Potentials of Smart dynamometer use for clinical and self-management of rehabilitation in breast cancer survivors: a feasibility study

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Abstract

The aim of this study was to examine the feasibility of the Smart dynamometer as a rehabilitation exercise device in a daily care by comparing with the existing medical devices. We used and analyzed clinical and measurement data of breast cancer survivors who have used Smart dynamometer during their rehabilitation after breast cancer surgery. The Smart dynamometer was compared with the two existing devices of Takei dynamometer and surface electromyography (sEMG) that were used in routine care, respectively. Three key components of the rehabilitation exercise devices were analyzed to validate the feasibility of the Smart dynamometer: grip strength, reaction time, and grip endurance time. Pearson's correlation analysis was performed to compare the statistical significance between the devices. The data of 12 and 15 female breast cancer patients were analyzed for comparing the Smart dynamometer with Takei dynamometer and sEMG, respectively. There was a very weak correlation between the maximum values from the Takei and the Smart dynamometers in the affected and non-affected arms of breast cancer patients ($r=0.5321, 0.4733$). Comparisons of 3 features between the Smart dynamometer and sEMG showed that there were strong positive correlations for both reaction time and endurance time in the affected and non-affected arms ($r>0.9$). The feasibility of the Smart dynamometer for the possible use in a daily rehabilitation exercise was partially verified. Moreover, since the Smart dynamometer was highly correlated with time-related variables, it was important and significant to measure both grip strength and time-related information.

Keywords Dynamometer · Resistance exercise · Electromyogram · Breast cancer · Feasibility study

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1 Background

Secondary lymphedema may occur in some breast cancer survivors because of damage to the axillary lymphatic system following surgery or radiotherapy. Lymphedema occurs from the accumulation of lymph fluid and proteins in the tissues near the lymph node on the affected side, and it exhibits the characteristic of regional limb swelling [1]. Symptoms related to lymphedema, such as pain, decreased range of motion, physical discomfort, and functional impairment, interrupt daily life and post-operative care [2]. In addition, disfigurement of the patient's appearance can lead to anxiety, depression, and emotional distress. These are more common in women with secondary lymphedema than in women without it. As a result, they may have a decreased quality of life [2–4].

Evidence from several studies have indicated that progressive resistance exercise increased muscular strength and

endurance, reduced the severity of arm and hand symptoms, and reduced the incidence of lymphedema exacerbations [5, 6]. These studies also suggest that appropriate progressive resistance exercises are important to prevent patients' long-term side effects. They report that it is important to develop an effective therapy regimen that prevents the patients' fear and avoidance of use of the affected arm, which could worsen their symptoms [3, 7–11]. Accordingly, hospitals recommend continued rehabilitation exercise and participation in rehabilitation programs in the treatment of breast cancer patients. Unfortunately, program adherence among these patients is very low [12, 13].

The first reason why adherence is low is related to physical factors. Because most breast cancer patients suffer from severe pain and weakness, their physical activity level decreases and the time spent resting and sleeping naturally increases. These two conditions can cause loss of muscle mass and disuse atrophy [14–16]. Moreover, most patients are very difficult to convince when it comes to starting or maintaining an exercise program due to social isolation and depression. The second reason is related to environmental factors, such as the high costs of therapy and a lack of facilities. Patient engagement is especially low due to the lack of exercise facilities tailored for cancer patients. Previous studies have confirmed that some patients preferred rehabilitation exercises that they could perform at home over exercising at a gym or fitness center designed for healthy people [14]. In order to resolve such problems, the introduction and application of new rehabilitation exercise devices is necessary to promote rehabilitation exercise, especially resistance exercise, and to lower the exercise barrier for breast cancer survivors.

The Smart dynamometer, which was developed for the purpose of hand resistance exercises, is a device that allows the patient to consistently perform resistance exercise in a fun and enjoyable way by using games on the smartphone and tablet personal computers (PC). However, because the first version of the Smart dynamometer developed was a pilot version, additional feasibility testing is needed for clinical application in breast cancer patients. Accordingly, the objective of this study was to test the clinical feasibility of the Smart dynamometer as a breast cancer rehabilitation device by comparing its use data to existing data measured with a standard dynamometer and surface electromyography (sEMG).

