Expert Review of Medical Devices

ISSN: 1743-4440 (Print) 1745-2422 (Online) Journal homepage: www.tandfonline.com/journals/ierd20

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To cite this article: Rachel Mason, Gill Barry, Rodrigo Vitorio, Oisin Lennon, Hugh Robinson, Ben O'Callaghan, Rosie Morris, Alan Godfrey & Samuel Stuart (2025) Smart clothing for human movement analysis: future application in sport and clinical practice, Expert Review of Medical Devices, 22:2, 111-116, DOI: 10.1080/17434440.2025.2454933

To link to this article: https://doi.org/10.1080/17434440.2025.2454933

Published online: 21 Jan 2025.

EXPERT REVIEW OF MEDICAL DEVICES
2025, VOL. 22, NO. 2, 111–116
https://doi.org/10.1080/17434440.2025.2454933

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EDITORIAL

Smart clothing for human movement analysis: future application in sport and clinical practice

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ARTICLE HISTORY Received 6 September 2024; Accepted 14 January 2025

KEYWORDS Smart clothing; human movement analysis; sensors; gait; balance; mobility

1. Introduction – 'expert commentary'

Human movement analysis is a multifaceted discipline encompassing the study of various aspects of human motion, including mobility (walking or running gait, physical activity), balance, upper limb control, trunk control, head movement, and fine motor control (i.e. hand or finger movement). Human movement analysis has gained significant traction across a wide array of domains, including sport [1], clinical [2–5], animation/entertainment [6], video surveillance [7] and robotics [8]. Human movement analysis measures the mechanics of motion and the relationship of the measured outcomes with various clinical diseases or injuries affecting the neurological, musculoskeletal, and cardio-pulmonary systems [2–5]. Accurate examination that is relatively quick to provide objective measures of human movement is important in the assessment of athletes and clinical populations, as early detection of issues with performance or injury/disease could allow quicker intervention that will reduce the impact on the individual [9]. Equally, an objective immediate 'real-time' assessment can reinforce movement patterns and be used for positive feedback that can subsequently lead to many benefits, including increased engagement and motivation, as well as performance [10]. In traditional practice, human movement analysis is performed through subjective expert observation, often with stopwatch timed tasks that lack the precision and objectivity necessary for comprehensive evaluation, particularly in the context of identifying subtle changes indicative of injury or pathology [11]. For example, within sport, the SCAT5 involves several balance (or dynamic balance) tasks that are observed and rated by a practitioner, and similarly, clinical practice tests such as the 6-min walk test or timed up-and-go task are commonly used in various conditions to denote a person's movement capabilities [12]. There is a need to improve on these traditional subjective scales with objective technological approaches that can comprehensively assess human movement across a range of healthy and clinical populations.

In recent years, there has been a growing emphasis on the implementation and development of wearable technologies for human movement analysis, particularly technologies that offer the ability to provide measurements within any environment for intermittent or even continuous monitoring in clinical or free-living settings [13]. Recent advancements in wearable sensor technology have revolutionized human movement analysis by enabling objective, real-time measurement in various environments [14]. Wearable sensors, such as inertial and pressure sensors, offer the ability to capture spatial-temporal, kinematic, and kinetic data with high levels of accuracy, facilitating intermittent or continuous monitoring in both clinical and free-living settings [15,16]. This paradigm shift toward objective, data-driven assessment methods that underscore the need for innovative solutions capable of providing rapid, accurate, and comprehensive analysis of human movement across diverse populations and domains. Wearable technologies have traditionally involved specific devices, such as smartwatches or inertial sensors, created to provide performance or health-related data within any environment [17]. However, the relatively obtrusive nature of usual wearable devices (i.e. they can be seen by the wearer and others) means that they have several limitations that could be overcome with modern technology that can be embedded into clothing [18].

Smart clothing is a term that refers to a broad field of products that combine textiles and electronics that could sense the environment or the user, stimuli from the environment, user behavior, etc. Smart clothing can include a wide range of sensors, such as electrocardiogram, electromyography, electroencephalography, inertial measurement units (accelerometers, gyroscopes, magnetometers), thermocouples, barometers, shape-sensing fabrics for movement, luminescent elements for bio-photonic sensing, carbon electrodes for sensing oxygen, moisture, salinity, or contaminants in the environment. Smart clothing provides an unobtrusive 'smart system' that is capable of monitoring vast amounts of health or performance-related data from the wearer and the environment [19]. The future application of smart clothing within usual daily life, but particularly in sporting or healthcare environments, will enable greater

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insights into underlying issues and more targeted intervention [20].

