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Computerized Biofeedback Knee Goniometer: Acceptance and Effect on Exercise Behavior in Post-Total Knee Arthroplasty Rehabilitation

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Abstract

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Objective

To assess device accuracy, patient acceptance, and effect of a computerized biofeedback knee goniometer (CBG), on patients' compliance with active range of motion (AROM) exercises after total knee arthroplasty (TKA).

Design

Two-stage study: measurement validation on asymptomatic controls and an unblinded, multiple crossover trial.

Setting

Inpatient rehabilitation.

Participants

Asymptomatic controls (n=14) and post-TKA inpatients (n=11).

Interventions

For measurement validation, CBG-angle measurements were compared with manual, clinician-obtained angles. To assess motivational effect, the CBG was worn after TKA; on alternating days, it either monitored AROM silently (no feedback) or provided audiovisual feedback about reaching preset range of motion (ROM) goals and prompted the patients to exercise when idle.

Main outcome measures

To assess accuracy, the device's readings were compared with manual measurements. Patient satisfaction was determined by a self-report questionnaire; exercise compliance was assessed by calculating activity rate and stratified interactivity intervals.

Results

CBG readings reproduced clinician measurements reliably between 0° and 100° (η^2=98.5%). Auditory feedback was more helpful than visual feedback for motivating exercise. During feedback-on days, the mean total activity rate ± standard deviation was 15.1±10.9 activity counts per hour, and the interactivity interval was 6.7±5.7 minutes. The activity rate was higher on feedback-off days—22.5±11.1 counts/hour (*P*=.11)—and the mean interactivity interval was 3.6±2.7 minutes (*P*=.07).

Conclusions

The CBG provided reliable, unbiased estimates of clinician measurements of joint angle within the range of 0° to 100°. The CBG was accepted well by most patients. Surprisingly, slightly more ROM activity was noted during feedback-off days than feedback-on days.

Keywords

Arthroplasty, replacement, knee, Biofeedback, Patient compliance, Rehabilitation

TOTAL KNEE ARTHROPLASTY (TKA) has become a common orthopedic procedure and is the standard of care for patient's with severe knee osteoarthritis. In 1999, over 250,000 TKAs were performed in the United States

alone.1[p42] The number of knee arthroplasties is growing because of aging demographics in the United States. The rehabilitation of the TKA patient is becoming more reliant on outpatient therapy and self-motivated exercises, rather than on long hospital stay. The length of stay in acute care is decreasing annually, and more patients are discharged to immediate self-care at home.

In physical therapy (PT), therapists monitor and regulate exercises performed by patients during therapy sessions and encourage patients to continue self-exercise programs. The therapists' motivating effect must last until the next meeting to maintain high patient compliance. Unfortunately, there is often no one to regulate or encourage patients while exercising on their own. Clearly, a need exists to supplement therapists' motivating effect and monitoring eye in the current environment of shorter postsurgical hospitalization and diminished intensity of PT. One strategy to achieve this reinforcement is a biofeedback device. Patients who use a biofeedback device may easily recognize when they have met their specified goals. They can self-monitor their activity and limit it to safe degrees of motion. The feedback device may motivate patients to exercise when not in therapy and provide quantitative measurements of their progress. Finally, if the device incorporates data-logging capabilities, it can monitor patients' compliance with a home exercise program.

We have developed a goniometer-based, joint position, computerized biofeedback device to encourage and monitor active range of motion (AROM) exercises. The present study reports its application to post-TKA patients in an inpatient rehabilitation setting. The study objectives were (1) to assess the accuracy of an electric goniometer in monitoring knee angle when integrated into an appropriate knee orthosis, (2) to evaluate patient acceptance of using a biofeedback device that provides both visual and auditory feedback while performing AROM exercises as part of the treatment plan, and (3) to determine what effect the biofeedback function would have on patient exercise activity.

Methods

Biofeedback knee orthosis design

A computerized biofeedback knee goniometer (CBG) was constructed, consisting of a custom knee orthosis with an electric goniometer attached to a lateral pocket and a microcomputer-monitoring device (fig 1). The knee orthosis has enlarged anterior and posterior cutouts that reduced most of the forces restricting flexion and extension, while achieving a firm adherence to the limb.[a] The electric goniometer was constructed from 2 anatomically aligned metal stabilizers with a potentiometer at the hinge. It was placed on the lateral side of the orthosis. The battery-powered monitoring unit was mounted on a waist belt worn by the patients (see fig 1).

