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Empowering recovery: a remote spirometry system and mobile app for monitoring and promoting pulmonary rehabilitation in patients with rib fracture

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ABSTRACT

Background Multiple rib fractures commonly result from blunt chest trauma. These fractures can lead to prolonged impairment in pulmonary function and often require long-term rehabilitation. This pilot study aimed to evaluate the feasibility of a remote spirometry device for continuous monitoring of lung function in patients with multiple rib fractures.

Methods Between January 2021 and April 2021, we implemented a remote spirometry system for adult patients with multiple rib fractures and collected their clinical data. We used a Restart system to monitor the respiratory parameters of patients. This system included a wireless spirometer and a Healthy Lung mobile application. A portable spirometer was used to measure forced vital capacity (FVC), peak expiratory flow (PEF), and forced expiratory volume in 1 second.

Result In total, 21 patients were included in this study. We categorized the participants into two age groups: those older and those younger than 65 years. No significant differences were observed between the two groups regarding demographic characteristics or device adoption rates. However, we observed that patients under 65 years demonstrated more remarkable improvement in pulmonary function than their older counterparts, with significant differences in FVC (110% vs 10%, p=0.032) and PEF (64.2% vs 11.9%, p=0.003).

Conclusion The adoption of the remote spirometry device is similar between older and younger patients with rib fractures. However, the device improves pulmonary function more in patients in a younger age group. This tool may be effective as a real-time, continuous pulmonary function monitoring system for patients with multiple rib fractures.

Level of evidence Level IV.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Multiple rib fractures resulting from chest trauma can lead to prolonged impairment of pulmonary function, often necessitating long-term rehabilitation.

WHAT THIS STUDY ADDS

⇒ This study introduces a pilot study that explored the feasibility of using a remote spirometry system to monitor lung function continuously in adult patients with multiple rib fractures.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ The findings suggest that remote spirometry can be successfully used in both younger and geriatric patients.

⇒ However, younger patients demonstrate more significant improvements in pulmonary function.

⇒ This study highlights the potential of integrating technology to enhance the care and rehabilitation of patients with rib fractures, with implications for future research and clinical practice.

INTRODUCTION

Multiple rib fractures often result from blunt chest trauma and cause significant physiological and anatomic consequences. Patients with multiple rib fractures frequently experience pain, restricted thoracic movement, and compromised lung function that can persist for several months,[1–4] which may have significant physiological and anatomic impacts on the pulmonary function of such patients. Assessment of the fundamental pulmonary functions in patients with multiple rib fractures is essential for predicting the risk of pulmonary-related complications such as pneumonia or atelectasis.[5] Traditional methods for monitoring pulmonary function, such as self-reporting questionnaires, are often unreliable due to the influence of subjective factors, including the complexity of the questions, the recall abilities of patients, and the impact of social factors.[6 7] An alternative tool for monitoring these patients is a spirometer, a device that measures basic pulmonary function. However, arranging for frequent pulmonary function evaluations is challenging and not very accessible. Nevertheless, the hospital-based nature of these pulmonary function tests (PFTs) and the lack of continuous follow-up options limit their effectiveness and ability to provide clinicians with up-to-date results.

In recent years, telemedicine has gained prominence in the health sector. Notably, an internet-based telemedicine trial improved the survival outcomes of patients with lung cancer who reported their symptoms to medical professionals.[8] Consequently, various platforms have been developed for patients with trauma, particularly chest trauma.[9 10] Nevertheless, the beneficial effects of telemedicine on

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patients with trauma remain a subject of debate.[11–13] Integrating remote sensors with telemedicine-based applications offers a promising approach, allowing patients to record their health status and physicians to follow-up seamlessly. By harnessing emerging technologies such as wearable activity trackers and smartwatches, healthcare professionals can remotely monitor the pulmonary function of patients with rib fractures, potentially improving their overall quality of life.

To address this gap, this study aimed to assess the suitability of a digital health intervention protocol for monitoring lung function after rib fractures using a portable spirometer and a user-friendly app. The objective was to evaluate the feasibility and clinical value of remote pulmonary rehabilitation for patients with multiple rib fractures. In addition, we examined the influence of age on the design of digital health interventions.

