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Morphological Changes in Quadriceps Muscles through 3-Week Combined Exercise using a Wearable Robot (EX1) in Young Adult

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Objective: This study aims to analyze the effect of regular exercise through the combined walking-oriented aerobic and resistance exercises using EX1 in young adults.

Design: Experimental one group pre and post test

Methods: Participants comprised17 healthy young adults. All subjects performed a combined exercise program for 10 times using EX1. We measured quadriceps muscle thickness using ultrasound. Additionally, the hand grip strength test, and sit and reach test were performed before and after the exercise. Through paired t-test, we investigated whether there was a statistically significant difference in the measurement results after exercise program.

Results: The rectus femoris muscle contraction ratio showed significant difference after exercise(P< 0.01). In the sit and reach test, flexibility showed significant difference after exercise(P < 0.01). The hand grip strength test also showed significant difference after exercise(P < 0.05).

Conclusions: Healthy young adults can effectively perform various exercises commonly performed in daily life using EX1.

Key Words: Robotics, Wearable Electronic Devices, Quadriceps Muscle

Introduction

The importance of physical activity on health has been documented well through extensive research [1-3]. Physical activity offers several health benefits, such as counteracting age-related decline in neuromuscular function and strength[4-6]. Previous research has demonstrated the benefits of physical activity in preventing or treating ailments such as heart disease, high blood pressure, diabetes, and osteoporosis [7, 8]. The World Health Organization (WHO) recommends 150 minutes of moderate-intensity aerobic exercises or 75 minutes of vigorous-intensity aerobic exercises per week, or a combination of both to adults between the ages of 18 and 64 [9]. Additionally, adults should also engage in muscle-strengthening activities, at a moderate or greater intensity, that involve all major muscle groups at least twice per week. However,over 25% of the adult population worldwide currently fails to meet the recommended level of physical activity[10].

Walking is a beneficial, easily accessible, and

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preferred exercise suitable for people of all ages, genders, and physical abilities[11]. Itis a coordinated, rhythmical activity that engages major muscle groups of the lower body, including large muscles andthose of the arms and upper body to a lesser extent[12]. The quadriceps strength plays a critical role in walking, helping to maintain balance, generate power, and propel the body forward[13]. It contributes to stability [14], power [15], endurance[16], and speed[17]. Conversely, diminished quadriceps strength can heighten the likelihood of falls [18, 19] and cause persistent abnormal walking patterns and lack of symmetry in gait and biomechanics[20-22].

Hand grip strength measurement helps evaluate muscular strength and correlates with strength measurements in other muscle groups, including the lower limbs[23, 24], making it a valuable tool for identifying physical limitations and mobility impairments[25, 26]. Although the hand grip test is considered a reliable and valid procedure for assessing muscular strength of healthy individuals and various clinical populations [27], it has been utilized in previous studies to mainly evaluate health measuresof older adults [28-30].

The sit and reach (SR) test is most frequently used in health-related fitness test batteries to measure flexibility in the hamstrings and lower back[31]. Flexibility in these areas is crucial because it helps avoid the risk of falling, limitations in movement while walking, or deviations in posture[32].

The development in robotics has made available wearable exoskeleton devices thatare expanding beyond their original purpose in the medical field[33][34]. These devices are increasingly useful in enabling disabled and healthy people in performing routine physical tasks and functions [35].

Samsung Electronics Co., Ltd. (Suwon, Republic of Korea) has developed a lightweight, personalizable robot named EX1that can be worn on the hip joint. A previous study employed EX1 to examine the impact of EX1-assisted exercise in different environments on the physical function, muscle strength, and walking efficiency of older adults[36]. According to the study's findings, utilizing EX1 during exercise in diverse settings provides multiple benefits in terms of physical function, muscle strength, and cardiopulmonary metabolic energy efficiency for older adults.

The current study aims to explore the effects of regular exercise through the combined walking-oriented aerobic and resistance exercises using EX1 on changes in the quadriceps and hand grip strength, flexibility of hamstrings, and lumbar spine in young adults. This was conductedbased on the assumption that physical function wouldpositively improve in young adults, and not only in older or disabled adults.

Methods

Participants

We recruited 17healthy participants (12 males/5 females) between the ages of 26－42 years who voluntarily participated in the experiment. Inclusion criterion for the participants were as follows: (1) adults between the ages of 19 and 59 who have not recently exhibited symptoms of respiratory disease or fever, (2) adults interested in robots, and (3) adults willing to provide written consent of participation. Exclusion criterion for the participants were as follows: (1) individualswho cannot walk independently and need assistance, (2) individualswith a history of central nervous system disease, (3) adults diagnosed with severe arthritis or osteoporosis and whose movement has been restricted by their doctor, and (4) adults at a risk of falling while walking because of severe dizziness.

