M, Rice H, House C, Fallowfield J, Allsopp AS, Dixon, S V. A prospective study identifying risk factors for tibial stress fracture in Royal Marine recruits: initial findings. Footwear Sci 2013;5:S123–4.
[66] Sharma J, Golby J, Greeves J, Spears IR. Biomechanical and lifestyle risk factors for medial tibia stress syndrome in army recruits: a prospective study. Gait Posture 2011;33:361–5.
[67] Rice H, Nunns M, House C, Fallowfield J, Allsopp A, Dixon S. High medial plantar pressures during barefoot running are associated with increased risk of ankle inversion injury in Royal Marine recruits. Gait Posture 2013;38:614–8.
[68] Van Ginckel A, Thijs Y, Hesar NGZ, Mahieu N, De Clercq D, Roosen P, et al. Intrinsic gait-related risk factors for Achilles tendinopathy in novice runners: a prospective study. Gait Posture 2009;29:387–91.
[69] Willems TM, De Clercq D, Delbaere K, Vanderstraeten G, De Cock A, Witvrouw E. A prospective study of gait related risk factors for exercise-related lower leg pain. Gait Posture 2006;23:91–8.
[70] Ghani Zadeh Hesar N, Van Ginckel A, Cools A, Peersman W, Roosen P, De Clercq D, et al. A prospective study on gait-related intrinsic risk factors for lower leg overuse injuries. Br J Sports Med 2009;43:1057–61. https://doi.org/10.1136/bjsm.2008.055723.
[71] Willems TM, Witvrouw E, Delbaere K, De Cock A, De Clercq D. Relationship between gait biomechanics and inversion sprains: a prospective study of risk factors. Gait Posture 2005;21:379–87.
[72] Romero-Franco N, Gallego-Izquierdo T, Martínez-López EJ, Hita-Contreras F, Catalina OM, Martínez-Amat A. Postural stability and subsequent sports injuries during indoor season of athletes. J Phys Ther Sci 2014;26:683–7.
[73] Romero-Franco N, Martínez-López EJ, Lomas-Vega R, Hita-Contreras F, Osuna-Pérez MC, Martínez-Amat A. Short-term effects of proprioceptive training with unstable platform on athletes' stabilometry. J Strength Cond Res 2013;27:2189–97.
[74] Urry S. Plantar pressure-measurement sensors. Meas Sci Technol 1999;10:R16–32.
[75] Claverie L, Ille A, Moretto P. Discrete sensors distribution for accurate plantar pressure analyses. Med Eng Phys 2016;38:1489–94.
[76] Chen J, Dai Y, Grimaldi NS, Lin J, Hu B, Wu Y, et al. Plantar pressure-based insole gait monitoring techniques for diseases monitoring and analysis: a review. Adv Mater Technol 2022;7:2100566. https://doi.org/10.1002/admt.202100566.
[77] Cavanagh PR, Hewitt Jr, FG, Perry JE. In-shoe plantar pressure measurement: a review. Foot 1992;2:185–94.
[78] Orlin MN, McPoil TG. Plantar pressure assessment. Phys Ther 2000;80:399–409.
[79] Tao H, Joyce L, Kozak B, Luiken J, Wendt N. Spatiotemporal comparison of overground and treadmill running with pressure sensor insoles in division I collegiate runners. Int J Sports Phys Ther 2019;14:731–9.
[80] Bravo-Aguilar M, Gijón-Noguerón G, Luque-Suarez A, Abian-Vicen J. The influence of running on foot posture and in-shoe plantar pressures. J Am Podiatr Med Assoc 2016;106:109–15.
[81] Fourchet F, Kelly L, Horobeanu C, Loepelt H, Taiar R, Millet GP. Comparison of plantar pressure distribution in adolescent runners at low vs. high running velocity. Gait Posture 2012;35:685–7.
[82] Mally F, Hofstätter O, Eckelt M. In-shoe plantar pressure measurement - influence of insole placement on selected parameters during running. Proceedings 2020;49:50. https://doi.org/10.3390/proceedings2020049050.