MATERIALS AND METHODS

This was a prospective pilot study on the feasibility and clinical value of remote spirometry in patients with multiple rib fractures. It was conducted at a tertiary trauma center between January 2021 and April 2021. Patients with more than three rib fractures were defined as having multiple rib fractures and enrolled in the study. The exclusion criteria included hemodynamic instability requiring resuscitation, intubation, a Glasgow Coma Scale Score <13, airway injuries, severe facial bone fractures, and the presence of neurogenic or cognitive disorders that prevented spirometry. Informed consent was obtained from all patients.

In our study, adequate pain control was paramount in the management of patients with rib fractures. Oral non-morphine analgesics and surgical interventions were used for pain control. Participants received acetaminophen 500 mg four times a day and ibuprofen 400 mg three times a day as part of their baseline pain control. In patients where flail chests were identified, internal fixation was performed within 72 hours postinjury with patient consent, aligning with guideline recommendations. For patients without flail chest who experienced persistent daytime pain (Visual Assessment Score >7), a regional nerve block was administered within 24 hours. To address night-time pain (Visual Assessment Score >5 at night), a combination of tramadol and acetaminophen was prescribed. Additional intravenous morphine was administered for unsatisfactory pain control results after previous treatments. Furthermore, patients could choose an external fixation band for additional pain control, promoting flexibility and individualization of pain management.

We used a Restart system to monitor the respiratory parameters of patients. This system included a wireless spirometer (ezOxygen, Genius Holding, Taiwan) and a Healthy Lung mobile app (ezOxygen). Additionally, a portable spirometer was used to measure forced vital capacity (FVC), peak expiratory flow (PEF), and forced expiratory volume in 1 second (FEV1). This measurement was based on passive ultrasonic detection of the airflow rate. The app allows patients to receive spirometry data and record clinical variables such as associated discomfort and analgesic use. The app also facilitates digital data transfer to medical staff, making it easier for healthcare providers to monitor patients remotely. The system architecture is presented in figure 1, which outlines the various components of the Restart system and provides real-time monitoring of the respiratory parameters.

The patient managers visited these patients within 24 hours to record acute-phase lung function. They also evaluated the patients' experience with wearable devices and smartphones.

Figure 1 The Restart system's architecture which including a remote spirometry, a mobile phone and App.

Both the patients and caregivers were taught about the use of the entire system. The participants' tasks included starting their devices, launching the app, inputting information, using the spirometer, reviewing, retaking, or accepting captured data, responding to questions, and submitting the data. These tasks were carefully assessed to ensure the system was easy to use and understand. The revised System Usability Scale (SUS) was administered to all participants to evaluate their comprehension and satisfaction with the model. In patients where the SUS yielded a score below 8, a targeted re-education process was implemented to ensure that all participants clearly understood their required tasks.

On initiating the Restart system, patients' parameters were promptly recorded and displayed on the accompanying app. The data input was synchronized with the mobile device and transmitted to the server when internet access became available, facilitating subsequent analyses. During hospitalization, patient managers visited and trained the participants. The patients were instructed to use the portable spirometer at least once daily during the study period, which extended to 8 weeks postdischarge. Patients were encouraged to engage with the system as frequently as desired, without restrictions. Furthermore, the frequency of system usage was evaluated as a good metric of system adoption. Given the absence of standard validated tools, we established specific criteria to define good system adoption: more than three uses per week and consistent input of PFT data for >10 days during the follow-up period. Conversely, patients that failed to meet either criterion were categorized as having poor adoption.

