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Technological transformation of hand grip measurement devices: Key developments and trends

Abstract

Hand grip strength measurement is widely used in clinical practice to assess muscle function, nutritional status, and overall health. Over time, hand grip measurement devices have evolved from simple mechanical dynamometers to advanced digital, sensor-based, and Internet of Things (IoT)-enabled systems. This transformation has improved measurement accuracy, real-time monitoring, and data accessibility in rehabilitation and healthcare applications. Recent developments involving embedded systems, wearable technologies, wireless communication, and smart monitoring platforms have expanded the role of hand grip assessment in modern digital healthcare. However, challenges related to standardization, reliability, calibration, and clinical validation remain. This review discusses the technological evolution of hand grip measurement devices, highlights major developments in smart and IoT-based systems, and examines future trends shaping the field of rehabilitation and personalized healthcare.

Keywords: Hand grip strength; Dynamometer; Sensor-based systems; Internet of Things (IoT); Wearable devices; Rehabilitation; Smart healthcare.

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Introduction

Hand Grip Strength (HGS) is a non-invasive indicator of muscle performance and systemic health, providing important insights into functional status. Its use has expanded beyond rehabilitation into geriatrics, sports science, and digital health, where it is recognized as a key biomarker for broader health monitoring [1]. With the shift toward data-driven healthcare, the demand for accurate and connected HGS measurement tools has increased.

Traditional mechanical and hydraulic dynamometers, although simple and widely used, are limited to single-point measurements and cannot capture dynamic patterns such as fatigue or longitudinal changes. Recent studies highlight concerns regarding device reliability and inter-instrument variability, showing that results from different systems are not always interchangeable [2,5]. This emphasizes the need for improved measurement technology and standardized protocols across clinical settings.

With ongoing digital transformation, HGS devices have evolved into sensor-integrated and wireless systems. Modern IoT-based dynamometers can enable real-time data recording and remote monitoring, improving clinical assessment, follow-up, and interpretation of grip strength trends [6].

Clinical importance of hand grip strength

Hand Grip Strength (HGS) has evolved from a simple measure of muscular performance to an important systemic biomarker used across multiple medical fields. In addition to reflecting muscle strength, HGS has been associated with cardiovascular health, where reduced grip strength is linked to increased cardiovascular disease risk and poorer long-term outcomes [7].

In geriatrics and rehabilitation, HGS is widely used to assess frailty, sarcopenia, and functional decline. Low grip strength is strongly associated with reduced independence, increased fall risk, and impaired physical performance in older adults [8,9]. HGS assessment is also important in neurological rehabilitation, particularly after stroke, where it reflects neuromuscular recovery and functional improvement [10,11]. The introduction of IoT-based continuous monitoring systems has further improved rehabilitation assessment by enabling real-time tracking of recovery progress and treatment effectiveness [12,13].

Beyond rehabilitation, HGS is also applied in nutritional assessment and sports performance evaluation. Reduced grip strength may indicate malnutrition and declining physical capacity, while dynamic monitoring can help evaluate endurance and fatigue during athletic performance [1]. However, the clinical usefulness of HGS assessment is still affected by inter-device variability and lack of standardization between measurement systems [14].

Conventional hand grip measurement devices

Mechanical dynamometers

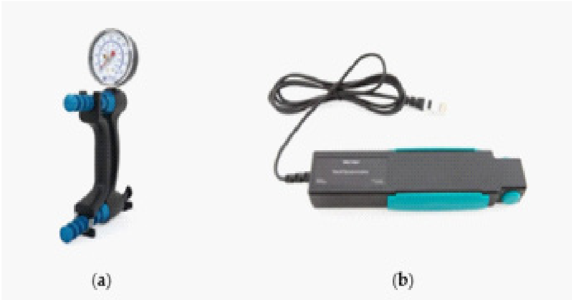

Figure 1: Conventional hand grip dynamometers [15].

Mechanical dynamometers are among the earliest hand grip strength measurement devices and operate using springs or lever-based mechanisms that convert applied force into analog readings. Due to their simplicity, durability, and low manufacturing cost, these devices have been widely used in rehabilitation centers, hospitals, and large-scale clinical screenings, especially in low-resource settings [16].

Despite their widespread use, mechanical dynamometers are limited to measuring only peak grip force and cannot evaluate dynamic parameters such as endurance, fatigue, or force variation over time. In addition, analog readings increase the possibility of observer error, reducing measurement accuracy and reproducibility during repeated assessments [17].