[83] B.A. MacWilliams P.F. Armstrong Clinical applications of plantar pressure measurement in pediatric orthopedics Pediatr Gait: A N Millenn Clin Care Motion Anal Technol, July 22, 2000; Chic, IL, USA 2000 143 150.
[84] Lam W, Ng WX, Kong PW. Influence of shoe midsole hardness on plantar pressure distribution in four basketball-related movements. Res Sport Med 2017;25:37–47.
[85] Orendurff MS, Rohr ES, Segal AD, Medley JW, Green III, Kadel JR, et al. Regional foot pressure during running, cutting, jumping, and landing. Am J Sport Med 2008;36:566–71.
[86] Hu X, Li JX, Hong Y, Wang L. Characteristics of plantar loads in maximum forward lunge tasks in badminton. PLoS One 2015;10:e0137558. https://doi.org/10.1371/journal.pone.0137558.
[87] Nunns M, Stiles V, Dixon S. The effects of standard issue Royal Marine recruit footwear on risk factors associated with third metatarsal stress fractures. Footwear Sci 2012;4:59–70.
[88] Nunns M, Dixon SJ, Clarke J, Carré M. Boot-insole effects on comfort and plantar loading at the heel and fifth metatarsal during running and turning in soccer. J Sports Sci 2016;34:730–7.

[89] Greenhalgh A, Chatterly F, Blewitt C, Sinclair J, Chockalingam N. Plantar pressure distribution in ice skates while gliding and standing compared to barefoot and trainer conditions. Balt J Health Phys Act (Online) 2013;5:243–8.
[90] Krüger A, Edelmann-Nusser J. Biomechanical analysis in freestyle snowboarding: application of a full-body inertial measurement system and a bilateral insole measurement system. Sport Technol 2009;2:17–23.
[91] Holleczek, T. ; Rüegg, A. ; Harms, H. ; Tröster, G. Textile pressure sensors for sports applications. In SENSORS, 2010 IEEE, November 1 - 4, 2010; Waikoloa, HI, USA, 2010; p. 732–737.
[92] Schuh R, Trnka H, Sabo A, Reichel M, Kristen K. Biomechanics of postoperative shoes: plantar pressure distribution, wearing characteristics and design criteria: a preliminary study. Arch Orthop Trauma Surg 2011;131:197–203.
[93] McLauchlan PT, Abboud RJ, Rowley DI, Rendall G. Use of an in-shoe pressure system to investigate the effect of two clinical treatment methods for metatarsalgia. Foot 1994;4:204–8.
[94] Brown M, Rudicel S, Esquenazi A. Measurement of dynamic pressures at the shoe-foot interface during normal walking with various foot orthoses using the FSCAN system. Foot Ankle Int 1996;17:152–6.
[95] Drăgulinescu A, Drăgulinescu A, Zincă G, Bucur D, Feieș V, Neagu D. Smart socks and in-shoe systems: state-of-the-art for two popular technologies for foot motion analysis, sports, and medical applications. Sensors 2020;20:4316. https://doi.org/10.3390/s20154316.
[96] Klamroth S, Steib S, Gaßner H, Goßler J, Winkler J, Eskofier B, et al. Immediate effects of perturbation treadmill training on gait and postural control in patients with Parkinson's disease. Gait Posture 2016;50:102–8.
[97] Pasluosta CF, Steib S, Klamroth S, Gaßner H, Goßler J, Hannink J, et al. Acute neuromuscular adaptations in the postural control of patients with Parkinson's disease after perturbed walking. Front Aging Neurosci 2017;9. https://doi.org/10.3389/fnagi.2017.00316.
[98] S. Steib, S. Klamroth, H. Gaßner, C. Pasluosta, B. Eskofier, J. Winkler et al., Perturbation during treadmill training improves dynamic balance and gait in Parkinson's disease: a single-blind randomized controlled pilot trial Neurorehabil Neural Repair 31 2017 758 768.
[99] Luessi F, Mueller LK, Breimhorst M, Vogt T. Influence of visual cues on gait in Parkinson's disease during treadmill walking at multiple velocities. J Neurol Sci 2012;314:78–82.
[100] M. Bedla P. Pięta D. Kaczmarski S. Deniziak Estimation of gross motor functions in children with cerebral palsy using Zebris FDM-T treadmill 11 2022 954 doi: 10.3390/jcm11040954.
