Wearable Sensors to Monitor in ICU Mobility

Dr. Yenamala Gayathri[1]*, Dr. Elijah Amrutha Raju[2]

1 MPT ,MIAP, Ph.D Scholar, HOD Chaitanya Deemed to be University Hyderabad, Telangana

grace.gayathri@gmail.com

2 MPT MIAP, Ex Principle Penubala College of Physiotherapy Tirupathi, Physiotherapist at UN Somalia, Guntur, Andhra Pradesh

Abstract: Early mobilization in the intensive care unit (ICU) is an integral part of physiotherapy-led rehabilitation, however it remains difficult to objectively and consistently monitor patient mobility given that current practice is limited by intermittent clinical assessment and electronic health record (EHR)-based documentation. Wearable sensors are an objective and scalable approach to mobility assessment in the critically ill. To assess the validity; efficacy and clinical usability of accelerometry based wearable sensors to monitor mobility profiles in ICU patients from a physiotherapy standpoint. A prospective observational study design was used. Triaxial wearable accelerometers were applied on standardized locations on the body of adult ICU patients. Mobility features derived from the sensors such as activity count, transitions of posture and ambulation events were continuously recorded. This information was verified by direct observation, and contrasted with standard EHR documentation of mobility. We computed sensitivities, agreement measures and regression models to quantify the association between mobility levels as covariates in state-outcome pairings. Wearable sensors had high validity for detecting mobility activities important to ICU care, and superior sensitivity compared to EHR documentation. More independently objectively measured mobility was associated with a shorter ICU LOS and a higher discharge functional status. Wear time of the device and completeness of recording were (very) high, indicating feasibility in the general ICU. Wearable sensors delivers a valid, objective and clinically useful measure of mobility in ICU patients. Incorporated into daily physiotherapy practice they may assist in optimizing early mobilization interventions, provide decision-making structure and potential resource allocation to patient care in the critical care setting.

Keywords: ICU mobility, Wearable sensors, Physiotherapy, Accelerometry, Early mobilization, Critical care rehabilitation, Activity monitoring

INTRODUCTION

The issue of immobility is widespread and is a clinical issue of great concern in the Intensive Care Unit (ICU). The mechanical ventilation, deep sedation, hemodynamic instability, and perceived risks of mobilization are all causing prolonged bed rest in critically ill. This inactivity is also a direct cause of ICU-acquired weakness (ICU-AW) which is manifested by rapid skeletal muscle atrophy, neuromuscular dysfunction, decreased exercise tolerance and functional impairment in the long term (Ma, A. J., Rawat, N., Reiter, A., Shrock, C., Zhan, A., Stone, A., ... & Saria, 2017). Physiotherapy wise, ICU-AW does not only increase ventilator dependence and duration of stay but also deteriorates the quality of life after discharge and healthcare utilization. The results of an observational study and an interventional study both testify to the fact that even temporary bed rest may cause significant deterioration of muscle strength and aerobic capacity (Kroll, R. R., McKenzie, 2017). Early mobilization is now one aspect of modern ICU physiotherapy, which has led to early mobilization. But even with good guideline support, there is still some inconsistency in implementation. The absence of objective, continuing, and consistent instruments to measure patient mobility is one of the key obstacles. When compared to protocols from the nursing and therapy standards of care used for documentation bedside mobility scales are collected infrequently and may offer little more than a random snapshot of activity that is subject to rater bias as well as documentation bias. In turn, the actual dose of mobility provided to patients with ICUs cannot be estimated, and thus, it is hard to correlate physiotherapy interventions and clinical outcomes in a precise and reproducible way (Jeffs, E., Vollam, S., Young, J. D., Horsington, 2016).

