International Journal of Advanced Culture Technology Vol.7 No.1 209-215 (2019)
DOI 10.17703/IJACT.2019.7.1.209

IJACT 19-3-28

A Smart Bench Press Machine: Automatic Weight Control Sensitive to User Tiredness

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Abstract

In order to provide a safe free-weight-training environment to people without workout trainers, we suggest a smart bench press machine with an automatic weight control system sensitive to user tiredness. Physical weight plates on the machine are replaced with a hydraulic cylinder as a press load and the cylinder knob is coupled with a step motor to change its tensile force automatically in-between lifting exercises. Three subjects participated to verify the usability of the smart bench press machine. They were asked to lift a 6-RM press load 10 times with 3 different lifting conditions: 1) no assistance, 2) a human assistance, and 3) the automatic weight control. All subjects were not able to complete the 10 sets without assistance due to tiredness, but they finished the full sets under the two assistive conditions. Average lifting speeds under the automatic weight control condition showed the most consistent level. Normalized quasi-tension data based on surface electromyogram signals of both Pectoralis Majors revealed that the subjects maintained the target muscle activation level above 50% but not more than 80% throughout the 10 sets. Therefore, the smart bench press machine is expected to both keep pace with the lifting exercise and reduce risk of injuries due to excessive muscle tensions.

Keywords: *Fitness, Weight training, Home training, Bench press machine*

1. INTRODUCTION

With interests for physical fitness steadily increasing, the global market size of fitness and health club industry had reached 87.2 billion dollars in 2017 [1]. Particularly, global home fitness equipment market is rapidly growing and expected to reach 4.29 billion dollars by 2021 [2]. Both bodyweight trainings that use individual's own weight to train against gravity and free weight trainings that use dumbbells or other weighted machines are considered appropriate for home exercises. Free weight trainings usually have more advantage over bodyweight trainings since intensive exercises on target muscles with a wide range of training weights are possible.

Despite the advantage, bodyweight trainings are leading home training method because free weight trainings often accompany injuries due to excessive exercises and wrong postures. Almost 90 percent of injury experiences happen during free weight trainings and US hospital emergency department reports more than 970,000 injury cases from 1990 to 2007 during free weight trainings [3]. More people will be exposed to risks of injuries such as strains, tendinitis, or sprains on their shoulders, lower back, knees, elbows, wrists, and hands since the free-weight-training population keeps increasing [4-6].

Manuscript received: December 6, 2018 / revised: January 25, 2019 / Accepted: March 5, 2019
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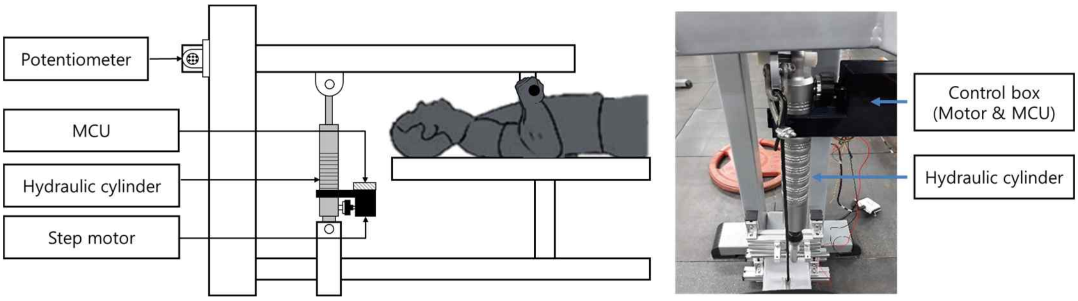

Figure 1. Modified bench press machine

A hydraulic cylinder is implemented on a conventional bench press machine. The cylinder acts as a lift load instead of weight plates. Coupled with the cylinder knob, a step motor rotates to change cylinder tensile force thus automatically adjusting pressing weight.

In order to prevent injuries and efficiently stimulate target muscles, personal trainers usually advise exercise routines with appropriate workout weights and postures. However, a number of free weight trainees are reluctant to have personal trainers and choose to exercise on their own at gyms and homes. This is because most personal training sessions are far more expensive than their expectations [7,8]. Also, low reliability on trainers and their sessions is reported to be another reason [8].