This method allowed us to discern the depth of patient engagement with the system and assess its overall adoption within the study cohort. Clinical follow-ups were consistently scheduled for all participants at 2 weeks, 6 weeks and 12 weeks after discharge to monitor patient progress comprehensively. During

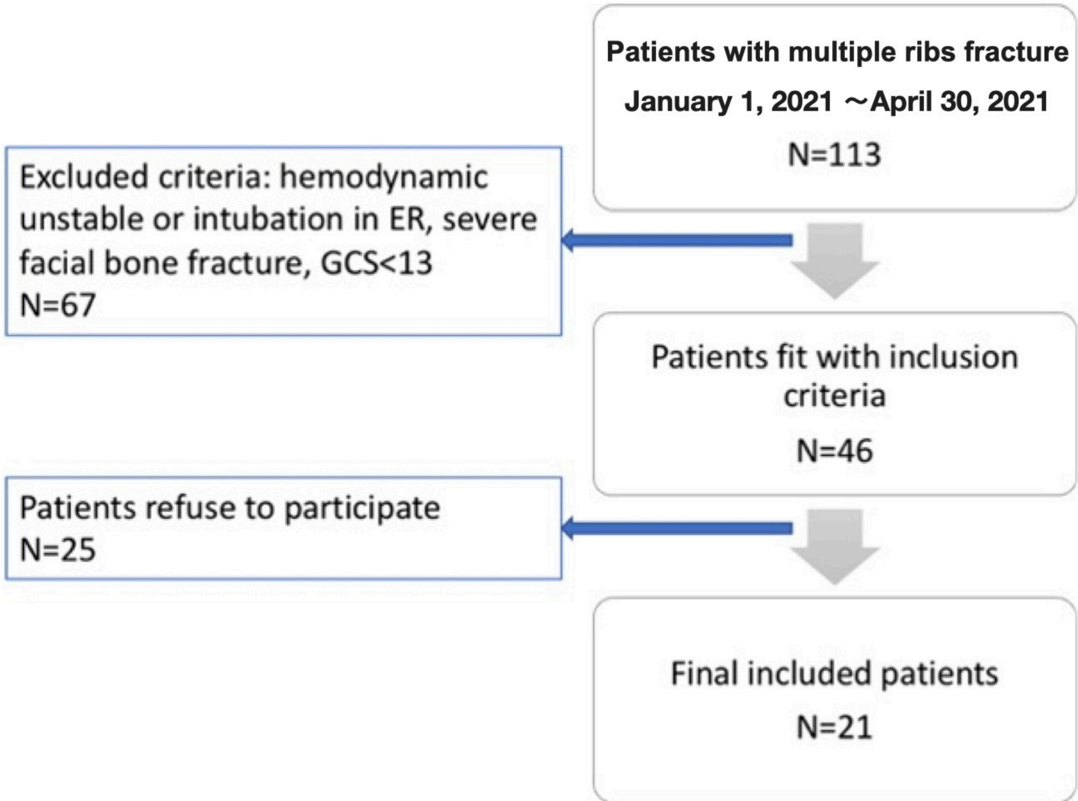

Figure 2 Flow chart of the study. ER, Emergency department; GCS, Glasgow Coma Scale.

each outpatient clinic visit, plain posterior-anterior chest radiography was performed to evaluate for residual pleural effusion. Combining both online and offline approaches enabled us to not only gauge the adoption of the system but also to understand its impact on clinical outcomes during the entire follow-up period. To further evaluate the relationship between adoption rate and age, we conducted an independent analysis of 11 participants with good adoption.

Another blinded health provider[8 10] who did not participate in designing this system was responsible for reviewing and analyzing the data independently. This system aimed to assess whether remote rehabilitation systems had a positive impact on the use of analgesics and impaired lung function. Complications, imaging findings, and unexpected returns to the hospital were also recorded.

Statistical analysis

Statistical analysis was performed using the commercially available software package SPSS (V.21.0; IBM, Armonk, New York, USA). Numerical data were presented as means with SD or medians with IQRs and were compared using the Mann–Whitney U test. Nominal data were presented as numbers with percentages and were compared using Pearson's χ^2 and Fisher's exact tests. Statistical significance was set at $p<0.05$.

RESULTS

During the study period, 113 patients were diagnosed with multiple rib fractures. Of these, 67 patients were excluded based on the exclusion criteria. Of the remaining 46 patients, 25 refused to participate. Ultimately, 21 patients were enrolled in the study (figure 2). Table 1 shows the participants' demographic characteristics.