2. 'Key issues' - smart clothing solutions

Smart clothing may offer a solution to address the need for rapid unobtrusive human movement analysis. Smart clothing assessments could serve as valuable tools for objective diagnostics, monitoring data, measurement of response to interventions, prevention, or prognostics for injury or disease assessment or rehabilitation management. The integration of electronics into textiles creates a more unobtrusive measurement of human movement that can be used in controlled or real-world sport or clinical settings.

There are several smart clothing technologies that exist to measure aspects of human movement, such as gait, including Sensoria or Palarum Socks [21–23] or Moticon insoles [24]. However, these systems are limited in the technology contained within the device which limits the human movement outcomes available to obtain. For example, Sensoria and Palarum socks have inertial sensors on the ankle but only have a limited number of sensors on the bottom of the foot that sense pressure (e.g. three textile-integrated sensors) and Moticon insoles have inertial sensors and more pressure sensors (16 sensors) but can be uncomfortable/difficult to wear within patient shoes (e.g. if they have orthotics, etc.) and are only useful if patients constantly wear their shoes (i.e. cannot continuously record at home). Alternatively, here we provide a specific example of a package of human movement analysis tools offered by DANU Ltd., a company who have developed a high-end smart clothing digital technology (Smart Socks) that can be deployed with healthy and clinical populations to comprehensively assess or monitor human movement within any environment (https://www.danusports.com/). The DANU Smart Clothing solutions offer a unique technology to measure a comprehensive range of human movement outcomes, such as walking or running gait, balance, jump performance, or potentially other movement aspects (e.g. falls).

2.1. DANU smart clothing system

The DANU Smart Socks are smart clothing that involve a multi-modal system for movement (balance, gait, jumps) assessment, which is designed for sport practitioners, clinicians, and researchers. The DANU Smart Socks (Figure 1) consists of a pair of textile socks that were worn on both feet. Each sock contains 15 silicone-based capacitive pressure sensors, and an IMU module that attaches to the medial surface of the mid-shank of tibia. Each IMU module is Bluetooth enabled for data transmission and is comprised of two configurable tri-axial accelerometers (Accelerometer 1 ± 2 g, ±4 g, ±8 g, or ±16 g, Accelerometer 2 ± 100 g, ±200 g, and ±400 g), gyroscope (±2000°/s), magnetometer, and with variable sampling rates (60–250 hz). The IMU module includes in-built memory for data collection. A seated calibration trial is recorded prior to participant assessment. Data is collected via Bluetooth on Apple devices 2018 or later (iPad or iPhone devices are required to have at least Bluetooth 5.0 connectivity), and data processing is run through a custom-made Apple application (with cloud-based Python algorithms) for real-time feedback and visualization, as per the manufacturer's guidelines.

2.2. Assessments

There is a need for smart clothing to offer a series of standardized assessment protocols tailored to the needs of clinicians and researchers (Table 1). For example, DANU