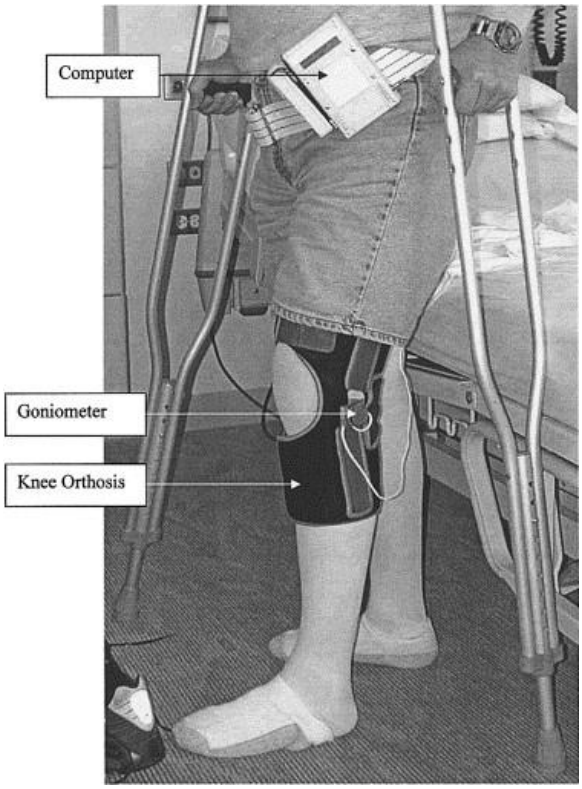

Fig 1. A patient using the CBG. The electric goniometer is attached on the lateral side to the customized knee brace. The computer device is mounted on a belt at the waist.

The CBG provides audio and visual feedback whenever flexion and extension joint angle pass a present threshold goal. The device can be set for feedback-on mode, in which both audio and visual feedback are on, or feedback-off mode, in which the device monitor and log every motion that passes the present threshold but does not provide either visual or auditory feedback. The monitoring unit also acts as an electronic reminder for the patients to range their knee at least once every 30 minutes. The audio prompt can be silenced by the patient by moving the knee through both flexion and extension threshold triggers or by pressing an override button. The monitoring unit has counters that track and record each event and how long the device is worn. The recorded information can be easily downloaded into a portable computer.

Validation of computerized joint angle measurements

Fourteen healthy subjects were fitted with the device and their knee measurements were taken to determine if systematic biases existed in the machine's measurements. Manual measurements were taken with a 7-in (17.8-cm) arm goniometer: the axis of the goniometer was aligned with the knee axis, the proximal arm was placed in line with the greater trochanter, and the distal arm was placed in line with the lateral malleolus. Machine and manual measurements were taken at 5 different positions: (1) straight knee, (2) mid flexion, (3) 90° of flexion, (4) maximal flexion, and (5) hyperextension. We used a 2×5 repeated-measures analysis of variance (ANOVA; with a Geisser-Greenhouse adjustment for sphericity violations2) to evaluate differences between CBG and manual measurements.

Patient selection

Patients admitted to the Rehabilitation Institute of Chicago for post-TKA rehabilitation within 7 days of surgery were candidates for the study. The inpatient rehabilitation population is mostly comprised of complicated cases who portray a slower rehabilitation process because they have existing comorbidity, such as severe rheumatoid arthritis, morbid obesity, or a psychosocial predicament that may slow recovery. Patients

were excluded if they had revision surgery or if they had any severe postsurgical complications. Eleven patients (10 women, 1 man; mean age ± standard deviation [SD], 63.2±11.8g) were enrolled in the study.

Treatment protocol

All patients received the same therapy protocols, which included 2 hours a day of PT, an hour a day of occupational therapy, and an hour of group therapy. Pain medication was prescribed regularly to all patients. They all used a continuous passive motion machine for an average of 3 hours every night of their stay in the department. The CBG was administered to all patients every morning by a single investigator, and was worn throughout the active hours of the day. All measurements, adjustments, and settings were conducted by the same investigator. After 1 day for orientation, the device was placed in feedback-on mode and feedback-off mode on alternating days. The CBG flexion and extension thresholds were adjusted each day to be within 5° of the end of the patient's AROM.