Hydraulic dynamometers

Hydraulic dynamometers represent a more advanced category of conventional grip strength devices and are considered the clinical standard in many healthcare settings. These devices operate through a fluid-filled hydraulic system that converts applied grip force into pressure, producing stable and reliable measurements displayed on a calibrated gauge [15].

Hydraulic systems provide improved accuracy and reduced sensitivity to hand positioning compared to purely mechanical devices, making them suitable for rehabilitation assessment and clinical evaluation of neuromuscular disorders. However, they still mainly measure maximum force and lack the ability to capture continuous or real-time muscle performance data. In addition, manual recording of results limits their usefulness in long-term monitoring and digital healthcare integration [14].

Standard clinical devices and their applications

Conventional dynamometers, particularly hydraulic models such as the Jamar dynamometer, are extensively used in clinical and research environments to evaluate muscle strength in patients with neurological, musculoskeletal, and chronic diseases. Their clinical value is supported by standardized testing procedures and normative data, allowing consistent assessment across different populations [15].

In rehabilitation, these devices are commonly used to monitor recovery after stroke and other neurological conditions, where grip strength reflects both muscular recovery and functional improvement [10]. Reduced grip strength has also been associated with increased risk of falls, physical disability, and poor health outcomes in older adults [8,9]. However, differences in device type and testing conditions continue to create concerns regarding reliability and inter-device variability [14].

Limitations of conventional devices

Although conventional hand grip measurement devices remain widely used, their limitations have become increasingly evident in modern healthcare environments. A major limitation is their inability to provide continuous or real-time monitoring, as they only measure a single peak force value and cannot capture dynamic muscle characteristics such as endurance, fatigue, and temporal variability [17].

Another important limitation is the absence of digital integration. Conventional devices do not support automatic data storage, trend analysis, or remote monitoring, which restricts their usefulness in long-term rehabilitation and telemedicine applications [14]. Furthermore, measurement outcomes are influenced by operator technique, patient posture, grip span, and testing conditions, leading to inconsistencies and reduced reproducibility between clinical settings [14].

Digital transformation of hand grip measurement devices

Emergence of digital dynamometers

The transition from conventional to digital hand grip measurement devices marked a major advancement in muscle strength assessment. Unlike traditional analog systems, digital dynamometers use electronic sensors to convert applied force into electrical signals that are processed and displayed numerically. This reduces manual reading errors and improves measurement accuracy and reliability [18,19].

In addition to improved precision, digital systems introduced data storage and automated recording capabilities, enabling clinicians to monitor patient progress over time. Many digital devices also support functions such as peak force detection, average force calculation, and repeated trial analysis, providing a more comprehensive evaluation of muscle performance than conventional systems [20].

Integration of sensors and embedded systems

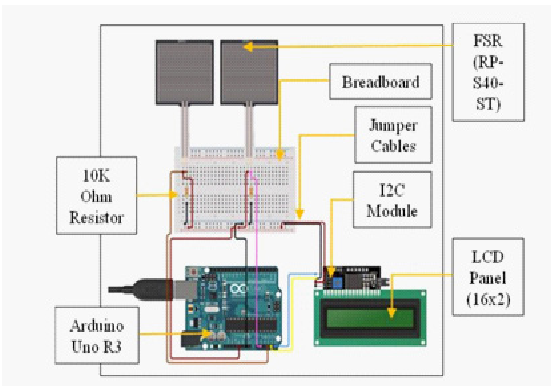

Figure 2: Block diagram of sensor-based hand grip measurement system [22].

A major aspect of digital transformation in hand grip measurement devices is the integration of advanced sensing technologies. Modern systems commonly use load cells, strain gauges, and Force-Sensitive Resistors (FSRs) to accurately detect grip force and monitor dynamic changes in muscle performance [21,22].

The addition of embedded systems, particularly microcontrollers, has further enhanced device functionality. Microcontrollers receive and process sensor signals in real time, allowing continuous monitoring, automated calculations, and improved output visualization [23]. This integration forms the foundation of modern smart grip measurement systems.

Sensor-integrated devices also provide improved adaptability to different users and testing conditions. Unlike conventional systems that measure only peak force, digital sensor-based devices can evaluate endurance, fatigue, and force variability over time, making them highly useful in rehabilitation and sports applications [21].