To provide safe as well as effective free-weight-training environment to the people, we suggest a smart bench press machine consists of an automatic weight control mechanism. Monitoring user's exercise characteristics, the machine detects user tiredness and automatically changes the press weight to an appropriate magnitude in-between lifting exercises.

2. MATERIALS AND METHODS

2.1 System Components

As shown in Figure 1, we implemented the automatic load control system to a conventional bench press machine. A hydraulic cylinder (U2W-Type A, WATA Corporation) was mounted under the Y-shape press bar to replace the physical weight plates. A step motor (iHSS57-36-10, Shenzhen Just Motion Control Electro-mechanics Co.) is coupled with the cylinder knob so that the tensile force of the cylinder can be automatically adjusted during lifting exercises. To detect the position of the press bar, a rotary potentiometer was connected to the hinge of the press bar.

2.2 Control Algorithm

Since inappropriate workouts and injuries happen when a user exercises with too heavy press weight under muscle fatigue, the smart bench press machine should detect the user's tiredness and automatically adjust the press weight to a manageable magnitude.

To identify the user tiredness, several subjects did bench press exercise until they got tired and we monitored their workouts. Among many kinematic parameters we measured, their press bar lifting velocity was the most intuitive measure of tiredness since the magnitude clearly decreased as depicted in Figure 2. Therefore, we concluded that a user feels heavy and exhausted when the current bar lifting speed is lower than a threshold based on his past lifting speeds. The press weight is then designed to change after finishing the slow lift.

The tensile force range of the hydraulic cylinder is from 10 kgf to 130kgf and there is a knob that can be turned to adjust the magnitude of the force. To suggest an exact press weight to a user, we derived the cylinder's mathematical model.

$$F(v,I) = (1.1 \cdot 10^{-5} \cdot I - 1.6 \cdot 10^{-4}) \times v^2 + (-9.7 \cdot 10^{-4} \cdot I + 9.3 \cdot 10^{2}) \times v + (13.7 \cdot I + 9.4) \quad \ldots(1)$$

The quadratic equation estimates the tensile force of the hydraulic cylinder based on the indicator level of the knob (I) and the pulling speed of the cylinder stroke (v). When implemented on the smart bench press

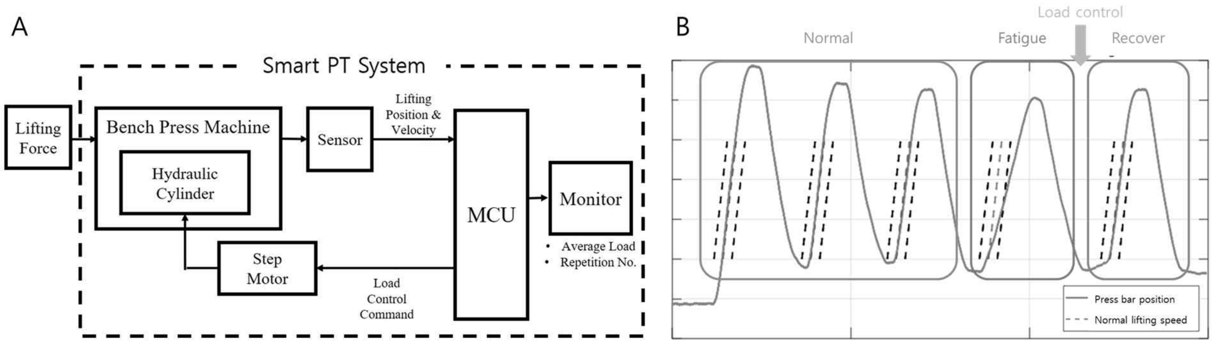

Figure 2. Automatic weight control algorithm of the smart bench press machine

(a) A control block box diagram of the smart bench press machine. (b) User tiredness detection and load control algorithm. If a user's bar lifting speed slows down compare to his past speeds, the system determines that the user is exhausted and adjusts the press weight appropriately after the current lifting cycle to help user recover his lifting speed afterwards.

machine, instead of the pulling speed, user's average lifting speed is substituted into the equation.

3. EXPERIMENTS

The experiment was conducted for system validation. Three healthy male subjects (24.3±2.7) who have at least 6 months of weight training experience participated in this study. The subjects are asked to complete 10 bench lifts with three difference workout conditions. The subjects did the first 10 lifts on the hydraulic bench press machine without any workout assistance. After 5 minutes of rest, the subjects began the second set with the automatic weight control assistance. After 5 minutes, subjects did the last set with human assistance.