Table 1 Demographic data of all the patients in the study

	n=21
Age (years)	59±6
Male genders (n, %)	17 (80.9%)
BMI (Median±IQR)	25±2.3
Rib fracture number (median±IQR)	5±1
Flail chest (n,%)	1
Segmental fracture (n,%)	14
ISS (median±IQR)	17±8
SUS (median±IQR)	85±7
Hemothorax (n,%)	10 (47.6%)
Pneumothorax (n,%)	9 (42.9%)
Chest tube (n,%)	7 (33%)
Length of stay (days, median±IQR)	6±3.5
ICU admission rate (N,%)	3 (14%)
Length of ICU stay (days, median±IQR)	4±0.5
Liver laceration	1
Head injury	4
Pelvic fracture	2
Operation	3
Well adoption	11
Re-admission rate in 30 days	4
Complication (n,%)	7 (33%)
Pneumonia (n,%)	2 (9.5%)
Persist pleural effusion >6 weeks (n,%)	7 (33%)
Mortality (n,%)	0 (0%)

BMI, body mass index; ICU, intensive care unit; ISS, Injury Severity Score; SUS, System Usability Scale.

Table 2 Comparison of the clinical outcomes between the geriatric and young groups

	Young n=16	Geriatrics n=5	P value
Male gender (N,%)	13, 81.2%	4, 80%	1
Body mass index (median IQR)	25.4 (3.4)	24.9 (1.9)	1
ISS (median IQR)	18.5 (16.2)	13 (9)	0.561
Associated injuries			
Head injury (n, %)	2, 12.5 %	2, 40%	0.22
Liver laceration (n, %)	1, 6.2%	0,0%	1
Pelvic fracture (n, %)	2, 12.5%	0, 0%	1
Number of ribs fractured (median IQR)	5 (2)	5 (3)	0.8
Flail chest (n, %)	1, 6.2%	0, 0%	1
Hemothorax (n, %)	8, 50%	2, 50%	1
Pneumothorax (n, %)	6, 60%	3, 27.3%	0.313
Creatinine	0.9 (0.1)	0.9 (0.1)	0.257
Blood urea nitrogen	14.2 (4.7)	19.1 (6.1)	0.038
Alanine aminotransferase	44 (50.1)	22(9)	0.021
Underlying disease			
Hypertension	4,25%	4, 80%	0.047
Diabetes mellitus	5,31.2%	4, 80%	0.119
Coronary arterial disease	0,0%	1, 20%	0.238
Chest tube insertion (n, %)	6,37.5%	1, 20%	0.313
Improvement of FVC (%)	110% (270)	10％ (25)	0.032*
Improvement of FEV1(%)	99%(270)	31％(42)	0.063
Improvement of PEF	64.2%(140)	11.9％(3)	0.003*
Length of stay (days, median IQR)	8.5 (7)	4 (2),	0.058*
Surgical intervention (n, %)	3,18.8%	0, 0%	0.09
Complications	7, 43.75%	2, 40%	1
Pneumonia	2, 12.5%	0, 0%	1
Presence of pleural effusion >6 weeks (n, %)	5, 31.2%	2, 40%	1
Re-admission in 90 days (n, %)	3, 18.8%	1, 20%	1
Poor adoption	9, 56.2%	1, 20%	0.311

*p value < 0.05.
FEV1, forced expiratory volume in 1 second; FVC, forced vital capacity; ISS, Injury Severity Score; PEF, peak expiratory flow.

Precisely 17 of the participants were male, and the average age of the participants was 59±6 years. The median Injury Severity Score (ISS) was 17±8, and the median fractured ribs were 5±1. Segmental fractures were present in 14 participants, with one having a flailing chest. Hemothorax was observed in 10 participants, and 9 had pneumothorax. However, only seven participants required chest tube insertion for decompression. The median length of stay in the hospital was 6±3.5 days, and three participants required intensive care during hospitalization. These patients were admitted to the intensive care unit because of pain-induced respiratory distress. No mortality was recorded among the participants. Complications such as pneumonia occurred in two participants, and seven had residual pleural effusion after 6 weeks. On adoption of the Restart system, 11 participants had good adoption, and 10 did not.

Five participants belonged to the geriatric group, and the remaining individuals belonged to the younger group. A comparison between the two groups is presented in table 2.