2 Methods

2.1 Instruments

The Smart dynamometer has the benefits of portability and simplicity. The measurement part was designed in the shape

of a hand gun to allow for easy grip (Fig. 1). A load cell (TAS606, HT sensor, China) that measures up to 50 kg is embedded in the measurement part, so that when the patient applies force, it provides a voltage output value according to the handgrip pressure. This analog voltage value is converted to a digital value by a 12-bit analog-to-digital (AD) converter, which is stored in flash memory at a sampling cycle of 10 ms (100 Hz). The communication part of the Smart dynamometer can transmit the stored voltage value in real time to any paired smartphone or tablet PC via the Bluetooth 2.0 communication protocol.

2.2 Data

We collected the clinical and measurement data of breast cancer patients who visited the cancer center at the department of rehabilitation medicine in a tertiary hospital for rehabilitation therapy between January and September 2017. Patients who had used a Smart dynamometer at least once during their rehabilitation therapy after breast cancer surgery were included. The measurement data comprised three different types of measured values from three different devices. The first was the time-varying pressure value from the Smart dynamometer. The second was a pressure value measured using the Takei dynamometer (TKK5401, Takei Scientific Instruments, Japan). The Takei dynamometer is the device that was often used as a standard in previous studies to compare to the usefulness of another dynamometer [17–19]. The third value was the EMG signal measured using a sEMG

Fig. 1 Smart dynamometer (pre-market device: NEOFECT)

measurement system (FreeEMG1000, BTS Bioengineering, USA), which allowed us to compare the exact time spent in, and clinical significance of, muscle activation. This was a retrospective, observational study that used clinical data collected during examinations at the department of rehabilitation medicine, therefore informed consent was not required by Institute review board (IRB). The study was conducted after receiving IRB approval for the use of such data (IRB No. B-1801-447-101).

2.3 Data collection protocol

Each set of data was measured using a different protocol. The first protocol (*Smart–Takei*) was used to measure the handgrip pressure values of the Takei and the Smart dynamometers, while the second protocol (*Smart–sEMG*) was used to simultaneously measure the handgrip pressure and the sEMG signal.

1. Smart–Takei

The handgrip pressure was measured using the Takei and the Smart dynamometers to validate the grip strength. The grip strength was determined by the maximum voluntary contractions (MVC) that each patient could achieve. The duration of each contraction was 1 s, and the contraction was repeated three times consecutively. The maximum value was recorded among the three peak values. Each participant performed four tests in each hand, meaning the standard grip strength device and the Smart dynamometer were utilized to measure this parameter in both hands. Moreover, to reduce muscle fatigue, a 10 s interval resting time was provided between sessions (Fig. 2). All patients were seated upright with their elbow flexed (90°) so that the forearm was horizontal and supported with a cushion. The upper arm was abducted at 0° based on the American Society of Hand Therapists (ASHT) guidelines [20], so that the grip strength was not affected by the elbow position [21]. For consistent results, continuous verbal directions were given as follows: “This task will be testing your grip strength. When I say ‘start’, give your maximum

effort for 1 s, and then relax for 1 s. After repeating this 3 times, we will switch hands and measure again in the same manner.” Before the actual measurement, the physiotherapist trained the patients on where and how to grip the equipment.

2. Smart–sEMG

With the sEMG sensor already attached, the grip strength, grip reaction times, and grip endurance times were measured with the Smart dynamometer simultaneously. The *Smart–sEMG* protocol comprised 3 parts: as strong as you can (ASA), as fast as you can (AFA), and as long as you can (ALA) (Fig. 3). In the first ASA part, the protocol for measuring the grip strength was same as the *Smart–Takei* protocol. The grip strength was determined by the MVC, which was performed to the maximum level that the patient could achieve. The duration of each contraction was 1 s and the contraction was repeated three times consecutively. In the AFA part, the grip reaction time was measured. The grip reaction time was determined by having the patient grasp as fast as he/she could after counting for 3 s. The stopwatch function in the software in the surface EMG system was used for counting. Both hands were measured one time each, and the reaction time was recorded as the total measured time subtracted by 3 s. In the ALA part, the grip endurance time was measured. The grip endurance time was defined as the maximum amount of time that a patient could maintain their MVC, and the time was recorded in seconds using the stopwatch in the EMG software. Both hands were measured one time each. All patients were seated upright in a chair with their forearm in a neutral position, and with the elbow straight and fully extended at the side, and with the upper arm abducted at 0°. The placement of the electrodes was determined according to recommendations of Delagi et al. [22]. Four silver/silver chloride (Ag/AgCl) electrodes were positioned over the flexor carpi radialis (FCR) and the extensor digitorum (ED) muscles of the both hands. In addition, ground electrodes were connected to the side of the electrodes in the distal direction according to the manufacturer specification [23]. Before the measurements, the physiothera-