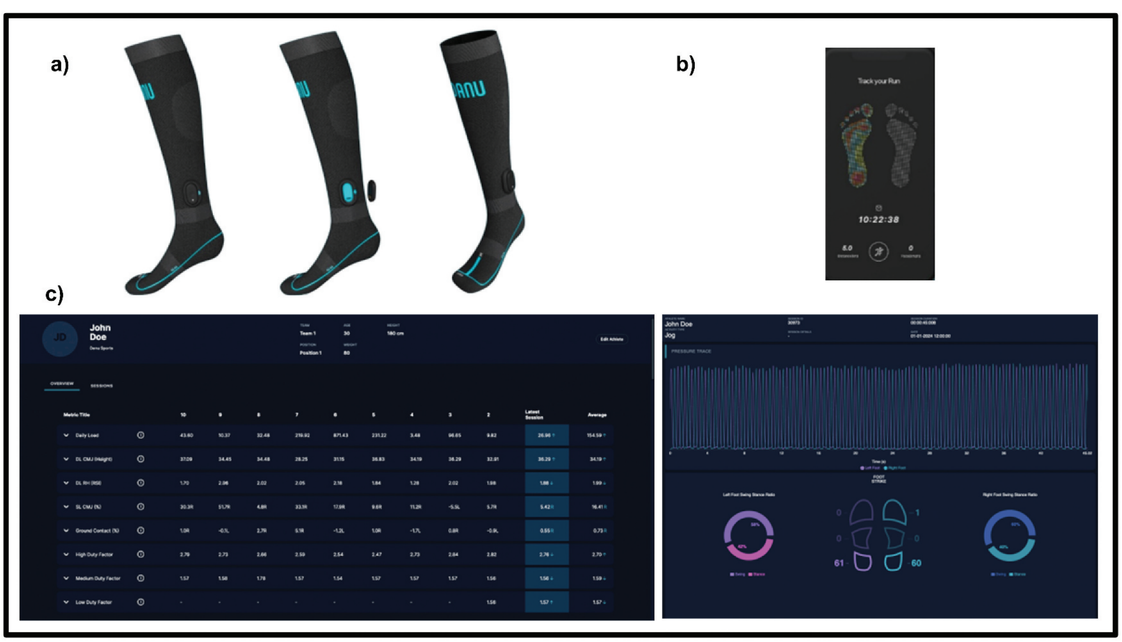

Figure 1. DANU human movement analysis system: a) DANU socks, b) smartphone or tablet application for data collection, c) data analytics on smartphone or tablet application (or computer).

Table 1. Examples of DANU assessments and metrics.

Human movement domain	Example DANU assessments	Example Metrics obtained
Gait/Mobility	• 1MWT • 2MWT • 6MWT – 10 m, 20 m, or 30 m • 12MWT • Timed up and go – 3 or 7 m • L Test • Free walk • Free run	– step velocity/gait speed (mean, SD and asymmetry) – step length (mean, SD and asymmetry) – step time (mean, SD and asymmetry) – stance time (mean, SD and asymmetry) – swing time (mean, SD and asymmetry) – step width (mean, SD and asymmetry) – stride time (mean, SD and asymmetry) – stride length (mean, SD and asymmetry) – Double and single support time/phase – cadence – step count/frequency – Ground contact time (mean, SD and asymmetry) – Flight time – Peak tibial acceleration (mean, SD and asymmetry) – Centre of pressure – Foot strike pattern – Ground clearance – Duty factor – Drive index – Turn angle (mean, SD) – Turn velocity (mean, SD) – Turn jerkiness (mean, SD) – Turn duration (mean, SD) – Walk time – Walk distance
Balance	• Balance error scoring system • Modified Clinical Test for Sensory Interaction on Balance (M-CTSIB) • Romberg test • Single Leg Stance • Four Stage Balance Test • Y Balance Test • Free stand	***Pressure:*** – Centre of Pressure (COP) displacement/trajectories – medio-lateral, anterior-posterior – COP path length – COP frequency – COP amplitude – COP ellipse area – COP RMS/standard deviation – Equilibrium score – Postural stability index – Total angular momentum – Romberg quotient – Symmetry index – Weight-bearing asymmetry – Sample entropy ***Inertial sensor:*** – Acceleration and angular displacement – medio-lateral, anterior-posterior – Sway Area – Sway Velocity – Jerk – Sway Frequency – RMS Sway – Centroidal frequency – Path length – Sway Range – Sample entropy
Jumping*	• Counter movement jump • Drop jump • Repeated hops	– Jump height – Flight time – Peak power – Reactive strength index

*All can be performed either as a double legged or single leg exercises.

have assessment protocols, derived from established clinical or performance tests, which have been instrumented to facilitate objective data collection and analysis. Moreover, DANU assessments can be customized to accommodate specific research objectives or clinical requirements, ensuring flexibility and adaptability across diverse applications. By providing a standardized framework for data collection, DANU assessments enhance consistency and comparability across studies, thereby facilitating evidence-based decision-making and intervention planning.