Each subject was asked to lift with a press weight of 6-RM. 1-RM is the maximum weight that a person can exercise once and 6-RM is correspond to 85% of 1-RM. A number of studies about resistance training related to the number of RM have shown the correlation between RM and muscular strength, hypertrophy and endurance which indicates different RM determines the different dominant factor of muscle improvement. [9-11]. However, considering the risk of injury and to get accurate enough of surface electromyogram, we chose 6-RM for subject to lift up with a press. We used Earle's indirect mensuration recommended by National Strength & Conditioning Association (NSCA) to estimate each subject's 1-RM.

$$\text{1-RM} = W_0 \times (1 + 0.025 \times R) \quad \ldots(2)$$

W_0 is a press weight and R is the number of lifts made with the press weight. For example, if a person lifts 50 kg 8 times, his 1-RM is estimated to be 60 kg. Then 6-RM is 51 kg which is 85% of 1-RM.

To analyze the effect of exercise on target muscles, surface electromyogram signals on right and left Pectoralis Majors were measured using Biopac MP160 with a sample rate of 1 kHz. The raw sEMG signal is processed to obtain quasi-tension which shows a high correlation with actual muscle tension using the second-order, low-pass filter shown below [12].

$$Quasi\text{-}tension(t) = \sum_{j=1}^{m} h(j) * sEMG(t - j + 1) \quad \ldots(3)$$

$$h(\tau) = 6.44 * (e^{-10.80\tau} - e^{-16.52\tau}) \quad \ldots(4)$$

The quasi-tension signal of each subject is normalized by the magnitude of the maximum voluntary contraction (MVC). The post-processing on the sEMG signal was done using MATLAB R2016b.

