Comparison of joint kinematics and pedaling force in the young and the elderly

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Abstract. [Purpose] Proper pedaling posture can improve muscle strength and cardiopulmonary function. To investigate proper pedaling posture for the elderly, this study compared the pedaling efficiency of the elderly with that of the young by using an index of effectiveness (IE) and kinematic results. [Subjects and Methods] Eight adults in their twenties and eight in their seventies participated in 3-min, 40 rpm cycle pedaling tests, with the same load and cadence. The joint angle, range of motion (ROM), and IE were compared by measuring 3-dimensional motion and 3-axis pedal-reaction force during 4 pedaling phases (Phase 1: 330–30°, Phase 2: 30–150°, Phase 3: 150–210°, and Phase 4: 210–330°). [Results] The knee and ankle ROM, maximum knee extension, and maximum ankle dorsiflexion in the elderly were significantly decreased compared with those in the young. Moreover, there were significant differences in IE for the total phase, Phase 1, and Phase 4 between the elderly and young. IE of the young was greater than that of the elderly, except in Phase 3. [Conclusion] Joint movement in the elderly during pedaling was limited. This study provides information that will facilitate the proposal of an efficient pedaling method for the elderly.

Key words: Pedaling, Elderly, Index of effectiveness

INTRODUCTION

Cycle ergometer exercise is very consistent since it comprises constant movement in a sitting position, which reduces the load on joints1) and has a low risk of falls; the load and pedaling types are readily controllable. Therefore, the cycle ergometer is appropriate for elderly persons, who tend to have reduced exercise ability compared with the young. Age-related weakening of the lower-limb muscles causes physical deterioration and postural and movement instability. Therefore, it is necessary for the elderly to perform suitable lower limb muscle-strengthening exercises, which can improve the quality of life2). Cycle ergometer exercise activates mainly the hamstring, vastus lateralis, tibialis anterior, and gastrocnemius muscles due to movement of the hip, knee, and ankle joints. These muscles are important for daily living, particularly for gait. Cycle exercise has been reported to increase endurance, heart function, and balance and gait function, as well as muscle and physical strength3). Cycle ergometer exercise is similar to walking since it involves repetitive flexion and extension by alternating contraction of antagonistic muscles4). Therefore, cycle ergometer exercise is suitable for enhancing muscle strength in the elderly.

Proper pedaling posture can improve muscle strength and cardiopulmonary function. However, improper pedaling postures increase the likelihood of injury5, 6). Improper pedaling postures affect joint movement; thus, excessive contraction and relaxation of muscles due to immoderate joint movement can lead to injury. The likelihood of injury due to improper pedaling posture is increased in the elderly because of low bone density and muscle weakness. Therefore, proper pedaling posture is more important for the elderly than the young. Many studies have been conducted on the pedaling characteristics in the young...
and the elderly. Published studies have addressed the difference in cadence efficiency between the young and the elderly using power and oxygen consumption\(^7\), and the leg muscle activities in the elderly performing cycle ergometer exercise\(^2\). For the determination of proper pedaling posture, it is necessary to study pedaling efficiency based on the pedaling force. However, few studies on pedaling force in the elderly have been reported. The index of effectiveness (IE) is a suitable variable for studying pedal force\(^4\). IE explains how pedal force is transmitted to the pedal. The direction and magnitude of pedal force depends on the movement of the joint and the activation of muscles, and it is necessary to investigate the pedaling characteristics of the elderly due to age-associated changes\(^5\). To investigate pedaling characteristics, kinematic and pedal force analysis is needed. Thus, the purpose of this study was to compare the joint angle, range of motion (ROM), and pedaling effectiveness in the young and the elderly using IE under identical cycling conditions.

**SUBJECTS AND METHODS**

The study involved 8 young male adults (age: 26.3 ± 0.7 years, height: 174.6 ± 5.3 cm, weight: 70.5 ± 11.2 cm) and 8 elderly male adults (age: 76.4 ± 5.1 years, height: 163.3 ± 4.6 cm, weight: 63.8 ± 5.0 cm) with no history of musculoskeletal disease and who could pedal normally. The protocol for this study was approved by the Ethics Committee of Konkuk University. Experimental procedures were explained to the subjects, and written consents were obtained.

A 3-dimensional (3D) motion analysis system with 6 infrared cameras (Motion Analysis Corp., USA) and a 3-axis pedal force plate (Dacell Corp., Korea) (hysteresis: ± 0.5%, nonlinearity: ± 0.5%) were used to acquire kinematic and pedal reaction force data at the frequencies of 120 Hz and 1,200 Hz, respectively. Twenty-three reflective markers were attached as a plug-in set, and pedaling was conducted over 3 min at 40 rpm. The saddle height was set to a 155° knee flexion angle (identical to the 25° knee angle method that is generally accepted for saddle height with proper posture\(^8\)) with the pedal crank at the 6 o’clock position. I-Magic trainer (Tacx, Netherlands) and SRM power meter (SRM, Germany) were used to maintain constant conditions. Knee and ankle ranges of motion (ROMs) and angles of the lower joints were calculated using motion data. IE has been used as a measure of effective pedaling\(^4\), and is defined as the ratio of the force perpendicular to the crank (effective force, EF) and the total force applied to the pedal (resultant force, RF) over a complete crank revolution\(^6\)–\(^7\) (Fig. 1).