2.3. Reporting

There is also a need for smart clothing to provide accessible (real-time) and remote reporting. For example, the DANU Cloud Platform (used on smartphone, tablet, or computer) serves as a centralized hub for data management, analysis, and reporting. This cloud-based infrastructure enables seamless integration of data collected from DANU Smart Socks and other compatible devices, facilitating comprehensive analysis and interpretation. The platform offers intuitive interfaces and graphical outputs, allowing users to visualize

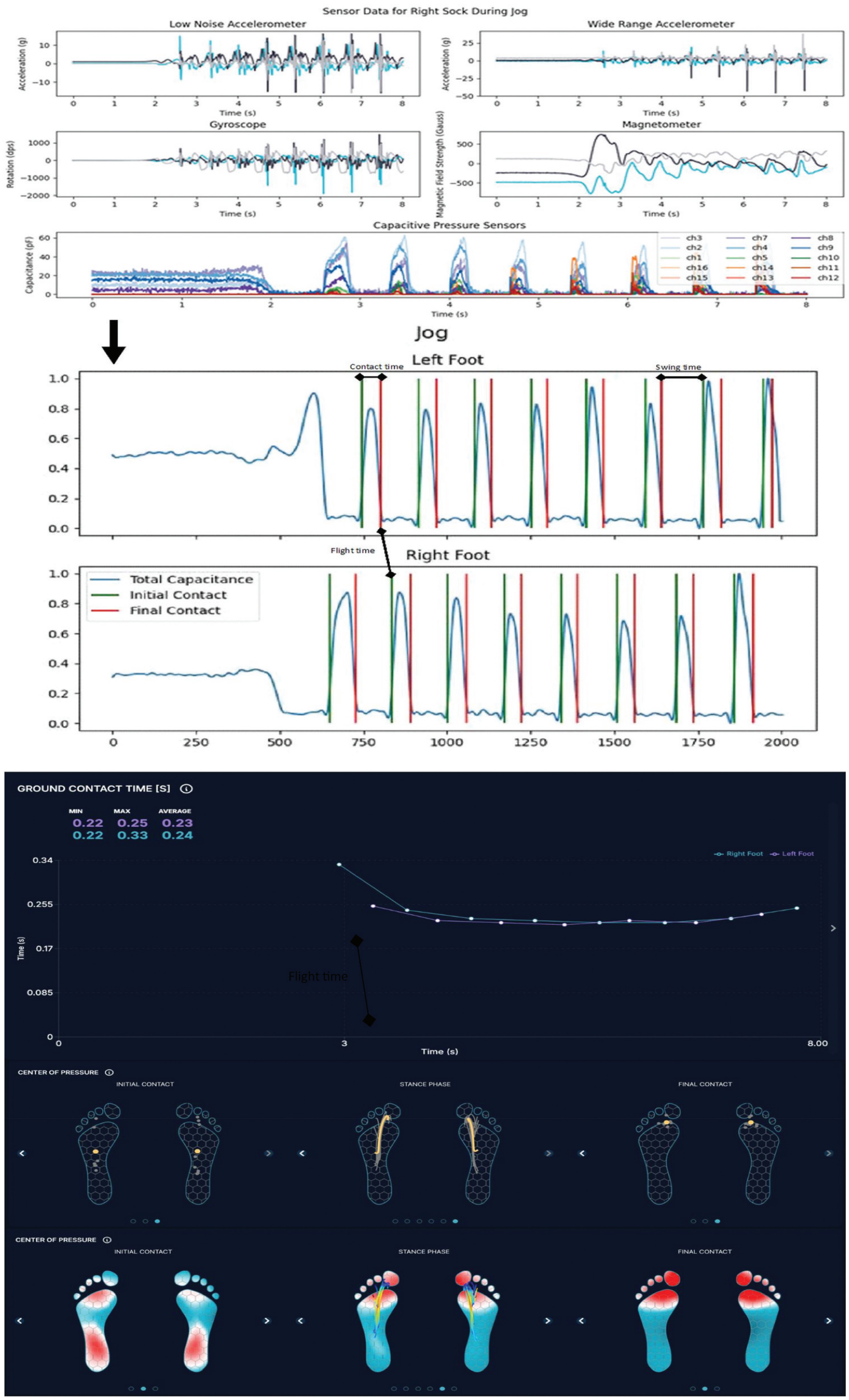

Figure 2. An example of raw (top) and processed (bottom) data outputs from the DANU human movement analysis system during a 20 m jog. The figure illustrates sensor data collected from the right sock, including accelerometer, gyroscope, and capacitance readings. The capacitance graphs (third line) represent the aggregated pressure across 15 vertical-plane sensors, used to distinguish between stance and swing phases of the gait cycle. *note: the socks measure pressure within the shoe rather than externally, the graphs seldom approach zero, as a baseline level of pressure is consistently present.*