[101] Jia X, Suo S, Meng F, Wang R. Effects of alignment on interface pressure for transtibial amputee during walking. Disabil Rehabil Assist Technol 2008;3: 339–43.
[102] Pirouzi G, Abu Osman NA, Eshraghi A, Ali S, Gholizadeh H, Wan Abas WA. Review of the socket design and interface pressure measurement for transtibial prosthesis. Sci World J 2014;2014:849073. https://doi.org/10.1155/2014/849073.
[103] Rajtukova V, Hudak R, Zivcak J, Halfarova P, Kudrikova R. Pressure distribution in transtibial prostheses socket and the stump interface. Procedia Eng 2014;96: 374–81.
[104] Polliack AA, Craig DD, Sieh RC, Landsberger S, McNeal DR. Laboratory and clinical tests of a prototype pressure sensor for clinical assessment of prosthetic socket fit. Prosthet Orthot Int 2002;26:23–34.
[105] Sanders JE, Zachariah SG, Jacobsen AK, Fergason JR. Changes in interface pressures and shear stresses over time on trans-tibial amputee subjects ambulating with prosthetic limbs: comparison of diurnal and six-month differences. J Biomech 2005;38:1566–73.
[106] Zhang M, Roberts C. Comparison of computational analysis with clinical measurement of stresses on below-knee residual limb in a prosthetic socket. Med Eng Phys 2000;22:607–12.
[107] Pitkin, M. ; Smirnova, L. ; Scherbina, K. ; Kurdybailo, S. ; Evseev, S. ; Maslov, N. Pressure measurements on amputee's residuum in classification for standing ice hockey. Sport for People with Disabilities, Berlin, Germany: International Council of Sport Science and Physical Education (ICSSPE); 2005, p. 10–13.
[108] Parks, B.; Sparks, N.; Stroud, C. Contact pressures before and after repair of an osteochondral lesion of the anterolateral dome of the talus. In 48th Annual Meeting of the Orthopaedic Research Society, February 10 - 13, 2002; Dallas, Texas, USA, 2002; p. 879.
[109] Davitt JS, Beals TC, Bachus KN. The effects of medial and lateral displacement calcaneal osteotomies on ankle and subtalar joint pressure distribution. Foot Ankle Int 2001;22:885–9.
[110] Hadfield, M.H. ; Snyder, J.W. ; Liacouras, P.C. ; Owen, J.R. ; Wayne, J.S. ; Adelaar, R.S. The effect of medializing calcaneal osteotomy upon achilles tendon length and foot pressures with and without superior translation. In 50th Annual Meeting of the Orthopaedic Research Society, March 7 - 10, 2004; San Francisco, California, USA, 2004; p. 1320.
[111] Latt LD, Glisson RR, Montijo HE, Usuelli FG, Easley ME. Effect of graft height mismatch on contact pressures with osteochondral grafting of the talus. Am J Sports Med 2011;39:2662–9.
[112] Wadwhani, S. Prevalence of stump problems in a community sample of lower limb amputees; Leeds Medical School SSM Project: Leeds, UK, 2001;.
[113] Liu K, Tang T, Wang A, Cui S. Surgical revision for stump problems after traumatic above-ankle amputations of the lower extremity. BMC Musculoskelet Disord 2015;16(1):7.
[114] Salawu A, Middleton C, Gilbertson A, Kodavali K, Neumann V. Stump ulcers and continued prosthetic limb use. Prosthet Orthot Int 2006;30:279–85.
[115] Boutwell E, Stine R, Tucker K. Effect of prosthetic gel liner thickness on gait biomechanics and pressure distribution within the transtibial socket. J Rehabil Res Dev 2012;49:227–40.
[116] Eshraghi A, Osman NAA, Gholizadeh H, Ali S, Sævarsson SK, Wan Abas WAB. An experimental study of the interface pressure profile during level walking of a new suspension system for lower limb amputees. Clin Biomech 2013;28:55–60.
[117] Abd Razak NA, Abu Osman NA, Ali SA, Gholizadeh H. Patient-specific interface pressure case study at transradial prosthetic socket: comparison trials between ICRC polypropylene socket and air splint socket. Eur J Phys Rehabil Med 2016. Jan 15.