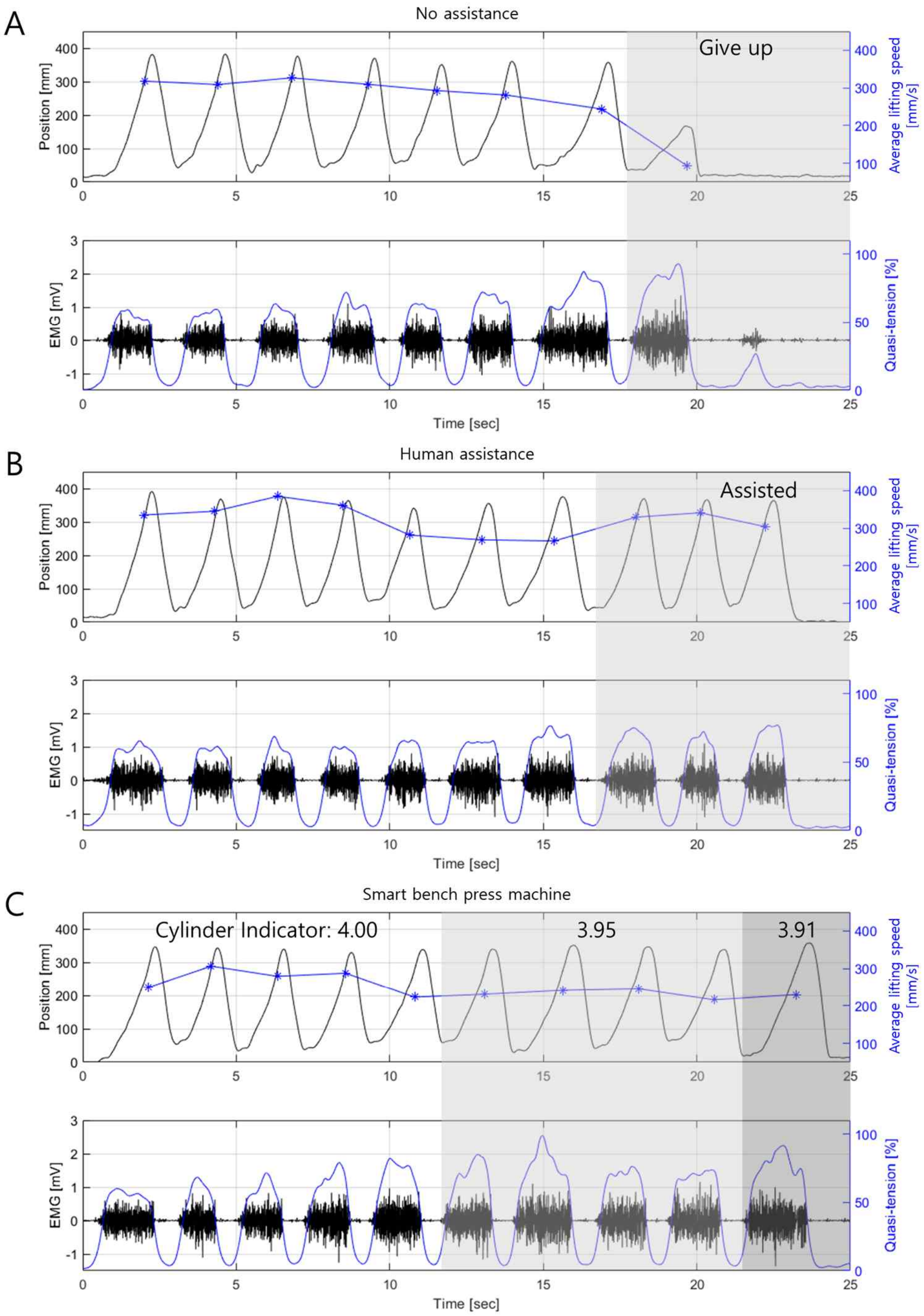

Figure 3. Exercise characteristics of a representative subject with different assistance conditions

(a) When there was no training assistance, the subject gave up the exercise at his 8th lift. (b) The subject managed to finish 10 lifts with an aid of a human trainer from his 8th lift. (c) The subject also completed 10 lifts with the smart bench press machine. The automatic load control algorithm changed the pressing load two times to appropriate magnitudes if the subject's previous lifting speed is lower than the average.

4. RESULTS AND DISCUSSIONS

From the experiment result, we could observe a possible moment of injury when exercised without workout assistance. In Figure 3A, the subject gives up his 8th lift due to lack of lifting force. However, the quasi-tension of Pectoralis Majors on his 8th trial has reached more than 90%. If a person continued to lift the press bar repeatedly more than his 90% of quasi-tension, muscle fatigue may develop rapidly and lead to the risk of injury. We could easily predict the use of excessive muscle tension from his 7^{th} average lifting speed in Figure 3A. Maintaining the speed close to 300 mm/s until his 6^{th} trial, the subject shows 8^{th} lifting speed near 200 mm/s. Therefore, the subject should have finished his workout at 7^{th} trial or asked for assistance.

When there was assistance, the subject managed to finish 10 lifts. As the human trainer assists the lift from 8^{th} trial, we observe increase in average lifting speeds in Figure 3B. In addition, the sharp increase in quasi-tension is not found, so we can conclude that the human trainer helped the subject to maintain moderate level of muscle tension as well as to finish a complete set.

With automatic weight control, the subject also completed 10 lifts. From Figure 3C, we observe that the cylinder indicator decreases if average lifting speed declines. For example, when the subject shows a sharp decrease in the speed on his 5^{th} trial, weight control unit changes the cylinder indicator from 4.00 to 3.95 before