During pedaling, when the pedal is located at the top of the crank (0°), the position is called the top dead center, and when at the bottom of the crank (180°), the bottom dead center. The pedaling phase can be divided into the power phase for propulsion (30–150°) and the recovery phase for restoration (210–330°). In this study, pedaling was divided into the following 4 phases: Phase 1 (330–30°), Phase 2 (30–150°, power phase), Phase 3 (150–210°), and Phase 4 (210–330°, recovery phase), as shown in Fig. 2. In general, Phase 2 is a propulsive phase and Phase 4 is a recovery phase\(^9\). All calculations were carried out using Matlab R2013a (Mathworks Inc., USA) software. Data were statistically analyzed using SPSS (IBM Co., USA) version 22, and a p-value less than 0.05 was considered to indicate significance for all cases.

**RESULTS**

Kinematic results showed that knee ROM, ankle ROM, maximum knee extension, and maximum ankle dorsiflexion in the elderly were significantly decreased compared with those in the young (Table 1). However, there were no significant differences in maximum knee flexion and maximum ankle plantar flexion.

There were significant differences in IE for the total phase, Phase 1, and Phase 4 between the elderly and the young, but no significant differences for Phase 2 and Phase 3, as shown in Table 2. The IE of the young was greater than that of the elderly, except in Phase 3.
Proper pedaling posture can improve muscle strength and cardiopulmonary function. However, improper pedaling postures can increase the likelihood of injury. To investigate pedaling characteristics, kinematic and pedal force analysis is needed. Thus, to evaluate the proper pedaling posture for the elderly, this study compared the pedaling efficiency in the elderly with that in the young using IE and kinematic results.

The kinematic results showed that the knee ROM in the elderly was less than that of young adults (Table 2), because the maximum knee extension in the elderly was less than that of the young. Therefore, the elderly could not extend the knee sufficiently during Phase 3, which affects the flexion of the ankle joint. However, there was no significant difference in IE in Phase 3 and maximum plantar flexion of the ankle between the 2 groups. Therefore, knee extension did not affect pedaling effectiveness significantly. The maximum knee flexion during Phase 1 was not significantly different between the 2 groups; however, the maximum dorsiflexion in the young adults was greater than that in the elderly. It is believed that ankle movement had an effect on IE during Phase 1. Therefore, ankle joint movement has an effect on the IE; i.e., the pedaling effectiveness, rather than knee joint movement. The ankle joint ROM in the young was greater than that in the elderly because of activation of the tibialis anterior (TA) muscle. Ankle joint movement is generally controlled by the agonistic and antagonistic function of the TA muscle and gastrocnemius medialis muscle. The TA muscle is also important during gait. The TA muscle is activated at the start of the swing phase and during toe clearance, and ankle joint ROM in the elderly is generally reduced during gait. This is due to the weakness of the ankle plantar and dorsiflexor muscles in the elderly. Aging has a profound effect in terms of decreases in the distribution and properties of muscle fibers, and therefore on pedal force. The ankle flexion results in the elderly indicated that ankle movement is less free than that in the young.

Pedaling is generally carried out by applying a downward force during the propulsive phase (Phase 2) and an upward force during the recovery phase (Phase 4). The young exerted greater downward force than the elderly (Fig. 2) during the propulsive phase (Phase 2) and relatively efficient pedaling, although the difference was not significant. Moreover, the resistive force in the young was greater than that in the elderly. The effective force was negative during Phase 3 and Phase 4, which involve application of a resistive force to the pedal. The fact that the young pedaled more effectively indicated that the elderly have weak muscles and poorer kinematic movement than the young do. Falling is a major cause of morbidity in the elderly, and can result from an abnormal gait. To prevent falls, it is important to increase joint flexibility and muscle activation. Pedaling can enhance the joint flexibility and muscle strength in the lower extremities. There was a significant difference in joint movements between the 2 groups, particularly in the resistive force of ankle movement. To overcome the resistive force and pull the pedal upward effectively, the use of a cleat or toe clip pedal is recommended, to enhance the power of the pulling muscle.

This study compared the pedaling efficiency in the young with that in the elderly using the IE concept. The young pedaled more effectively at all phases than the elderly, except in Phases 2 and 3. The elderly exhibited limited joint movement during pedaling. To propose an efficient pedaling method for the elderly, a further comparative study using electromyography is underway.

### DISCUSSION

**Table 1.** Significant differences in kinematic variables between the young and elderly (mean ± SD)

| Kinematics | Knee ROM | Knee flexion max | Knee extension max | Ankle ROM | Dorsiflexion max | Plantar flexion max |
|------------|----------|------------------|--------------------|-----------|------------------|---------------------|
| 20s mean   | 71.43 ± 3.17* | 86.25 ± 5.31 | 157.68 ± 5.39* | 30.04 ± 7.90* | 20.45 ± 4.92* | −9.59 ± 8.38 |
| 70s mean   | 65.22 ± 6.54* | 80.78 ± 7.80 | 146.01 ± 9.81* | 20.33 ± 6.62* | 17.37 ± 8.71* | −3.20 ± 9.53 |

### Table 2.** Significant differences in IE variables between the young and elderly (mean ± SD)

| IE         | Total phase | Phase1 | Phase2 | Phase3 | Phase4 |
|------------|-------------|--------|--------|--------|--------|
| 20s mean   | 0.34 ± 0.05* | 0.30 ± 0.14* | 0.82 ± 0.03 | −0.11 ± 0.10 | −0.68 ± 0.06* |
| 70s mean   | 0.25 ± 0.04* | 0.07 ± 0.13* | 0.79 ± 0.03 | −0.08 ± 0.13 | −0.78 ± 0.05* |

**t-test, *p<0.05, Unit: dimensionless ratio of effective force to resultant force**
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