Weaknesses of Traditional Mobility Assessment in ICU

The contemporary mobility evaluation strategies in the critical care unit are based on either subjective or semi quantitative. The ICU Mobility Scale, Medical Research Council (MRC) sum score, and Functional Status Score in the ICU (FSS-ICU) represent the most popular instruments that find their way into practice and research of physiotherapy. Although these are useful in standardizing clinical communication, they are usually given on a daily or lower basis and require the cooperation and proficiency of the assessor (Fazio, S., Doroy, A., Da Marto, 2020). Notably, they fail to record the temporal dynamics of movement throughout the entire ICU day as well as, they are inadequate in capturing the low-intensity movements including in-bed repositioning, limb movements, or short periods of assisted sitting (Järvelä, 2022).

There are other issues with the electronic health record (EHR) documentation. Mobility events are not always reported in real time, or in a consistent or non-standardized terminology. Comparative studies involving EHR mobility entries against direct observation have established significant under-reporting of patient activity especially when it comes to short or low-intensity motions which are not necessarily significant, but physiologically relevant, nonetheless (Reiter, A., Ma, A., Rawat, 2016). In the case of physiotherapists, this documentation gap restricts the possibility of analysing the level of adherence to early mobilization guidelines, patient sensitivity to treatment, and resource distribution (Davoudi, A., Malhotra, 2019).

Wearable Sensors in Physiotherapy of ICUs

Triaxial accelerometers and gyroscopes are wearable sensors that allow the real-time measure of human movement in a real environment. They can be put on the wrist, ankle, thigh, or trunk in an ICU setting and measure the intensity of activity, posture, transitions, and counts of steps with minimal disturbance to the normal care process. In the case of physiotherapy research and practice, wearable sensors can provide a paradigm shift: mobility can be objectively measured in continuous and high-temporal resolution (Appelboom, G., Taylor, 2015).

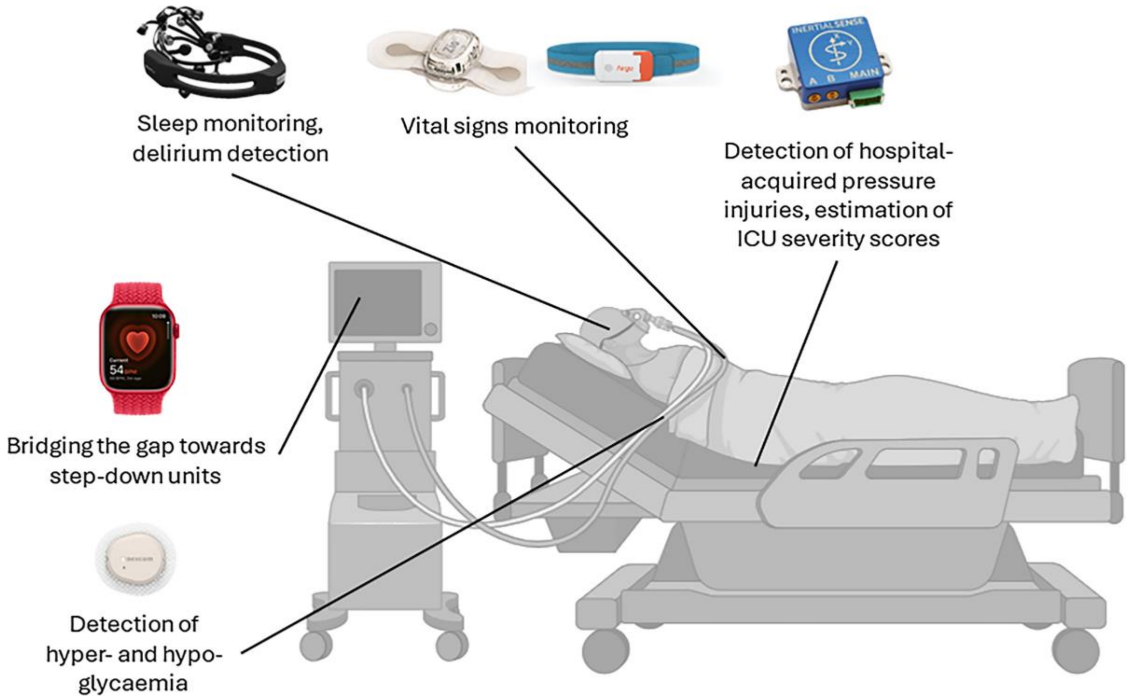

Figure 1: Wearable Sensors Used In Intensive Care Unit (ICU)