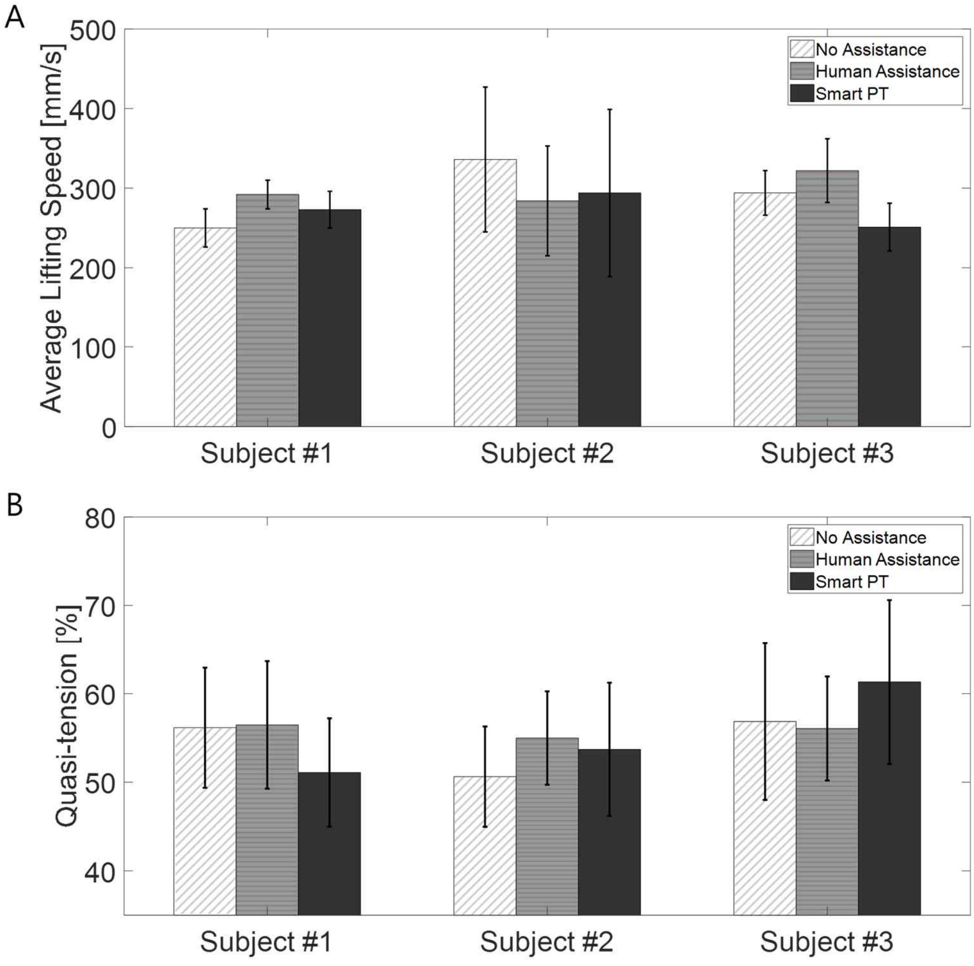

Figure 4. Lifting speed and quasi-tension with different assistance conditions

(a) Average lifting speed of the subjects with the three exercise conditions. (b) Quasi-tension of the subjects with the three exercise conditions.

his 6th trial. In addition, we see that the average lifting speeds throughout the session are quite consistent compare to other exercise conditions. Therefore, the system was able to imitate the role of the human trainer.

Figure 4 shows exercise characteristics of the three subjects with the different exercise conditions. All subjects failed to complete a set of 10 lifts when there was no assistance but finished a set with human and weight control assistance. Since we observe moderate lift speeds and quasi-tensions for all subjects with the automatic weight control, the smart bench press machine is quite valid to guide users to exercise.

Since the hydraulic cylinder we used was one-way actuator, the bench press machine provided only lifting exercise. Thus, only concentric training (CON-T) was possible and eccentric training (ECC-T) was almost ignored compare to conventional bench press. In order to provide effective training, either the weight of the press bar is moderately heavy or the cylinder should be replaced with two-way actuator to encourage eccentric training. It is questionable that concentric dominant muscle training can be as effective as the conventional, balanced weight training [13,14].

We are planning to implement the automatic weight control system to many different types of free weight trainings such as squat or deadlift. Rather than disassembling conventional machines, we are designing a machine that provide the three exercises – bench press, squat, and deadlift – with the automatic load control system.

5. Conclusion

The smart bench press machine implemented with the automatic weight control system sensitive to user tiredness is proposed to ensure a safe free-weight-training environment. Based on user's press bar lifting speed from which we could infer user tiredness, the system adjusted lifting weight appropriately. From experimental results, we concluded that the smart bench press machine prevented excessive muscle tension and guided user to finish a complete set with a consistent workout pace. Therefore the system successfully imitated the role of personal trainers. The system is expected not only to encourage users to conduct free weight training at gyms and homes but also to reduce personal trainer's work intensity of work.

6. Acknowledgement

This paper is supported by CESEE (Convergence Education for Sustainable Energy and Environment) program funded in part by the Ministry of Education (ME, Korea), and National Research Foundation of Korea(NRF) grant funded by Korea government(MOE) (No. 2017R1D1A3B03035973).

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