Fig. 2 Smart–Takei protocol flow

Fig. 3 Smart-sEMG protocol flow: **a** ASA (as strong as you can) test flow, **b** AFA (as fast as you can) test flow, **c** ALA (as long as you can) test flow

pist trained the participants on where and how to grip the measurement devices and the standard dynamometer. The measurements began with a verbal signal to start. The EMG signals were obtained simultaneously in all parts with 1000 Hz of acquisition sampling and AD-conversion with 16-bit resolution using a surface electromyography measurement system.

2.4 Evaluation measures

Three features in the rehabilitation exercise device from which the components could be used to validate the feasibility of the Smart dynamometer as a resistance exercise device included: grip strength, grip reaction time, and grip endurance time.

2.5 Signal processing

For the signal processing environment, a freeware Python 2.7.10, Spyder 3.0.0 version was used. EMG signals were pre-processed to transform into the curve, and the evaluation features were extracted from each waveform using the same signal processing algorithm.

1. EMG pre-processing

First, the offset and low frequency signals generated by external factors (e.g., sweat and movement) were eliminated using an infinite impulse response (IIR) high pass filter. IIR filter which has no phase lag was used to accurately compare the time-varying variables, such as reaction time and endurance time. Filtered signals were full-wave rectified using the absolute value func-

tion [24], after which, the root means square (RMS) calculation by De Luca et al. [25] was used to derive the integrated form of the RMS waveform.

2. Grip strength

The Smart dynamometer reported pressure waveform per second according to the strength of the user's grip. Peak values of the waveform were detected by a simple wavelet-based peak detection algorithm [26–28], and the maximum value among the peak values was recorded as the sensor value for that test. The same peak detection algorithm was used to derive the peak values of the EMG RMS waveforms, and the maximum value among the peak values was recorded as the sensor value for that test.

3. Grip reaction time

Grip reaction time was defined as the time taken from the last count to the rising edge time (RT). The one-dimension (1D) edge detection algorithm defined by Canny [29] was used to derive RT, which was the point reached after a rapid increase from baseline. This algorithm derives the slope using each point on the original graph based on the assumption that the point on the graph with peak slope is an edge where the graph suddenly bends. In other words, in the graph from the first order differentiation of the pressure curve and the EMG curve, the maximum peak point that first appears is recorded as RT in calculating the grip reaction time.

4. Grip endurance time

Grip endurance time was defined as the time difference between RT and the falling edge time (FT). To derive FT, the same 1D edge detection algorithm by Canny was used [29], and the peak point in the nega-

tive direction of the slope was assumed to be the falling edge. In other words, in the graph from the first order differentiation of the pressure curve and the EMG curve, the point where a negative peak value finally appeared was recorded as FT in calculating the endurance time.

2.6 Data analysis

The raw data extracted from the Smart dynamometer were not converted to kg. All of the data extracted from the waveforms outside the residual variance of 99%, as derived by the linear regression method, were discarded as outliers. In the *Smart–Takei* protocol, correlations between maximum grip strength measured by the standard dynamometer and maximum pressure value measured by the Smart dynamometer were analyzed for the affected and non-affected arms. In the *Smart–sEMG* protocol, we used Pearson's correlation analysis to determine correlations between RMS peak, RT, and FT extracted from EMG RMS waveforms, and between pressure peak, RT, and FT extracted from the Smart dynamometer pressure curve. It was assumed that p value < 0.05 represented significant differences between the groups. All data analyses were performed using freeware R 3.3.1.

3 Results

3.1 Patients' characteristics

The data of 12 female breast cancer patients were collected from the *Smart–Takei* protocol. The mean age of the patients was 47.2 years old (SD: 9.6). All patients from the *Smart–Takei* protocol group received breast cancer surgery on the left or right breast, while one patient had surgery on bilateral breasts. For the patient who had surgery on bilateral breasts, both her left and right arms were classified as affected arms. In other words, the total number of affected arms was 13 (12 + 1), while the total number of non-affected arms was 11 (12 – 1). The data of 15 female breast cancer patients were collected from the *Smart–sEMG* protocol. The mean age of the patients was 50 years old (SD: 9.6). All patients from the *Smart–sEMG* protocol received breast cancer surgery on the left or right breast, and no one underwent surgery on bilateral breasts (Table 1). There were no patients who overlapped in both protocols. Ninety-five percent of the patients were right-handed. All patients' data collected from the present study were de-identified, and study IDs were assigned to classify the data as follows: F1 to F12 for the *Smart–Takei* protocol, and S1 to S15 for the *Smart–sEMG* protocol.