Improved data handling and user interaction

Digital transformation has also improved data handling and user interaction in hand grip measurement systems. Modern digital devices can store data internally or transmit it to external systems for analysis, enabling trend evaluation, patient record management, and long-term monitoring [20].

Many digital systems include user-friendly interfaces such as LCD screens, software dashboards, and feedback mechanisms that improve usability for clinicians and patients. Some systems provide visual or auditory guidance during testing to ensure consistency and reduce operator-related variability [22].

By automating data collection and reducing dependence on manual recording, digital systems improve standardization, reduce variability, and enhance reproducibility in both clinical and research settings [19].

Limitations of digital systems

Despite the advantages of digital dynamometers, several limitations remain. The cost of advanced digital systems may limit their accessibility in low-resource healthcare environments. Furthermore, many digital devices still focus primarily on peak force measurement and may not fully capture complex muscle performance characteristics without additional technological enhancement [18].

Another major issue is variability in device design and sensor calibration, which may lead to inconsistencies between systems. Differences in sensor type, calibration procedures, and testing protocols can affect measurement outcomes and reduce comparability between devices [19].

In addition, many digital dynamometers still lack advanced connectivity features such as cloud integration and real-time remote monitoring, limiting their application in telemedicine and continuous patient assessment.

Sensor-based and smart hand grip measurement systems

Force sensors in grip strength measurement

The integration of force sensors has significantly advanced hand grip measurement technology. Modern systems commonly use load cells, strain gauges, and Force-Sensitive Resistors (FSRs) to capture grip force with high sensitivity and accuracy, improving response time and adaptability compared with conventional devices [24,25].

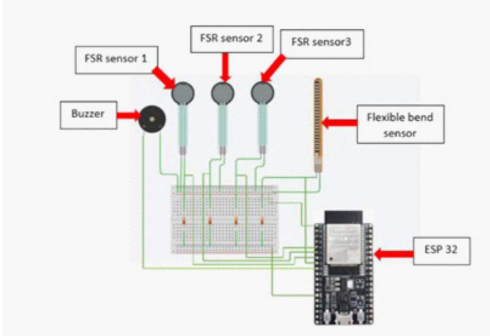

Figure 3: Sensor configuration and ESP32-based grip measurement system [21].

Load cells convert mechanical force into electrical signals through strain measurement and are widely used because of their high precision. Strain gauges provide accurate deformation-based measurements, while FSRs offer flexibility and compact size, making them suitable for portable and wearable systems [26]. These sensors enable continuous monitoring of force variation, endurance, and fatigue, which were not possible with traditional analog dynamometers.

Smart sensor integration and data acquisition

The combination of smart sensors with embedded systems has improved the functionality of hand grip measurement devices by enabling real-time data acquisition and continuous monitoring. These systems integrate sensors, microcontrollers, and signal-processing units to provide detailed information about muscle performance over time [27].

Advanced signal-processing algorithms improve measurement accuracy by reducing noise and enhancing data interpretation. In addition, smart systems support multi-parameter analysis, allowing simultaneous evaluation of peak force, grip duration, variability, and fatigue, providing a more comprehensive assessment than conventional single-value measurements [28].

Wearable and smart grip devices

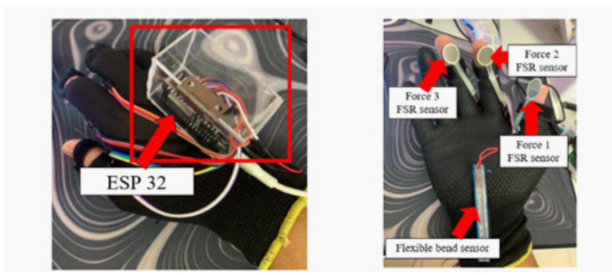

Figure 4: Wearable smart glove showing sensor placement and ESP32 integration [21].

Recent developments in sensor technology have led to wearable and smart grip devices designed for continuous and remote monitoring. These systems are often integrated into gloves, rehabilitation tools, or handheld devices, enabling natural hand movement while recording grip strength in real time [29].

Wearable smart systems are widely used in post-stroke rehabilitation, where they assist in monitoring patient recovery and tracking therapeutic progress. Sensor-based rehabilitation devices also improve patient engagement by providing real-time feedback and supporting personalized rehabilitation programs [30,31].