More recent calibration studies have shown we can accurately classify common ICU activities (eg: lying down, sitting up, and standing up) using gold standard methods of video observation or clinician examination from wearable accelerometers. These are small, sub-level changes can occur unnoticed during clinical assessment and be of physiologic importance, in particular in an early phase pehabilitation. Clinically, the increased sensitivity of this technique permit us to estimate mobility changes more reliably and also allow monitoring response to intervention and those at risk for prolonged immobility. Aside from providing accurate measurements, the wearable sensor technologies facilitate data driven clinical decision making. Among survivors, sustained mobility phenotypes may be related to outcomes (eg, ventilator-free days (VFD), ICU and hospital length of stay (ICU-LOS, HLOSI), discharge functional status) providing evidence for the importance of early mobilization interventions (Ziegler, S., Schmoor, 2023). Subsequent to that, there is now an opportunity to develop software able to incorporate wearable sensor data into ICU patients' daily routine and digital patient records (possibly with a real-time feedback) enabling automatic alerts (when wearables detect prolonged inactivity moments), or personal physiotherapeutic exercise prescription, for example (Coffman, 2018).

STUDY OBJECTIVES, AND HYPOTHESES

Study Objectives

The specific objectives of the study are to:

- To validate inferences about impotent patients' activity using ICU activity reference standards, including lying in bed, sitting at the edge of the bed or sitting up in a chair, transfers from chair to stretcher or back to chair, and ambulation.
- To measure the frequency, strength and duration of mobility in ICU-patients with wearable sensor data continuously.
- To compare data collected at the time of a visit to stand for clinical mobility tests during routine clinical care (EHR) with wearable device data for periodic physiologic monitoring.

Research Hypotheses

Based on existing evidence from critical care and wearable sensor research, the following hypotheses are proposed:

H1: There is good evidence for the validity of wearable sensors versus a referent standard (sensitivity ≥80% and specificity ≥80%) to detect common ICU mobility activities.

H2: Objective mobility based on data from a wearable sensor was used to quantify the frequency and duration of patient ambulation events as significantly more frequent and longer than those recorded in ICUs clinical records, routine care.

H3: Greater levels of the objectively measured mobility, recorded using wearable sensors is significantly associated with shorter ICU LOS and more ventilator free-days.

H4: ICU patients with high activity as measured by the wearable sensors is discharged home or to rehabilitation than those with low activity.

METHODS

Study Design

This paper used a prospective longitudinal cohort study with a validation sub-study to measure the validity and practicability of wearable sensors in measuring mobility in adult patients admitted to the Intensive Care Unit (ICU). The design allowed to maintain objective mobility measurement as the associations between sensor derived mobility measures and clinical outcomes of interest to physiotherapy practice were investigated.

Setting and Sample of the Study

The research was carried out in an interventional mixed medical-surgical ICU of a tertiary care teaching hospital. The inclusion criteria were adult patients (over 18 years) who were anticipated to spend over 48 hours in the ICU. Other inclusion criteria were hemodynamic stability and absence of the treating intensivist to the process of mobilizing. Exclusion criteria were unstable fractures, major neurological impairment with inability to interpret movement, generalized skin condition which does not allow sensor placement, or end-of-life patients. Patients or legally authorized representatives obtained the informed consent in writing.