No significant differences were observed in sex, body mass index, ISS, or associated injuries. Anatomic and pathophysiologic parameters, such as the number of fractured ribs and the presence of pneumothorax or hemothorax, were similar between the two groups. However, the geriatric group exhibited a higher prevalence of chronic diseases and a higher baseline BUN level than the younger group (hypertension: 80% vs 25%, p=0.048; 19.1 (6.1) vs 2 (4.7), p=0.038). The length of hospital stay was longer in the younger group (median, 8.5 days) than in the geriatric group (median, 4 days). Both groups showed a statistically significant improvement in pulmonary function (figure 3). However, the geriatric group showed less significant improvements than the young group in FVC (10% vs 110%; p=0.032), FEV1 (31% vs 99%, p=0.063), and PEF (11.9% vs 64.2%, p=0.003).

Concerning the system adoption rate, a poor adoption rate was noted in 20% of participants in the older group and 56.2% of those in the younger group. However, this was not statistically significant (p=0.311). The average number of uses per week in this study was 6.3. Three patients used the system less than three times per week starting in the second week and almost completely stopped using it afterwards. The rest of the patients maintained a good adoption rate, with an average of 5.62 uses per week. However, differences emerged starting in the second month. The good adoption group consistently used the system four times per week throughout the 3-month observation period. In contrast, nearly all patients in the poor adoption group stopped using the system after the second month. Consequently, the average number of uses per week dropped to 1.2 thereafter. As shown in figure 4, a better adoption rate was associated with greater improvements in PEF and FVC, although no significant difference was found in FEV1.

DISCUSSION

In this study, we successfully developed a remote spirometry system designed to offer daily pulmonary rehabilitation and record and analyze PFT results during 8 weeks in patients with rib fractures. Our results highlight a significant improvement in PFT outcomes with improved adherence to remote spirometry regimens. Notably, geriatric patients demonstrated adoption and acceptance rates similar to those observed in younger patients. These findings highlight the potential effectiveness and broad applicability of remote spirometry systems in diverse patient demographics. Although the use of telemedicine in the acute care of patients with fractures is limited, some studies have used it as a bridging method before interhospital transfer or for long-term follow-up.[14 15] In this study, we broaden the scope of the use of telemedicine systems in patients with rib fractures. These systems assist patients in rehabilitation and collect data that can be transmitted wirelessly to healthcare professionals, enabling remote, real-time monitoring of recovery progress.

An issue in the follow-up of patients with chronic rib fractures is the difficulty in recording the rehabilitation status. By integrating the Restart system, we can monitor patients' pulmonary function, recovery, analgesic use, and adoption rate for rehabilitation. Previous studies have shown good adherence to chest wall rehabilitation and good pulmonary outcomes in patients with trauma.[16–18] The performance of chest wall exercises with lung expansion is the key to improving pulmonary function in patients with rib fractures.[16–18] It is proven that good system adoption also reduces the risk of residual pleural effusion 8 weeks after a rib fracture when using this telemedicine system.[16] In this study, we presented a continuous follow-up for 8 weeks after patients suffered from multiple rib fractures, where we identified a greater improvement in PFT if the patient underwent regular pulmonary rehabilitation after the trauma.

However, the prospects of telemedicine are unpredictable.[19–21] Various technologies have been introduced to assist patients,