Data collection

General information including age, gender, and days from surgery was recorded for each patient. Patients' perceived pain (marked by the patient on a 0 to 10 visual analog scale) was recorded in the morning of the first day of the trial and on the morning of day of discharge. Participants' AROM was recorded when they entered into the study and at discharge. Flexion count, extension count, audio prompting count, prompt override count, and time worn were downloaded every day after removing the device. Any complications that arose were documented. Each patient filled out a satisfaction survey on discharge.

Outcome measures

A number of parameters were calculated from the logged data. The activity rate, defined as the total number of flexion or extension counts occurring per hour, was calculated to determine the average activity for the day. We used the interactivity interval to determine whether exercise was distributed evenly throughout the day or whether there were long periods of inactivity. The interval was calculated for each recorded action (extension or flexion goal that was reached) as the time that passed since the previous recorded action in minutes. The interactivity intervals were stratified as follows: group 1, less than 1 minute; group 2, 1 to 5 minutes; group 3, 5 to 30 minutes; and group 4, over 30 minutes. Means of measurements of all the patients on feedback-on and feedback-off days were compared by using a paired 2-tailed *t* test, with *P* less than .05 being considered statistically significant.

A patient satisfaction survey, on a 5-point Likert-type scale, was completed by each patient. On the day of discharge, the questionnaire was handed to the subjects by the investigator, who encouraged the patients to portray their critical impressions and reactions to the device, technical characteristics and use. Weighted means were calculated for each queried item, and the open remarks were collected and reviewed.

Results

ANOVA of the electrogoniometer measurements revealed no significant manual versus machine average differences ($F_{1,13}$=.08, *P*=.78; fig 2). Almost all variation (η^2=98.5%) was accounted for by differences in angle types. However, a significant overall interaction was found ($F_{4,52}$=4.04, *P*=.006; *P*=.045 when adjusted for sphericity violations). This interaction was primarily because of the CBG tendency to underestimate manual measures of knee angle in maximal flexion ($F_{1,52}$=5.06, *P*=.043). In this position, both the skin and brace were stretched and the goniometer did not always follow the whole extent of the bone movement. This effect (found only at the maximal flexion group between 110° and 160°) was disregarded for the purpose of the present study, because range of motion (ROM) of our postsurgical subjects was generally limited between 0° and 90°.

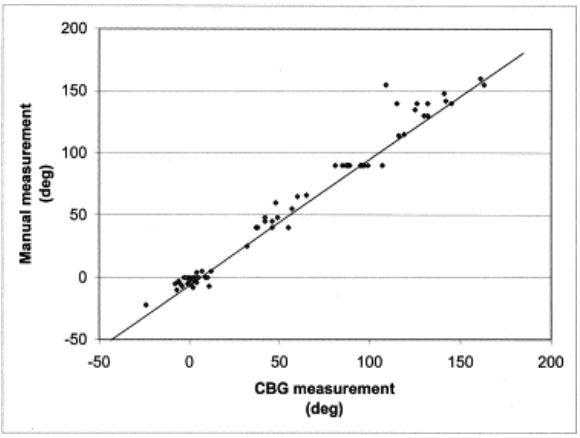

Fig 2. Knee angle measurements made by the CBG versus manual measurements.

In table 1 patients' ROM values at the trial's start are compared with their ROM at discharge. The number of days from surgery was 6.3±0.7 days. The number of days the device was worn was 5.1±1.7. Patients wore the device for 4 hours on the first day. On subsequent days, the brace was repositioned every 4 hours. Average AROM increased from 45° (day 1 of the study) to 69° (discharge). The increase was mainly due to a significant increase in the mean active flexion (60°–80°, *P*<.001). The increase in mean active extension was insignificant. The decrease in the average pain score was not statistically significant (paired *t* test, *P*=.13). There were no general or local adverse events in any of the participants.

Table 1. Comparison of Initial and Final AROM

Initial Values			**Discharge Values**		
Knee Flexion	**Knee Extension**	**AROM**	**Knee Flexion**	**Knee Extension**	**AROM**
59.6°±6.0°	14.5°±4.7°	45.2°±8.0°	79.5°±11.7°	−11.1°±6.6°	68.5°±14.5°

NOTE. Values are mean ± SD.