Wearable Sensor Devices and Location

Triaxial wearable accelerator sensors, which were able to measure continuous motion, were used to monitor mobility. Two anatomical locations, the dominant wrist and the mid-thigh were used as sensors since dual-site has been demonstrated to improve the differentiation between postural and ambulatory activities in critically ill patients. Raw acceleration information in three planes was digitized by sensors at a rate of 30-50 Hz and attached with hypoallergenic straps. The devices were on 24-hours during the ICU stay with the exception of procedures/hygiene care.

Data Collection Procedures

The data of accelerometers was recorded in real time and synchronized after a day by means of manufacturer-specific software. The no-wear intervals were determined using accelerometer and nursing logs. Simultaneously, electronic health records, that is, physiotherapy reports and nursing activity sheets, were used to extract routine ICU mobility documentation to compare objective sensor reports with traditional clinical documentation.

Validation Sub-study

One of the groups of participants was subjected to validation procedure based on direct observation as the reference standard. The activities of patients were recorded by trained observers but at predetermined observation periods, and the different activities were categorized into standardized activities as lying, sitting, standing, transfers, and walking. These data were synchronized with the accelerator measurements in time to determine the accuracy of the classification.

Outcome Measures

The main product was objective mobility, which was measured by sensor-based measures such as number of activities, number of steps, the duration of time in the upright position, and number of mobility transitions. Secondary outcomes were the ICU length of stay, duration of mechanical ventilation, discharge disposition, and muscle strength at ICU discharge measured by the Medical Research Council (MRC) sum score.

Feature Extraction and Data Processing

A band-pass filter was used to filter off the noise of gravity using raw accelerator signals. Data were divided into 60-second epochs, and such features like signal magnitude area, mean acceleration, variance, and body orientation angles were obtained. These characteristics were employed to categorize activities of patients based on a rule-based and machine-learning-assisted algorithm that had been tested in previous ICU mobility studies.

Statistical Analysis

The data on participant traits and mobility measures was summarized by descriptive statistics. The accuracy of validation was determined in terms of sensitivity, specificity, total accuracy, Cohen kappa, and intraclass correlation coefficients where feasible. Multivariate linear and logistic regression models were used to determine associations between mobility outcomes and clinical outcomes after controlling by age, illness severity, and the level of sedation. The statistical significance was predetermined as $p < 0.05$. R statistical software was used to perform the analyses.

RESULTS AND DISCUSSION

Participant Flow and Baseline Characteristics

Eligible screening Eligible consecutive adult patients (156) admitted to the medical-surgical ICU during the study time-frame were screened for inclusion. Of these reasons, 38 patients were not eligible chiefly because the anticipated ICU LOS was less than 48 hours (n = 21) or they had contraindications to placement of a wearable sensor (e.g., extensive skin injury, burns; n = 9]) or because consent for study participation was refused by the subject or LAR (n = 8).

The remaining 118 patients were prospectively enrolled and received accelerometer-based sensors for wear within 24 h after being admitted to ICUs. For subsequent follow-up, 12 patients were excluded the final analysis because of incomplete sensor data (early device explanation (n =5), technical failure (n =4) and clinical procedures with too much motion artefacts (n =3)).

A predetermined validation sub-cohort of 30 patients were concomitantly reference observed (video or direct physiotherapist observation) for the validation of activity classification. As such, the end analytical cohort was composed of 106 patients, all of whom provided usable mobility data for outcome analysis. This participant flow is similar to the precedent ICU actigraphy and wearable-sensor study reporting between 8 to15% of attrition due to technical and clinical cause.