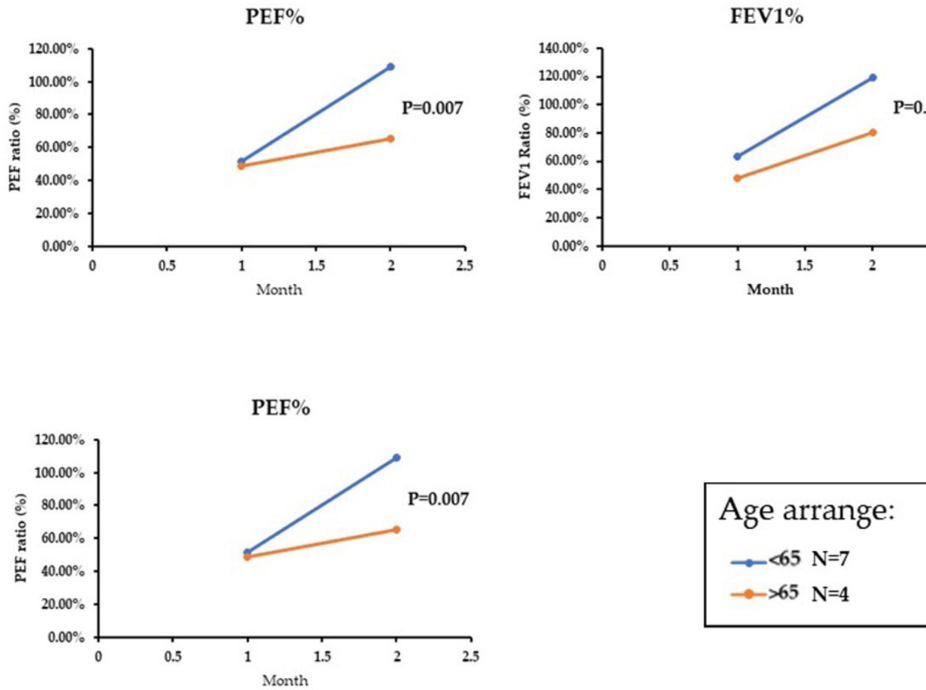

Figure 3 Improvement of lung function at different ages with good rehabilitation compliance. FEV1, forced expiratory volume in 1 second; PEF, peak expiratory flow.

caregivers, and healthcare providers. Geriatric patients are at a higher risk of complications after chest trauma than young adults.[22 23] The slow adoption of new technology is another hindrance to the application of telemedicine to patient groups. According to previous studies,[24 25] the acceptance of telemedicine is lower among older people than among younger ones. Furthermore, previous studies have reported that poor telemedicine performance is strongly related to poor patient adoption.[24 26] In