Table 1 Characteristics of the study participants

	Smart–Takei test (N = 12)	Smart–sEMG test (N = 15)
Age, mean $\pm$ SD	47.2 $\pm$ 9.6	50 $\pm$ 9.6
Breast surgery, n (%)		
Total mastectomy	4 (33.3)	7 (46.7)
Breast conservation surgery	7 (58.3)	8 (53.3)
Both	1 (8.3)	0 (0)
Axillary surgery, n (%)		
All lymph node dissection	6 (50)	10 (66.7)
Sentinel lymph node biopsy	6 (50)	5 (33.3)
Time since the surgery, n (%)		
≤ 1 year	1 (8.3)	8 (53.3)
1–2 years	9 (75)	3 (20)
> 2 years	2 (16.7)	4 (26.7)
Neo-adjuvant/adjuvant therapy, n (%)		
Chemotherapy	9 (75)	13 (86.7)
Radiotherapy	11 (91.7)	12 (80)
Chemo-radiotherapy	9 (75)	11 (73.3)
Chemo-drug, n		
Daunorubicin and cytarabine	0	1
Herceptin	1	4
Taxotere and cyclophosphamide	2	1
Docetaxel	4	6
Alimta	1	1
Paclitaxel	1	0
Hormone therapy, n		
Tamoxifen	4	4
Femara	1	0
Letrozole	1	0
Arimidex	1	0
Menopausal status, n (%)		
Pre-menopausal	0 (0)	0 (0)
Peri-menopausal	4 (33.3)	0 (0)
Post-menopausal	8 (66.7)	15 (100)
Surgical site, n (%)		
Right-side	7 (33.3)	6 (40)
Left-side	4 (58.3)	9 (60)
Both	1 (8.3)	0 (0)

3.2 Results of comparison between the Smart dynamometer and the Takei dynamometer

Pearson's correlation analysis revealed a very weak correlation ($r = 0.5321, 0.4733$) between the maximum values from the Takei dynamometer and those from the Smart dynamometer in the affected and non-affected arms of 12 breast cancer patients (Fig. 4).

Fig. 4 Comparison of the grip strength between the Takei dynamometer and the Smart dynamometer values: **a** affected hand, **b** non-affected hand

3.3 Results of the comparison between the Smart dynamometer and the sEMG dynamometer

The total number of participants in the Smart-sEMG test was 15, but the number of measurements of ASA, AFA and ALA was totally different. This was because unstable data among the data measured by the EMG device was excluded from the analysis. In the event of over-signalized data regardless of actual stimulus, or in the event of data loss due to device or patient factors, the data could not be relied on and ASA, AFA and ALA could not be measured accurately, thus those data were excluded for the analysis.

In the ASA test, both the affected and non-affected arms showed no correlations. However, after discarding the information of patient S9, who had biggest residual as an outlier, the results in the affected arms showed a weak positive correlation ($r = 0.6867$). In the AFA test, only the non-affected arms showed a strong positive correlation ($r = 0.9698$). Among data from the affected arm, after discarding the information of patient S14 as an outlier, due to an unstable EMG signal, the affected arms also showed a strong positive correlation. In the ALA test, both the affected and non-affected arms showed strong positive correlations ($r > 0.9$). In other words, grip force was not significantly associated with muscle activation, which is similar to the results of previous studies. However, forearm muscle activation and grip action were closely associated with each other. Outliers are expressed as black dots (Fig. 5).

4 Discussion

The present study was able to confirm partial feasibility of the Smart dynamometer through the two data collection protocols. In the *Smart–Takei* protocol, the grip strength using

the Smart dynamometer and standard dynamometer were compared under a method conducted in accordance with the protocol used in previous studies [30, 31]. The results showed low correlation coefficients in both the affected and non-affected arms ($r = 0.5321, 0.4733$). In the *Smart–sEMG* protocol, surface EMG was used to confirm correlations with the muscle activation variables. In the data measured from FCR and ED muscles that affect to the grip in the forearm muscles, data of the FCR from the initial analysis were more associated more with grip, and as a result, data from the FCR muscle were used in all subsequent analyses. Consequently, grip strength and FCR muscle activation were not correlated with each other, as reported in previous studies, while grip reaction time and grip endurance time were highly correlated. In other words, muscle activation time was probably estimated through gripping time.