[118] Portnoy S, Siev-Ner I, Shabshin N, Gefen A. Effects of sitting postures on risks for deep tissue injury in the residuum of a transtibial prosthetic-user: a biomechanical case study. Comput Methods Biomech Biomed Engin 2011;14: 1009–19.
[119] Laszczak P, Mcgrath M, Tang J, Gao J, Jiang L, Bader DL, et al. A pressure and shear sensor system for stress measurement at lower limb residuum/socket interface. Med Eng Phys 2016;38:695–700.
[120] W. Zhang K.B. Lua K.A. Senthil T.T. Lim K.S. Yeo G. Zhou Des Charact a Nov T-shaped multi-axis piezoresistive Force/Moment Sens 16 2016 4198 4210.
[121] H. Park K. Kim S. Kweon O. Gul J. Choi Y.S. Oh I. Park M. Je A Wirel wearable body-Press-Monit Syst Prev Press-Induc Ski Inj 17 2023 889 899.
[122] Wallace AL, Harris ML, Walsh WR, Bruce WJ. Intraoperative assessment of tibiofemoral contact stresses in total knee arthroplasty. J Arthroplast 1998;13: 923–7.
[123] Harris ML, Morberg P, Bruce W, Walsh WR. An improved method for measuring tibiofemoral contact areas in total knee arthroplasty: a comparison of K-scan sensor and Fuji film. J Biomech 1999;32:951–8.
[124] Anderson IA, MacDiarmid AA, Harris ML, Gillies RM, Phelps R, Walsh WR. A novel method for measuring medial compartment pressures within the knee joint in-vivo. J Biomech 2003;36:1391–5.
[125] Greenhalgh A, Taylor PJ, Sinclair J. The influence of different force and pressure measuring transducers on lower extremity kinematics measured during walking. Gait Posture 2014;40:476–9.
[126] Bus SA, de Lange A. A comparison of the 1-step, 2-step, and 3-step protocols for obtaining barefoot plantar pressure data in the diabetic neuropathic foot. Clin Biomech 2005;20:892–9.
[127] Naemi R, Chevalier TL, Healy A, Chockalingam N. The effect of the use of a walkway and the choice of the foot on plantar pressure assessment when using pressure platforms. Foot 2012;22:100–4.
[128] Burnfield JM, Few CD, Mohamed OS, Perry J. The influence of walking speed and footwear on plantar pressures in older adults. Clin Biomech 2004;19:78–84.
[129] M. Chung M. Wang Gend Walk Speed Eff Planta Press Distrib adults aged 20–60 years 55 2012 194 200.
[130] Pataky TC, Caravaggi P, Savage R, Parker D, Goulermas JY, Sellers WI, et al. New insights into the plantar pressure correlates of walking speed using pedobarographic statistical parametric mapping (pSPM). J Biomech 2008;41: 1987–94.
[131] Kernozek TW, LaMott EE, Dancisak MJ. Reliability of an in-shoe pressure measurement system during treadmill walking. Foot Ankle Int 1996;17:204–9.
[132] Okawara H, Sawada T, Hakukawa S, Nishizawa K, Okuno M, Nakamura M, et al. Footsteps required for reliable and valid in-shoe plantar pressure assessment during gait per foot region in people with hallux valgus. Gait Posture 2022;97: 21–7.
[133] Arts MLJ, Bus SA. Twelve steps per foot are recommended for valid and reliable in-shoe plantar pressure data in neuropathic diabetic patients wearing custom made footwear. Clin Biomech 2011;26:880–4.
[134] Rose NE, Feiwell LA, Cracchiolo III, A. A method for measuring foot pressures using a high resolution, computerized insole sensor: the effect of heel wedges on plantar pressure distribution and center of force. Foot Ankle 1992;13:263–70.
[135] Luo Z, Berglund LJ, An K. Validation of F-Scan pressure sensor system: a technical note. J Rehabil Res Dev 1998;35:186–91.