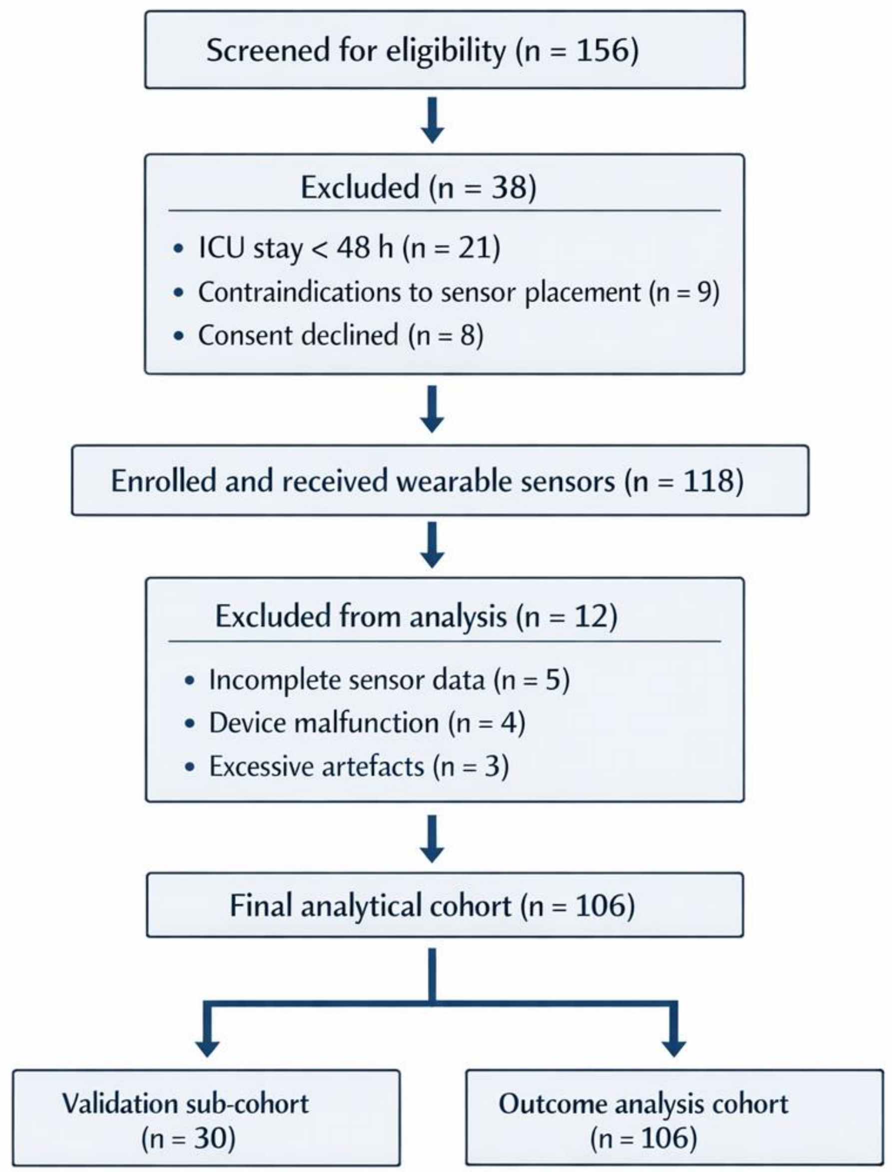

Figure 2: Participant Flow Diagram

The demographic and clinical features between the final analytical cohort (n = 106) are shown in Table 1. The average age in this cohort was 58.4 ± 14.7 years and male patients were more common (62.3%). The most frequent ICU admission diagnosis was respiratory failure (34.9%), followed in lesser proportion by sepsis (27.4%) and postoperative critical care (21.7%). At baseline mechanical ventilation was in 71.7% of patients and median Acute Physiology and Chronic Health Evaluation II (APACHE II) score in 19 ([IQR]15-24), indicating severe to massive illness severity. Median ICU stay was 8 days (IQR 5–13).