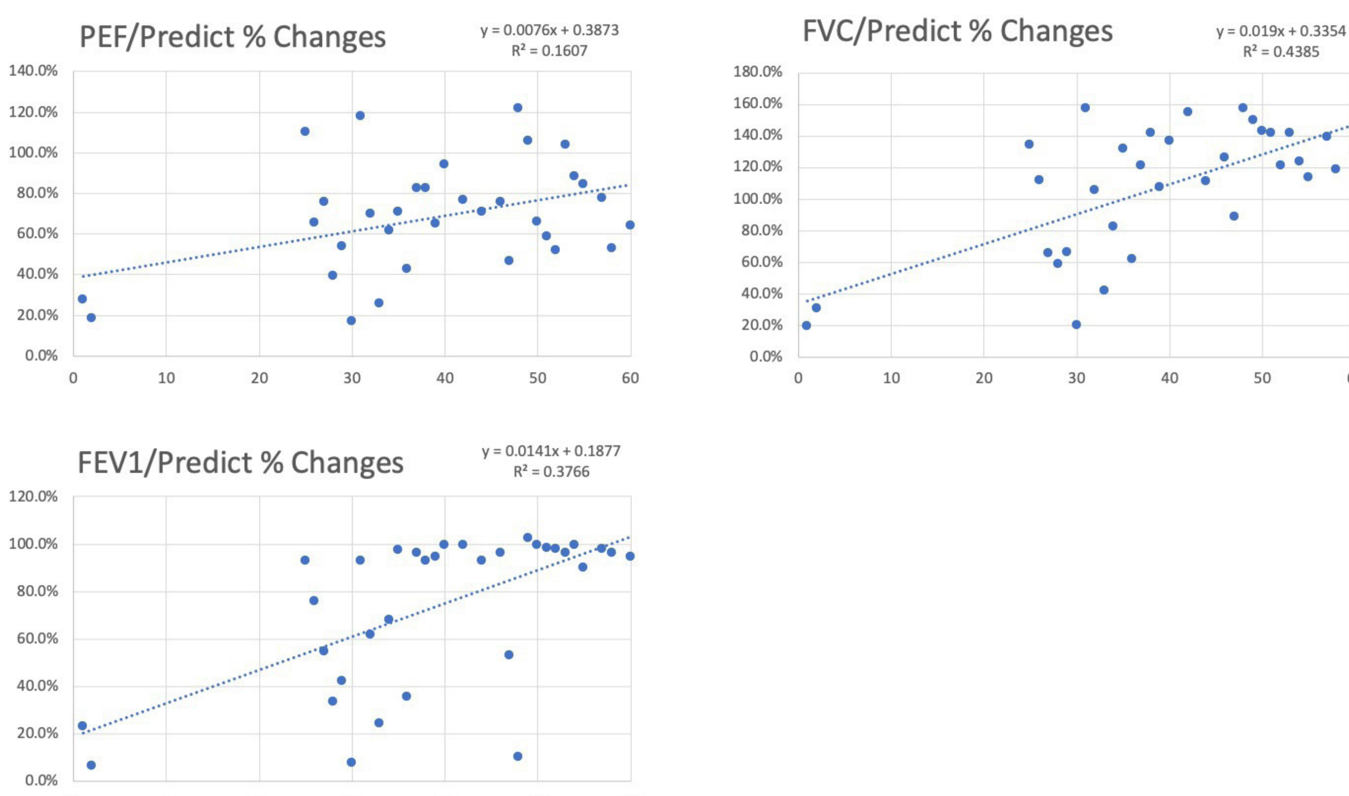

Figure 4 The details of pulmonary function parameters monitored by the Restart system and the illustration of biographic presentation during follow-up. FVC, forced vital capacity; FEV1, forced expiratory volume in 1 second; PEF, peak expiratory flow.

this study, we found that the adoption rate in geriatric patients (80%) was higher than that in younger patients (43.8%), although this difference was not statistically significant. This is an important and novel finding.[27] More studies have advocated that the use of telemedicine is more unsafe for geriatric patients than for younger patients.[28 29] First, telemedicine can be used as a continuous monitoring tool, particularly for rehabilitating vulnerable patients, as periodic outpatient follow-ups may be unsatisfactory for these patients.[28 29] Furthermore, geriatric patients require both physical and psychologic care. Hence, timely feedback from telemedicine ensures patients are more confident in their health status. This results in improved physical activity and social functioning. This is of significance when implementing national health policies.[30]

A previous study revealed greater improvement in pulmonary function among patients with a high Restart system adoption rate.[16] In the study, only 11 patients had good adoption of the new equipment, highlighting the challenge of introducing unfamiliar technologies to patients. To address this in our study, extensive efforts were made to familiarize patients with the system, including daily visits by patient managers for education and support during hospital stays. However, as the patients' pain decreased over time, their initial interest in and perceived benefits of the equipment decreased, leading to a decline in the adoption rate. This drop in adoption rate became more evident 6 weeks after the initial injury. Consequently, this study was designed with a 3-month follow-up period to comprehensively track patients' progress using clinical observations. Despite the ability of the system to provide timely feedback and interventions for decreased usage, sustaining patients' motivation for continued usage remains a challenge. Future studies may incorporate a sustained incentive system to encourage the ongoing use of telemedicine equipment.

When we considered the impact of age, the geriatric group had better adherence to the Restart system. Despite this, they experienced a lower improvement in pulmonary function when compared with the younger group. The presence of underlying medical conditions and reduced physiologic reserve may explain the poor improvement in geriatric group outcomes. The clinical outcomes in our study were similar between the geriatric and younger groups, with discrepancies existing only in pulmonary function improvement. In addition, no statistically significant difference in complication rates was observed between the two groups. Interestingly, the only two patients with pneumonia are in the younger group. Further studies on the role of lung function in the clinical outcomes of patients with rib fractures should be conducted. Finally, we found that the three patients who stopped using this system after being discharged from the hospital had no improvement in their pulmonary function.

Only four female patients were enrolled in our study, which may affect the interpretation of the study findings. However, no significant differences were observed between men and women. In Taiwan, most traumas are blunt injuries related to work and traffic. Although the patients were predominantly male, sex did not affect clinical outcomes in the study.