Only 9 of 11 subjects wore the CBG in both feedback-on and feedback-off modes; the other 2 subjects' data were omitted from further analysis Table 2, Table 3. The device was used for an equal number of hours on feedback-on and feedback-off days. Three of the subjects had higher activity rates during feedback-on days, and 6 had higher activity rates during feedback-off day (see table 2). When subject data were pooled, the effect of visuoauditory feedback was not significant. The activity rate during feedback-on days averaged 15.1 counts per hour, whereas during feedback-off days, it averaged 22.5 counts per hour (*P*=.10). Similarly, the aggregate mean interactivity interval showed a slight but insignificant trend to decrease from 6.7±5.7 minutes on feedback-on days to 3.6±2.7 minutes on feedback-off days (*P*=.07; see table 3). In 3 patients, the number of interactivity intervals per day that exceeded 30 minutes was smaller on the feedback-on days than on the feedback-off days. In the remaining 6 subjects, the results were the same or smaller on the feedback-off days.

Table 2. AROM Behavior for Feedback-On and Feedback-Off Days

Feedback Mode	**Hours Wearing Device (/d)**	**Total Activity Rate (counts/h)**	**Flexion Rate (counts/h)**	**Extension Rate (counts/h)**	**No. of Reminders (/d)**	**No. of Overrides (/d)**
On	6.3±0.7	15.1±10.9	7.0±5.1	8.1±6.2	4.9±2.1	4.1±1.6
Off	6.2±1.5	22.5±11.1	10.0±7.4	12.5±12.2		

NOTE. Values are mean ± SD.

Table 3. Stratified Average Interactivity Intervals by Feedback Mode

Feedback Mode	Mean Interactivity Interval*	% Intervals <1min†	% Intervals 1–5min†	% Intervals 5–30min†	% Intervals >30min†	Mean Total Counts (/d)
On	6.7±5.7	58.1±12.7	19.6±6.5	15.3±6.0	6.9±9.6	276.3±182
Off	3.6±2.7	63.7±16.1	20.7±6.9	13.2±8.0	2.5±2.4	268.4±239.4

NOTE. Values are mean ± SD.

*Mean interactivity intervals are in minutes.

†Mean of sums of interactivity intervals of specific stratum from all patients on matching feedback-mode days are percentage from the total number of intervals of same row.

In the analysis of patients' response to the exercise prompt sound, AROM movement was used to silence the beep an average of 19% of the time. The override button was used 81% of the time. However, patients frequently resumed their AROM exercise within 5 minutes of the override. This occurred, on average, 30% of the time (range across subjects, 7%–67%).

All but 2 of the 11 patients found the brace comfortable. Auditory feedback of flexion and extension success was found useful by 10 of the 11 patients, whereas visual feedback of joint angle was found useful and half of the patients reported to have used it frequently. Eight patients reported that the reminder beep encouraged them to do their AROM exercises. Four patients reported frequent use of the override button; however, the logged data showed that 9 of 11 patients used the override button at least two thirds of the time. Nine of 11 patients answered positively to the question, "If I had to have another knee replacement surgery, I would want to use the computerized knee brace again."

Finally, all subjects were encouraged to provide open comments regarding the use and effectiveness of the CBG. Patient 3 stated that while he was in the rehabilitation department he tried to conserve his energy for PT sessions and only did the additional AROM exercises that the device prompted him to do. Nevertheless, he stated that the device would be much more useful to him in an outpatient setting when he would not have such an intensive PT regimen. Patient 11 commented that, by the time she was through with formal PT, she was too tired to exercise on her own. Patient 7 stated that the device was most helpful during the PT sessions, in which both she and the physical therapist used it to monitor her activity.

Discussion

ROM considerations

The electrogoniometer provided accurate knee angle measurements within the 0° to 100° range. Because the commonly accepted goal of PT after TKA is to reach knee flexion of 90°, the CBG design is likely to be useful as a measurement and monitoring tool in the initial post-TKA rehabilitation period.

Patient acceptance

Our goniometric biofeedback device was well accepted by most patients in the study. The majority evaluated it as comfortable and helpful in encouraging exercise. Auditory feedback was found useful by both patients and therapists: patients to monitor the adequacy of their free-time exercises, therapists to monitor patient progress and achievements during formal therapy sessions. Visual feedback seemed to be of less value. Half the patients did not make good use of the information presented on the liquid crystal display (LCD) screen. The reasons for the poor use of the visual feedback may be mainly technical. The size of the LCD screen in the prototype was small (1×4cm), and there was no internal illumination to assist in the visibility of the written messages. Most of our patients undergoing TKA surgery were elderly, and almost all used reading glasses. Some patients reported that it was bothersome to put on glasses every time they needed to look at the device and they preferred to use

auditory feedback alone. Furthermore, the microcomputer was secured to a waist belt to free the patient's hands and to not interfere with activities of daily living—making it difficult for patients to view the screen. On the other hand, informal communications suggested that clinicians found the textual feedback of joint angle to be useful during therapy.