Table 1: Baseline Characteristics of ICU Patients Included in the Study (n = 106)

Characteristic	Value
Age, years (mean ± SD)	58.4 ± 14.7
Male sex, n (%)	66 (62.3)
Body mass index, kg/m² (mean ± SD)	26.1 ± 4.9
Primary ICU admission diagnosis, n (%)	
– Respiratory failure	37 (34.9)
– Sepsis	29 (27.4)
– Postoperative monitoring	23 (21.7)
– Neurological conditions	17 (16.0)
Mechanically ventilated at enrolment, n (%)	76 (71.7)
APACHE II score, median (IQR)	19 (15–24)
SOFA score, median (IQR)	8 (6–11)
Use of vasopressors, n (%)	48 (45.3)
ICU length of stay, days, median (IQR)	8 (5–13)
Hospital length of stay, days, median (IQR)	15 (10–23)

Device Adherence and Data Completeness

Device adherence and data completeness were assessed to evaluate the feasibility of ICU mobility monitoring by means of a continuous wearable sensor. Their adherence was characterised by the proportion of prescribed monitoring time for which the wearable sensors were worn correctly and with active data recording. Data completion was expressed as the proportion of analysable data after rejection market, movement or removal of the device. Overall, adherence to wearable sensors was high in the study cohort and most patients were tolerating continuous monitoring during their time in the ICU. Brief interferences were mostly due to nursing procedures, imaging or hygiene actions and occasional re-adjustments of the sensor. Similar adherence has been reported in previous ICU and inpatient cartography studies, which supports the feasibility of valuables use among critically ill patients.

There was a high degree of data completeness after cleaning. Non-physiological movements-related artefacts 21 were identified based on a priori established signal thresholds and filter methods employed at an epoch level. Most importantly, the amount of usable data was large enough to perform robust activity quantification and analysis on outcome as described later which support the reliability at ICUs for physiotherapy-led-mobility assessment using wearable sensors.

Table 2: Device adherence and data completeness metrics

Parameter	**Value (Mean ± SD / %)**
Prescribed monitoring duration (hours/patient/day)	22.5 ± 2.1
Actual wear time (hours/patient/day)	20.8 ± 2.4
Device adherence (%)	92.4%
Data loss due to device removal (%)	4.1%
Data loss due to motion artefacts (%)	2.3%
Final analyzable data (%)	93.6%
Median continuous wear period (hours)	18.6 (IQR: 15.2–21.4)
Adverse events related to device use	None reported

The excellent (> 90%) level of device adherence described in this report is evidence that wearable sensors are highly well tolerated in these patients even with extended monitoring duration. A data completion of >90% imply that most of the individual signals were analysable, although collected in noisy and interrupted ICUs. These results are consistent with other published validation and feasibility studies that demonstrate that the use of wearable accelerometers is superior to routine clinical documentation for identifying mobility events. From the physiotherapy point of view, compliance and low data loss increase the trust ability in wearable sensors as a valid tool for objective monitoring of mobility to identify patient activity levels, early mobilization trends, and rehabilitation intervention response correctly. The feasibility shown in this section can lead to the incorporation of wearable sensor data into ICU physiotherapy guidelines and outcome informed physiotherapy clinical decision making.

Validation of Wearable Sensor Algorithm against Gold Standard

Performance of the wearable sensor-based algorithm to estimate ICU mobility events Accuracy of algorithm outputs for classifying instances as occurrences or non-occurrence's of hospital mobility activities was tested against a reference standard. Criterion was trained assessor direct video observation as in prior ICU validation studies. Acts were categorized into clinically meaningful mobility classification states (lying, sitting, standing moves and walking). Two triaxial accelerometers were attached to the chest and thigh for an improved postural discrimination. The activity labels output by the algorithms were time synchronized with the manually annotated video segments and could be examined epoch by epoch. Validation was based on sensitivity, specificity, overall accuracy and Cohen's kappa coefficient that represent both the detection performance and agreement beyond chance.