and explore movement data (Figure 1). Moreover, the DANU Cloud Platform supports real-time collaboration and data sharing, fostering interdisciplinary research and clinical collaboration. By streamlining the data analysis process (Figure 2), DANU Cloud Platform enhances the efficiency and accessibility of movement analysis, ultimately empowering users to derive meaningful insights and make informed decisions.

2.4. Validity and reliability

Before routine implementation of smart clothing within sporting or clinical environments, the validity of the technology for human movement analysis needs to be established. For example, the DANU smart socks have been validated in healthy individuals (41 healthy adults; 26 M, 15 F, age 36.4 ± 11.8 years) for walking and running gait assessment [25], showing excellent agreement and reliability for treadmill gait and moderate to good agreement for overground gait to laboratory references. The total capacitance value, computed as the summation of measurements across all 15 channels, indicates the overall magnitude of vertical pressure applied during foot contact (Figure 2). This summation reflects the pressure distribution within the vertical plane, enabling differentiation of gait phases and potentially identifying asymmetries or abnormalities. Further work is required to establish the analytical and clinical validation of human movement analysis in specific clinical or sporting populations, to ensure accuracy of outcomes within controlled laboratory and real-world environments.

3. Future work – ‘five year view’

Smart clothing is fast-growing in the wearable technology industry with application within healthcare and sport rehabilitation settings. Within the next 5 years there needs to be increased research evidence generated to support the use of smart clothing devices within these settings, which will require collaboration across academia, industry, and healthcare/sport areas.

As a specific example, in 2020, DANU Ltd. and Northumbria University formed a collaboration to develop a series of studies across healthy and clinical populations to examine the initial analytical and clinical (or performance) validity of human movement analysis from the DANU smart clothing solutions. The first study that is currently underway and involves several groups of healthy and clinical (e.g. history of lower limb injury) participants undergoing laboratory and real-world human movement analysis testing with the DANU smart socks. All participants are assessed using the DANU Smart Socks during walking, running, and jumping assessments. The study will take 36 months to complete, with subjects recruited from the university, local sports clubs and teams, and external advertisement in the local Newcastle upon-Tyne area [26]. If findings demonstrate that DANU smart socks are useful in human movement assessment in healthy and clinical populations, this will support the integration of this smart clothing solution into sporting practice or healthcare settings across various environments.

In the long-term, there is a need to develop specific analytical and clinical validation studies of smart clothing solutions in clinical populations to determine their feasibility. As a specific example, a second study at Northumbria University will begin in 2024 that will involve analytical and clinical validation of DANU Socks for human movement analysis outcome measures, particularly gait, in Parkinson’s disease. This will involve both active assessments and passive monitoring of human movement in laboratory and real-world settings with participants with Parkinson’s disease recruited from local networks and the NHS.

Beyond collaborative research studies, we envisage that smart clothing solutions could be useful for disease/injury diagnosis or early detection, as well as disease or rehabilitation monitoring across a range of clinical conditions. This may include providing objective measures of medication or rehabilitation response, which could be performed in clinical or habitual settings.

3.1. Summary

The analytical and clinical validity of smart clothing solutions (e.g. DANU socks) for human movement analysis has begun to be established in healthy and clinical populations. Further research work is underway to assess the use of these solutions in clinical populations, which may provide evidence for relevant and accurate movement outcome measures (biomarkers) that could be used by non-experts or patients to assess and rehabilitation movement function.

Funding

This work was funded by a Northumbria University collaborative PhD, with partial funding from DANU Sports Ltd.

Declaration of interest

Rachel Mason is on a PhD program co-funded by DANU Sports Ltd. Oisin Lennon, Hugh Robinson, and Ben O’Callaghan are employed by DANU Sports Ltd. Samuel Stuart has previously received consultancy payment from DANU Sports Ltd. The authors have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed.

Reviewer disclosure

Peer reviewers on this manuscript have no relevant financial relationships or otherwise to disclose.

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