Another advantage of the system is that it reduces unnecessary travel for vulnerable patients. Since the pandemic, efforts have been made to reduce the spread of airborne diseases as much as possible. Traditional follow-up tools, such as standard PFTs, may increase the spread of the virus via air droplets during the procedure.[31] Our system provides patients with an alternative method of maintaining chest wall rehabilitation after hospital discharge without the risk of spreading disease.[19 32 33] Pulmonary function outcomes and pain scores are recorded digitally, which can reduce manual tasks. Additionally, home-based rehabilitation is more convenient. The pulmonary function parameters were measured immediately after the procedure. This positive reward mechanism may encourage patients to perform spirometry more frequently, making our system a good tool for home rehabilitation.[27]

The use of digital technology in healthcare has revolutionized the way patients receive treatment. The Restart system, designed for patients with rib fractures, is an excellent example of the use of digital interventions to improve treatment outcomes. This study investigated the effectiveness of the Restart system and the feasibility of an internet-based intervention for managing chest rehabilitation after rib fractures. The system can help patients build a habit of chest rehabilitation, which is crucial for improving clinical outcomes after blunt chest trauma, especially in geriatric patients. Future studies focusing on geriatric patients should help clarify the reasons for the effectiveness of the system and identify ways to improve its results. Overall, the Restart system offers a promising avenue for digital intervention in the management of patients with rib fractures and can be used to guide future research in this area. The Restart system represents a significant advancement in remote patient monitoring and has the potential to revolutionize the care of patients with respiratory disease. By providing patients with access to real-time respiratory data and facilitating communication with medical professionals, this system can help improve patient outcomes and reduce hospital re-admissions.

Limitations

This study had some limitations. First, we followed up with patients for just 3 months, focusing on short-term benefits. Hence, we could not assess the long-term impact of the Restart system on lung function, pain, and analgesic use. Furthermore, patients with severe cognitive or visual impairments may face challenges with instructions when using the device independently. In addition, the small sample size limited the strength of the academic evidence, which was partly attributed to patient recruitment difficulties after the pandemic and domestic government policy. Moreover, the study did not include a control group because of the regulatory challenges in gaining approval for non-remote interventions. Hence, approval limitations, including government and institutional ethics policies, confined the study to the testing group. This hindered a direct comparison between remote and non-remote approaches. Patients going to the hospital to undergo regular conventional spirometry examinations faced difficulties during and after the COVID-19 pandemic due to domestic regulations. This constraint poses a significant challenge to the comparison of the remote intervention with the conventional approach.

Despite these limitations, this study showed that telemedicine and mobile spirometry can potentially enhance the care of patients with rib fractures. This capability allows remote monitoring of respiratory function and clinical data, offering possibilities for prompt intervention and improved patient outcomes. With ongoing technological advancements, telemedicine is expected to play an increasing role in managing trauma patients.

CONCLUSION

This study presents our experience in developing a remote monitoring system for patients with rib fracture that can offer continuous PFT recordings and improve PFT after 8 weeks of follow-up. The adoption rate among geriatric patients was as high as that of young patients. However, pulmonary function improvement in the geriatric group was still more limited than in the younger group, although no inferior clinical outcomes were noted. This telemedicine tool can be used as a real-time continuous pulmonary function monitoring system for patients with rib fractures. Future research should focus on a prospective randomized study to thoroughly assess the benefits of telemedicine for patients with chest trauma.

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Contributors CAL and CHL designed this study. THY and SCK assisted with the development of the trial protocol and system. LWK, CAL, and SAC collected the patients and data. YST was the independent reviewer for trial operations. CTC, CAL, and CHL reviewed the data, performed statistical analysis and validation. CAL and CHL drafted the article. CAL, CYF, and CTC critically revised the article. CHL supervised the revisions. CHL is the guarantor of this work. ChatGPT was used to edit the sentences partially before sending for language editing.

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Competing interests None declared.

Patient consent for publication Not applicable.

Ethics approval This study involves human participants. The Institutional Review Board of Chang Gung Memorial Hospital approved the study protocol (201 900 495B0). The study was conducted according to the guidelines of the Declaration of Helsinki. Participants gave informed consent to participate in the study before taking part.

Provenance and peer review Not commissioned; internally peer reviewed.

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