Affected and non-affected grip strengths from each device were analyzed using the Student's t-test in order to determine whether the lower correlations in the *Smart–Takei* protocol were due to the effects of cancer or not. As a result, there were no differences between affected and non-affected grip strength from the three devices. Most previous studies also showed no differences between the affected and non-affected arms [4]. Consequently, it was determined that cancer did not have an effect within the scope of the present study. Other physical factors, such as low reliability of the Smart dynamometer and the position of where the device was held during measurements, may be causes of lower correlation, but the data related to these factors were not collected.

The three features that were used as evaluation measures have been used as predictors of various diseases and symptoms, owing to their simplicity [32–35]. Grip strength and grip endurance are the most typical impairments in breast cancer patients after treatment, and thus, they are useful indicators for following the condition of the patients [6, 36,

Fig. 5 Scatter plots for comparison between the Smart dynamometer and sEMG features

37]. Reaction time task is usually used in studies of cognitive assessment [38–40]. Breast cancer survivors show impaired neurocognitive performance as a result of neo-adjuvant or adjuvant chemotherapy. For this reason, the reaction time has been previously measured as the assessment measure, but other studies have reported that when assessing muscle power, the muscle that moves the hands as an extension of cognition has a bigger impact on reaction time than cognitive performance [38]. In view of these two conflicting reasons, what is clear is the fact that reaction time is a feature that provides good assessments of the physical state of breast cancer survivors.

One of the limitations in the present study was the small sample size. However, the present study showed meaningful results in assessing feasibility. We confirmed the correlations between the two dynamometers and sEMG, rather than

solely the statistical significance of specific features between patient groups. Another limitation was the simplification of the reliability protocol. In previous studies, repeated measurements such as test and re-test were performed first to confirm the reliability of a new tool, and then, internal consistency between all sessions was calculated to prove that there were no differences between sessions [15, 31, 41, 42]. However, because the measurement in the present study were made under outpatient settings, it was impossible to make multiple repeated measurements. Especially, time-varying variables such as grip reaction time and endurance time were limited. As the measurements of grip reaction times were repeated, the patients became accustomed to the protocol, and as a result, some patients reacted even before the verbal signal to start was given. Likewise, as the measurement of grip endurance time was repeated, some

patients became fatigued very quickly, even after just one measurement, and the next session could not be conducted. Consequently, repeated measurements were not performed. The range of maximum grip strength for each individual may vary according to grip span and grip type. A previous study showed that when the size of the measurement device was tailored to each individual, strength and endurance increased by 30–35% [43]. The Smart dynamometer developed in the present study cannot be adjusted according to the grip type of the patient, and applying the same sized dynamometer on all patients may have been the cause of low correlations [23, 32, 33]. Despite such limitations, the present study was beneficial in that it confirmed partial feasibility of the Smart dynamometer. The major findings in the study indicated that: (1) since the Smart dynamometer showed a weak positive correlation with grip strength, it can be used as a tool for patient condition and patient management, and (2) it can also be used as an exercise device for building speed and endurance, rather than for muscle strengthening exercise.

5 Conclusions

Through the present study, clinical feasibility of the Smart dynamometer was partially confirmed. By expanding on the concept of using an assessment tool for grip strength, the findings showed the possibility of its use as rehabilitation exercise for muscle strength. In particular, the Smart dynamometer had high correlations with time-varying variables, such as grip reaction time and grip endurance time. Therefore, measurements of the grip strength and the collection of time-related information were significant. Further testing is needed to examine the reliability and identify the clinical significance of this device by collecting information from more patients. Accordingly, future work will include improving adherence to rehabilitation exercise by applying game contents using this device, which was the original development goal.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

Ethical statement This study was funded by SK Telecom Co. Ltd. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research

committee and with the Helsinki declaration and its later amendments or comparable ethical standards. This was a retrospective, observational study that used clinical data collected during examinations at the department of rehabilitation medicine, therefore informed consent was not required by Institute review board (IRB).

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