Advantages of smart measurement systems

Sensor-based and smart hand grip systems offer major advantages over conventional and early digital devices. Unlike traditional systems that measure only peak force, smart systems provide continuous and real-time monitoring, allowing analysis of endurance, fatigue, and force variability [24].

Another important advantage is the ability to store and transmit data for long-term monitoring and remote assessment. These features are especially useful in rehabilitation and telemedicine applications, where patients can be monitored outside clinical settings. Automation also improves measurement consistency by reducing operator dependency and standardizing data collection [28].

Limitations and challenges

Despite their advantages, sensor-based systems still face several challenges. Proper calibration is essential because environmental conditions, sensor configuration, and hardware variability can affect measurement accuracy and consistency between devices [25].

System complexity is another challenge, as development and maintenance often require technical expertise. In addition, wearable devices must balance measurement accuracy with comfort and usability, since bulky or rigid designs may interfere with natural hand movement and reduce patient compliance.

Wireless and IoT-based hand grip measurement systems

Wireless communication in grip measurement devices

The integration of wireless communication technologies has significantly advanced hand grip measurement systems. Modern devices use Wi-Fi, Bluetooth, and low-power communication protocols to transmit grip strength data in real time to external devices such as smartphones, tablets, and computers for visualization and analysis [32].

Wireless connectivity improves usability by eliminating manual data transfer and enabling continuous monitoring without restricting patient movement. These technologies also improve accessibility by allowing clinicians to remotely monitor patient performance and make timely clinical decisions based on real-time information [33].

Internet of things (IoT) integration

The adoption of the Internet of Things (IoT) has transformed hand grip measurement devices into interconnected smart systems capable of continuous and remote monitoring. These systems integrate sensors, microcontrollers, and communication networks to collect, process, and transmit grip strength data to cloud-based platforms for clinical analysis [34].

IoT-enabled dynamometers can capture dynamic grip force data, automate recording processes, and present measurements through graphical interfaces, reducing human error and improving accuracy. In addition, cloud-based systems enable long-term storage and analysis of patient data, allowing monitoring of rehabilitation progress over extended periods [6].

Mobile applications and cloud-based monitoring

An important development in IoT-based hand grip systems is the integration of mobile applications and cloud computing. Mobile applications provide real-time visualization, interactive feedback, performance tracking, and progress reports, improving both patient engagement and clinical usability [12].

Cloud computing extends these capabilities by enabling secure storage and remote access to patient data. Clinicians can monitor rehabilitation progress remotely, supporting telemedicine and reducing the need for frequent hospital visits, especially in long-term rehabilitation programs [37].

Applications in remote patient monitoring

IoT-based hand grip systems have significant value in remote patient monitoring, allowing patients to perform assessments at home while transmitting results to healthcare providers in real time. This improves healthcare accessibility, particularly for individuals with mobility limitations or those living in remote areas [38].

In rehabilitation, remote monitoring enables clinicians to track recovery progress, modify treatment plans, and provide continuous support without requiring in-person visits. Continuous monitoring has also been shown to improve patient adherence and rehabilitation outcomes while reducing healthcare costs [6].

Challenges of IoT-based systems

Despite their advantages, IoT-based hand grip systems face several challenges. Data security and privacy remain major concerns because sensitive patient information is transmitted and stored digitally, requiring secure communication and compliance with healthcare data regulations [37].

System reliability is another important issue, as interruptions in network connectivity may affect monitoring accuracy and data transmission. In addition, the complexity of IoT systems may limit adoption in some healthcare environments due to the technical expertise required for setup and maintenance [34].

Validation, reliability, and standardization of hand grip measurement devices

Measurement accuracy and calibration

The accuracy of hand grip measurement devices is essential for ensuring reliable clinical assessment and effective patient monitoring. Modern digital and sensor-based systems rely on accurate calibration of sensors such as load cells and strain gauges to minimize measurement errors and ensure that recorded grip values truly reflect muscle performance [14].

However, variations in calibration procedures, sensor quality, environmental conditions, and device configuration may lead to inconsistencies between measurement systems. Even minor calibration errors can significantly influence clinical interpretation, particularly when evaluating rehabilitation progress over time [18].

Reliability and reproducibility

Reliability refers to the consistency of grip strength measurements when tests are repeated under similar conditions. High reliability is necessary to ensure that changes in grip strength reflect true physiological differences rather than measurement variability. Studies evaluating conventional and modern grip devices have shown generally acceptable repeatability, although variations between systems and testing protocols still exist [36,37].