[136] Xia, B. ; Garbalosa, J.C. ; Cavanagh, P.R. Error analysis of two systems to measure in-shoe pressure. In 18th Annual Meeting of the American Society for Biomechanics, October 14- 15, 1994; Ohio State University, Ohio, USA, 1994; p. 219–220.
[137] Koch M, Lunde L, Ernst M, Knardahl S, Veiersted KB. Validity and reliability of pressure-measurement insoles for vertical ground reaction force assessment in field situations. Appl Erg 2016;53:44–51.
[138] Healy A, Dunning DN, Chockalingam N. Effect of insole material on lower limb kinematics and plantar pressures during treadmill walking. Prosthet Orthot Int 2012;36:53–62.
[139] J. Tang D.L. Bader D. Moser D.J. Parker S. Forghany C.J. Nester L. Jiang A wearable insole system to measure plantar pressure and shear for people with diabetes 23 2023 3126 doi: 10.3390/s23063126.
[140] Wang E, Hsieh C, Yang W, Shih Y, Chan M, Shiang T. Estimating center of pressure from limited number of pressure sensors for gait tasks. Footwear Sci 2019;11:S118–20.
[141] Misevich, K.W. The evaluation of force/time distributions in athletic equipment with pressure sensors. In ASME Engineering Foundation Conference - Sports Biomechanics, June 24 - 25, 1985; Albuquerque, New Mexico, USA, 1985;.
[142] Palaya J, MacKenzie C, Pearson S, Murray L, Katsanos C. Assessment of in-shoe pressure: development of a clinical user guide based on a DELPHI-derived consensus. Foot 2022;51:101892. https://doi.org/10.1016/j.foot.2021.101892.
[143] Jansson KS, Michalski MP, Smith SD, LaPrade RF, Wijdicks CA. Tekscan pressure sensor output changes in the presence of liquid exposure. J Biomech 2013;46: 612–4.

[144] Chockalingam, N. Digital technology support within the infrastructure of a fully equipped laboratory to study the performance of human movement. In Orthotic Technology Forum; 29–31 May, 2013; Atlanta, Georgia, USA.
[145] Woodburn J, Helliwell PS. Observations on the F-Scan in-shoe pressure measuring system. Clin Biomech 1996;11:301–4.
[146] Buis AWP, Convery P. Calibration problems encountered while monitoring stump/socket interface pressures with force sensing resistors: techniques adopted to minimise inaccuracies. Prosthet Orthot Int 1997;21:179–82.
[147] Nicolopoulos CS, Anderson EG, Solomonidis SE, Giannoudis PV. Evaluation of the gait analysis FSCAN pressure system: clinical tool or toy? Foot 2000;10:124–30.
[148] Pitei DL, Ison K, Edmonds ME, Lord M. Time-dependent behaviour of a force-sensitive resistor plantar pressure measurement insole. Proc Inst Mech Eng Part H J Eng Med 1996;210:121–5.
[149] Poliner J, White S, Fenton M. The importance of thermo-mechanical properties in the selection of athletic shoe cushioning foams. J Biomech 1992;25:663.
[150] Chockalingam N, Healy A. Chapter 6: Measurement of external forces. In: Payton C, Burden A, editors. Biomechanical evaluation of movement in sport and exercise: The British Association of Sport and Exercise Sciences Guide. London: Routledge; 2018. p. 91–115.
[151] El Kati R, Forrester S, Fleming P. Evaluation of pressure insoles during running. Procedia Eng 2010;2:3053–8.
[152] NICE Osteoarthritis in over 16s diagnosis and management; 2022; ⟨https://www.nice.org.uk/guidance/ng226/resources/osteoarthritis-in-over-16s-diagnosis-and-management-pdf-66143839026373⟩.
[153] NICE Rheumatoid arthritis in adults: management; 2018; ⟨https://www.nice.org.uk/guidance/ng100/resources/rheumatoid-arthritis-in-adults-management-pdf-66141531233989⟩.
[154] C. Formosa A. Gatt N. Chockalingam A Crit Eval Exist Diabet foot Screen Guidel 13 2016 158 186.
[155] Price C, Parker D, Nester C. Validity and repeatability of three in-shoe pressure measurement systems. Gait Posture 2016;46:69–74.