This is not the first study to use electrogoniometric feedback to study lower-limb function. An electric goniometer was used as a biofeedback mechanism in transfemoral amputee gait training.3 The main technical problems in that study were the wires and the annoyance of the beeps to the patient, the therapist, and other patients. In our study, the patients did not report the beeps to be annoying and neither did the treating staff or the fellow patients. The connection between the electrogoniometer and the computer controller also was unobtrusive. The microcomputer was attached to the waist belt on the side of the operated knee. The wire connecting the goniometer to the computer was either tucked in the patient's pants or bundled within Velcro straps attached to the knee brace.

Several improvements to the system's design and implementation may be advantageous. First, the microcomputer unit of this prototype was fairly large and cumbersome. Clearly, a smaller and lighter microcomputer unit would be more convenient. A larger visual display would also be useful, so that patients could more easily view the presented information.

AROM exercise behavior

The results comparing AROM for feedback-on and feedback-off days are surprising. Our initial hypothesis was that the device would be more effective in motivating patients to exercise during feedback-on days than during feedback-off days. Although this pattern was seen in 3 patients, the majority had more ROM activity in feedback-off days. One explanation may be that the periodic "prompting" during feedback-on days inhibited spontaneous AROM activities. Although this may have been the case for the 6 subjects who had higher activity rates during feedback-off days, not all subjects responded to the feedback the same way, and the pooled subject data revealed no significant difference in activity rates between feedback-on and feedback-off conditions. The subjects who were more active during feedback-off days may have been more highly motivated by a device that quietly monitored their actions. They knew from experience during the feedback-on days that they were expected and were prompted to exercise at least 1 flexion and 1 extension every half hour when not in therapy. Because the device did not prompt exercises during feedback-off days, these patients seemed driven to exercise more often on those days. Unfortunately, we cannot deduce from the current results the effect of wearing the device with feedback as compared with not having any feedback at all; nor can we compare our results with standard therapy without any additional devices. These effects clearly need to be assessed in a larger future study.

During the feedback-on days, the periodic audiovisual prompt was only moderately successful in inducing AROM exercise. Nineteen percent of the time patients reacted to the reminder beep by immediately performing knee flexion and extension to the set goals and did not use the override button. If we presume that any exercise that followed within 5 minutes of the reminder beep can be attributable to the prompt of the device, then we may assume that 43.3% of the time the device's prompt feature succeeded in initiating AROM exercises. The poor performance of the periodic prompt in motivating exercise might represent the patient's unthinking response to turn off or ignore noxious stimuli. It is interesting to note that most patients reported that they did not use the override button frequently, when, in fact, most used it over two thirds of the time. The fact that the patient satisfaction questionnaires were collected by the investigator and not by an independent, unbiased observer may have played a role in creating this discrepancy.

The choice of subject population introduced a selection bias into our results. The inpatient rehabilitation population is typically comprised of complicated cases that portray a slower rehabilitation process. We chose

this population because it was important to be able to closely monitor the device and to provide an intimate follow-up on the patients and their progress to treat technical problems with immediacy.

Most TKA patients are sent home for self-rehabilitation immediately from the acute care department after surgery. Because of their diminished intensity of PT and greater reliance on a home exercise program, these active and motivated patients would likely find the CBG more acceptable and useful than the our study population did.

Conclusions

The wearable biofeedback device we tested measured post-TKA patients' knee motion accurately in angles from 0° to 100°. Acceptance of the device was evaluated and found to be good. Audio feedback had more patient acceptance than the visual feedback, possibly because of the visual display's limited accessibility. Audiovisual exercise prompting did not have a significant influence on the rate of exercise performance. However, for most subjects, the device motivated exercise more on feedback-off days when used in an alternating days feedback-on/feedback-off regimen. Further study is needed to assess the optimal feedback schedule and the short- and long-term effects of device usage and to evaluate the cost-benefit balance of using this type of device.

Supplier

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