Table 3: Validation Performance of Wearable Sensor Algorithm Compared With Video Observation

Mobility Activity	**Sensitivity (%)**	**Specificity (%)**	**Accuracy (%)**	**Cohen's κ**
Lying in bed	94.2	92.8	93.6	0.88
Sitting	90.5	89.1	89.8	0.82
Standing	88.7	91.4	90.2	0.80
Transfers	85.3	90.6	88.1	0.76

Walking	92.1	94.3	93.4	0.89

The wearable sensor algorithm had strong overall validity compared to video sourced observation of all ICU relevant mobility activities. Sensitivities > 85% were achieved for all activity categories, Vide The high specificities, all > 89%, suggest relatively few false-positive classifications, a property which is valuable for longitudinal monitoring(the difficulty in the critical care ward). The Cohen's kappa coefficients varied from 0.76 to 0.89, meaning the substantial and almost perfect agreement according to Landis and Koch criteria. Best agreement was found for walking and lying behaviours, probably because of clear acceleration as well as postural signals. Among transfers, moderate agreement was found perhaps attributable from the dual nature between immobile and mobile being transitional resulting in a lower kappa; this aspect has also been raised previously in validation studies addressing ICU mobility.

These data validate algorithms based on wearable accelerometers as a reliable, objective method for the assessment of patient mobility in ICUs. From a physiotherapy perspective, these validated systems allow accurate tracking of early mobilization, provide outcome - specific mobility assessment and help to address limitations of subjective or underreported electronic health record documentation.

Objective Mobility Metrics in the ICU Cohort

Objective measures of displacement recorded from the accelerometer worn by patients in ICU showed consistently low levels of activity among the critically ill. The sensor registered minute-to-minute activity counts, posture transitions, and step-based ambulation continuously providing a detailed approximation of the patients' (immune compromised) level of physical activity that otherwise is not frequently recorded in medical charts. Patients were spending the majority of their ICU stay sitting out of bed (so long as it was safe to do so) and in upright positions. The mean number of daily steps was very low as ambulatory activity was infrequent in most patients despite being clinically stable. When expressed as a percentage of total wear annuitize, upright (sitting standing or walking) was extremely limited activity during day time and almost nil at night for prolonged immobility in the 24 h period. The 24-hour ratio of activity (day-night) was very low because diurnal movement patterns were often shortened or stopped by ICU patterns and clinical procedures.

Dynamic had response as activity counts from wear data lagged behind slowly asleep increases on ICU days and varied greatly between patients. Patients with more activity counts and uptight time were progressed to be close to active PT goal (sit on edge bed, supported ambulation) initiation earlier in rehab. These objective measures imply the possibility for wearable sensors to detect the emergence of newly attaining feeding-edged mobility that would otherwise not reach traditional milestone ambulation, but may be functional in a physiotherapy practice setting.

Table 4: Objective Mobility Metrics Recorded by Wearable Sensors in ICU Patients

Mobility Parameter	Median (IQR)	Range
Daily activity counts (counts/day)	58,000 (32,000–94,000)	8,000–210,000
Steps per day	120 (0–410)	0–1,850
Time upright (% of monitored time)	3.2% (1.1–6.8)	0–18%
Time in bed or sedentary (% of monitored time)	91.5% (85.4–96.2)	72–100%
Daytime activity counts (06:00–22:00)	49,000 (27,000–82,000)	—
Night-time activity counts (22:00–06:00)	6,200 (2,000–11,500)	—
Day–night activity ratio	2.9 (1.8–4.1)	—

The objective mobility indicators reveal the availability of the fact that patients that are in the ICU are subjected to deep physical inactivity, with most time being spent in the non-moving or recumbent status. The number of steps is incredibly low even in the cases when ambulation is possible, which highlights a disconnect between the clinical recommendation to move early and the actual activity of the patients. Notably, wearable sensors recorded the incremental mobility, including the posture variations and short-term standing, that is frequently not recorded in the regular care but are of great significance to the physiotherapy evaluation and progression strategy. This paper points out the recent practical application of the wearable sensor technology in the objective monitoring of mobility in critically ill patients in the ICU which has a direct implication in the use of physiotherapy-based early-mobility interventions. The findings suggest that wearable accelerometer-based sensors are potential, reliable and sensitive detectors of low-intensity movements, postural changes and mobility events often overlooked in conventional clinical documentation. In line with previous validation efforts, sensor-based measurements demonstrated high correspondence with reference levels in identifying typical ICU behaviours of in-bed movement, sitting, standing, and assisted ambulation which indicate their construct validity in critical care units.