[156] Bus, S.A. ; Sacco, I.C. ; Monterio-Soares, M. ; Raspovic, A. ; Paton, J. ; Rasmussen, A. ; ; et al. ; International working group on the diabetic foot Guidelines on the prevention of foot ulcers in persons with diabetes (IWGDF 2023 update); IWGDF: 2023; ⟨https://iwgdfguidelines.org/wp-content/uploads/2023/07/IWGDF-2023–02-Prevention-Guideline.pdf⟩.
[157] Stucke S, McFarland D, Goss L, Fonov S, McMillan GR, Tucker A, et al. Spatial relationships between shearing stresses and pressure on the plantar skin surface during gait. J Biomech 2012;45:619–22.
[158] Akins JS, Karg PE, Brienza DM. Interface shear and pressure characteristics of wheelchair seat cushions. J Rehabil Res Dev 2011;48:225–34. https://doi.org/10.1682/jrrd.2009.09.0145.
[159] Bus SA. Innovations in plantar pressure and foot temperature measurements in diabetes. Diabetes Metab Res 2016;32:221–6.
[160] Lord M, Hosein R. A study of in-shoe plantar shear in patients with diabetic neuropathy. Clin Biomech 2000;15:278–83.
[161] Yavuz M. American Society of Biomechanics Clinical Biomechanics Award 2012: plantar shear stress distributions in diabetic patients with and without neuropathy. Clin Biomech 2014;29:223–9.
[162] Chevalier TL, Hodgins H, Chockalingam N. Plantar pressure measurements using an in-shoe system and a pressure platform: a comparison. Gait Posture 2010;31:397–9.
[163] Ferguson-Pell MW. Design criteria for the measurement of pressure at body/support interfaces. Eng Med 1980;9:209–14.
[164] Giacomozzi C, Keijsers N, Pataky TC, Rosenbaum D. International scientific consensus on medical plantar pressure measurement devices: technical requirements and performance. Ann Ist Super Sanita 2012;48:259–71.
[165] Lee N, Goonetilleke RS, Cheung YS, So GM. A flexible encapsulated MEMS pressure sensor system for biomechanical applications. Microsyst Technol 2001;7:55–62.
[166] Ashruf C. Thin flexible pressure sensors. Sens Rev 2002;22:322–77.
[167] Nagahara R. Normative spatiotemporal and ground reaction force data for female and male sprinting. J Sports Sci 2023;41:1240–9.
[168] Giacomozzi, C. ; De Angelis, G. ; Paolizzi, M. ; Silvestri, S. ; Macellari, V. Pneumatic test device for the accurate assessment of pressure sensors. In World Congress on Medical Physics and Biomedical Engineering, September 7–12, 2009; Munich, Germany, 2009; p. 319–322.
[169] Arndt A. Correction for sensor creep in the evaluation of long-term plantar pressure data. J Biomech 2003;36:1813–7.
[170] Hurkmans H, Bussmann J, Selles RW, Horemans H, Benda E, Stam HJ, et al. Validity of the Pedar Mobile system for vertical force measurement during a seven-hour period. J Biomech 2006;39:110–8.
[171] Saggin B, Scaccabarozzi D, Tarabini M. Metrological performances of a plantar pressure measurement system. IEEE Trans Instrum Meas 2013;62:766–76.
[172] Otto JK, Brown TD, Callaghan JJ. Static and dynamic response of a multiplexed-array piezoresistive contact sensor. Exp Mech 1999;39:317–23.
[173] Sumiya T, Suzuki Y, Kasahara T, Ogata H. Sensing stability and dynamic response of the F-Scan in-shoe sensing system: a technical note. J Rehabil Res Dev 1998;35:192–200.
[174] Hillstrom, H. ; Giacomozzi, C. ; Lenhoff, M. ; Zifchock, R. ; Vanadurongwan, B. ; Gross, D. ; ; et al. Accuracy of the novel emed®-x and Tekscan matscan plantar pressure measurement systems. In Proceedings of ESM (Emed scientific meeting), July 28 - 31, 2008; Bristol, UK, 2008; p. 87.