Reproducibility, which refers to obtaining consistent results across different devices, operators, and environments, remains a major challenge. Inter-device variability may reduce comparability between clinical settings and research studies, limiting the generalizability of measurement outcomes [14].

Clinical validation of modern devices

Clinical validation is necessary to establish the effectiveness and applicability of hand grip measurement devices in real healthcare environments. Validation studies commonly compare new digital and IoT-based systems with established conventional dynamometers to evaluate their accuracy and reliability. Recent studies demonstrate that many modern systems show good agreement with traditional devices [35].

Despite these promising findings, large-scale clinical validation studies remain limited because many smart and IoT-based technologies are still in early development stages. Additional research is needed to verify their effectiveness across different populations and clinical conditions before widespread routine adoption can occur [38].

Standardization challenges

One of the major challenges in hand grip strength assessment is the lack of universal standardization. Variations in device design, testing protocols, hand position, grip span, posture, and patient effort can all influence measurement outcomes and lead to inconsistent results [39].

The absence of standardized measurement procedures also complicates comparison between clinical studies and healthcare environments, particularly with newer technologies where differences in sensors, calibration methods, and data-processing algorithms may further increase variability [14]. Therefore, developing standardized protocols and regulatory guidelines is essential to improve reliability, reproducibility, and clinical acceptance of modern hand grip measurement systems.

Current challenges and limitations

Despite major technological advancements, several challenges continue to limit the widespread clinical adoption of modern hand grip measurement systems. One of the primary barriers is the high cost of advanced sensor-based and IoT-enabled devices, which may reduce accessibility in low-resource healthcare environments. In addition, technical complexity related to calibration, maintenance, and system configuration may affect usability and lead to inaccurate measurements if systems are not properly managed [34,35].

Concerns regarding data security and interoperability also remain significant. Cloud-based monitoring systems require secure communication protocols and compliance with healthcare data protection regulations to ensure patient confidentiality. Furthermore, the absence of universal standardization contributes to inter-device variability and inconsistent measurement outcomes across different healthcare settings [34,39].

Finally, limited large-scale clinical validation and issues related to wireless connectivity and power management continue to affect the reliability of long-term remote monitoring systems. These limitations slow the transition from conventional dynamometers to fully integrated smart healthcare solutions [38,40].

Emerging trends and future directions

The future of hand grip measurement systems is moving toward intelligent, interconnected, and personalized healthcare technologies. The integration of Artificial Intelligence (AI) and Machine Learning (ML) into smart monitoring systems enables automated analysis of large datasets, supporting predictive assessment and advanced clinical decision-making beyond simple force measurement [40].

Recent developments in wearable and soft robotic technologies have also contributed to the emergence of flexible sensor-based systems capable of continuous monitoring during natural hand movement. Smart gloves and flexible sensing platforms improve comfort, usability, and ecological validity while maintaining accurate grip force assessment [17].

At the same time, cloud computing and big data analytics are expanding the role of telemedicine and remote healthcare. Modern IoT systems allow clinicians to monitor rehabilitation progress in real time through centralized cloud platforms, improving accessibility and supporting population-level health analysis [32,37].

Efforts are also being directed toward low-cost and portable architecture to increase accessibility in resource-limited environments [37]. Overall, the convergence of IoT, AI, flexible sensing technologies, and cloud computing is expected to transform hand grip assessment into a core component of personalized digital healthcare and precision rehabilitation [40].

Conclusion

The technological transformation of hand grip measurement devices has progressed from simple mechanical dynamometers to advanced digital, sensor-based, and IoT-enabled systems. These developments have significantly improved measurement accuracy, real-time monitoring, data accessibility, and rehabilitation assessment.

The integration of sensors, embedded systems, wireless communication, and cloud-based technologies has expanded the clinical applications of hand grip assessment in rehabilitation, telemedicine, and personalized healthcare. However, challenges related to standardization, calibration, data security, and large-scale clinical validation remain.

Despite these limitations, ongoing advancements in AI, wearable sensing technologies, and smart healthcare systems are expected to further improve the effectiveness and accessibility of hand grip monitoring. Future innovations will likely establish smart hand grip assessment as an essential component of precision rehabilitation and digital healthcare systems.

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