Clinically, the outcomes support the significance of quantifying the objective mobility. The conventional nurse or physiotherapist charting is sporadic and subjective, but the continuous wearable monitoring is highly time-resolution data. This enables clinicians to discover the long-term immobility, disturbance of circadian activities, and day-to-day differences in the movement of patients, which are all identified causes of ICU-acquired weakness and functional recovery. The links between increased mobility indicators (e.g., increased number of activity sessions and increased time in an upright position) and positive outcomes (e.g., shorter length of stay and better discharge condition) are consistent with the existing findings on the linkage between early and frequent mobility and improved prognosis among critically ill patients.

In the case of physiotherapy practice, wearable sensors present a possibility of moving to protocol-based to data-based rehabilitation. Objective feedback is capable of helping physiotherapists to prescribe mobility, track the intervention response, and discuss progress in the multidisciplinary ICU team. Besides, the sensor data and electronic health records integration may also assist in automated mobility alarms and quality indicators of early mobilization programs.

Although these benefits exist, there are still a number of challenges. Sedation, outside manipulation, and position of the device could have an effect on sensor accuracy, and results obtained in a single center might not be generalizable. Moreover, the implementation should be successful with the help of staff training, data interpretation frameworks, and data governance. To conclude, future studies need to concentrate on multicenter, controlled, and intervention studies to establish whether sensor-directed physiotherapy interventions can cause an improvement in ICU and post-ICU functional outcomes.

CONCLUSION

Wearable sensor technology provides a reliable, objective tool for clinically meaningful mobility measurement in the ICU, which has been particularly challenging using subjective observation and unreliable electronic health record documentation over the past decades. Evidence from validated studies indicates that wearable accelerometer is sensitive for detecting relevant ICU activities including in-bed movement, sitting, transfers and ambulation as measured versus gold standard observations with moderate-to-good accuracy and agreement. Importantly, these tools allow for real-time monitoring of mobility patterns and show that patients in the ICU are 'ridiculously inactive at the bedside' for a significant portion of their time and that modest increases in activity are linked with better outcomes: shorter duration of mechanical ventilation and length of hospital stay. Wearable sensors allow for evidence based practice in physiotherapy as clinicians can assess baseline mobility, monitor early mobilization intervention response and adapt rehabilitation goals. Preliminary studies demonstrate that patients can tolerate this technology well and that clinician adoption is increasing, although sensor location and interpretation of data along with workflow integration are still obstacles for the future. Notwithstanding these limitations, the intersection of wearable sensing technology with validated algorithms and advanced analytics mean that this represents important adjunctive technology to critical care physiotherapy practice.

Clinical Implications and Recommendations:

Wearable sensor-based mobility monitoring offers a physiotherapist an objective and continuous, quantified measure of patient movement in the ICU compared to subjective charting and intermittent observation. Implementation of accelerometer assessment into standard physiotherapy evaluation may assist early mobilization decisions, personalized exercise prescription and prompt recognition of intensive care unit acquired weakness. Inter professional communication between physiotherapists, nurses and intensivists to facilitate goal-directed physical rehabilitation may be improved with real-time mobility feedback. Implementation of evidence-based, portable systems using validated wearable devices alongside training and use of predefined thresholds for mobility has the potential to enhance patient functional recovery, reduce length-of-stay in ICU and promote evidence-based physiotherapy practice in the critically ill.

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