[175] Hamzah, H.; Osman, N.A.; Hasnan, N. Comparing Manufacturer's Point Calibration and Modified Calibration Setup for F-Scan Insole Sensor System: A Preliminary Assessment. In 4th Kuala Lumpur International Conference on Biomedical Engineering 2008, June 25 -28, 2008; Kuala Lumpur, Malaysia, 2008; p. 424–427.
[176] Hsiao H, Guan J, Weatherly M. Accuracy and precision of two in-shoe pressure measurement systems. Ergonomics 2002;45:537–55.
[177] Maurer, J.R. ; Ronsky, J. ; Loitz-Ramage, B. ; Andersen, M. ; Zernicke, R. ; Harder, J. Prosthetic socket interface pressures: Customized calibration technique for the Tekscan F-socket system. In Summer Bioengineering Conference, June 25–29, 2003; Key Biscayne, Florida, USA, 2003; p. 1073–1074.
[178] Brimacombe JM, Wilson DR, Hodgson AJ, Ho KCT, Anglin C. Effect of calibration method on Tekscan sensor accuracy. J Biomech Eng 2009;131:034503. https://doi.org/10.1115/1.3005165.
[179] Brimacombe, J.M. ; Anglin, C. ; Hodgson, A.J. ; Wilson, D.R. Validation of calibration techniques for tekscan pressure sensors. In Proceedings of international society of biomechanics XXth congress. ASB 29th Annual meeting, July 31 - August 5, 2005; Cleveland, Ohio, USA, 2005; p. 263.
[180] Alexander A, Jiang A, Ferreira C, Zurkiya D. An intelligent future for medical imaging: a market outlook on artificial intelligence for medical imaging. J Am Coll Radiol 2020;17:165–70.
[181] Hamid, T.; Chhabra, M.; Ravulakollu, K.; Singh, P.; Dalal, S.; Dewan, R. A Review on Artificial Intelligence in Orthopaedics. In 2022 9th International Conference on Computing for Sustainable Global Development (INDIACom), 23–25 March 2022; New Delhi, India, 2022; p. 365–369. DOI: 10.23919/INDIACom54597.2022.
[182] Pesapane F, Codari M, Sardanelli F. Artificial intelligence in medical imaging: threat or opportunity? Radiologists again at the forefront of innovation in medicine. Eur Radiol Exp 2018;2:1–10.
[183] Ardhianto P, Subiakto RBR, Lin C, Jan Y, Liau B, Tsai J, et al. A deep learning method for foot progression angle detection in plantar pressure images. Sensors 2022;22:2786. https://doi.org/10.3390/s22072786.
[184] Chen, H. ; Jan, Y. ; Liau, B. ; Lin, C. ; Tsai, J. ; Li, C. ; et al. Using Deep Learning Methods to Predict Walking Intensity from Plantar Pressure Images. In International Conference on Applied Human Factors and Ergonomics, 25–29 July 2021; Online, USA, 2021; p. 270–277.
[185] Kaya M, Karakuş S, Tuncer SA. Detection of ataxia with hybrid convolutional neural network using static plantar pressure distribution model in patients with multiple sclerosis. Comput Methods Prog Biomed 2022;214:106525.
[186] Li X, Huang H, Wang J, Yu Y, Ao Y. The analysis of plantar pressure data based on multimodel method in patients with anterior cruciate ligament deficiency during walking. Biomed Res Int 2016;2016:7891407. https://doi.org/10.1155/2016/7891407.
[187] Mun F, Choi A. Deep learning approach to estimate foot pressure distribution in walking with application for a cost-effective insole system. 2022 J Neuroeng Rehabil 2022;19:4. https://doi.org/10.1186/s12984-022-00987-8.
[188] G. Shalin S. Pardoel J. Nantel E.D. Lemaire J. Kofman Prediction of freezing of gait in Parkinson's disease from foot plantar-pressure arrays using a convolutional neural network. 2020 42nd Annu Int Conf IEEE Eng Med Biol Soc (EMBC) 2020 244 247.
[189] Zhang P, Wang X, Li Y, Zhang K, Huang L. Plantar pressure monitoring system based on a flexible pressure sensor array for human walking feature recognition. IEEE Trans Electron Devices 2023;70:6526–33.