We calculated the sample size required for the study using G*power program version 3.1.9.4 (Universität Kiel, Kiel, Germany). The effect size was set to 0.85at a significance level of 0.05, power value was set to 0.95, and17 people were included. We initially recruited 21 participants; however, 20 %, i.e., 4 of them dropped out, leaving behind 17 participants in the sample size. The study was conducted from June 24, 2022 to July 22, 2022, and participants who met the selection criteria were recruited through Samsung Electronics’ in-house recruitment notice. This protocol was reviewed and approved by the Institutional review board at the Yonsei University (IRB No. 202208-HR-2734-04).

Exercise program

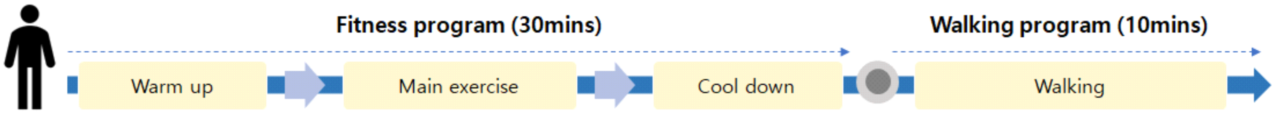

Figure 1. Exercise program

The exercise program was created in the SHP Exercise Science Lab (Seoul, Republic of Korea). It was conducted thrice a week for three weeks, with a total of 10 sessions(Figure 1). The goal wasto improve the muscular strength and endurance of the participants' lower extremities and core, and their cardiopulmonary and gait abilities. The program was preceded by another fitness program involving resistance exercises, and a walking program centered on aerobic exercises.

The fitness program required participants to perform 14 types of exercise movements using EX1's 5 levels of resistance and 5 levels of assistance whilethe walking program necessitated walking using 3 speeds, 5 levels of resistance, and 5 levels of assistance. The former comprises 1 warm-up exercise, 8 main exercises, and 1 cool down exercise, which wererepeated thrice and the required time was 30 minutes. The warm-up exercise consisted of step-like movements using EX1 assistive mode, which helped in releasing the tension in the joints and muscles in advance and raising the body temperature. The main exercise aimed to strengthen the lower body muscles, abdomen, and waist through body weight movements using EX1 resistive mode. The cool down exercise included static stretching movements using EX1 assistive mode; its purpose was to relax the muscles and increase recovery.

The walking program comprised three types of programs that were performed alternately. The amount of exercise was gradually increased after each round was repeated, and the required time was 10 minutes. The three types of programs were as follows: 1) a type in which the resistance gradually increases, 2) a type in which resistance and assisted walking with a small difference in intensity are repeated at long intervals, and 3) a type in which resistance and assisted walking with a large difference in intensity are repeated at short intervals.

Procedures

We began by gathering participants'' data pertaining to their age, gender, height, and weight before starting with the exercises that was supposed to be performed 10 times. We conducted an evaluation of outcome measurements twice; before and after the performance of the exercises 10 times. The primary outcome variable was the thickness of the quadriceps muscle, i.e., rectus femoris (RF), vastus intermedius (VI), vastus medialis (VM), and vastus lateralis (VL) through ultrasound measurement. An evaluator skilled in ultrasound measurement measured the thickness of the four muscles of the quadriceps muscle during rest and contraction, and derived the contraction ratio using the muscle rate formula. Secondary outcomes include hand grip strength and flexibility of trunk.Both the variables were measured twice; before and after performing the exercises 10 times. Hand grip strength was measured twice for both the hands, and flexibility was measured twice using the SR test; the highest values for both were recorded. The measurement order of the three variables was randomized for all the participants.

EX1

Hardware of EX1

EX1 is a lightweight robot weighing 2.9 kg thatcan be worn on the user's waist and thighs. Itconsists of two actuators, control box, power switch, thigh support strap, waist belt, and thigh support frame. The control box has a built-in rechargeable battery, central processor, and inertial measurement unit (IMU) sensor. The actuators include motor, angular position sensor, and a controller. The actuators provide assistive or resistive torque to hip joint flexion and extension, and this torque is provided to the user through the thigh support frame. The user operates the mobile device through a Bluetooth connection with the EX1, and it can be used continuously for two hours at a speed of 4 km/h, and generates a maximum noise of less than 45 dB at the height of the user's ear.

Software of EX1

EX1 generates torque based on the delayed output feedback control (DOFC) and does not include a gait phase estimator or reference lookup. When the hip join experiences flexion or extension while walking, each of the EX1 sensors on the side of the hip joint detects the motion at a frequency of 100 Hz. The appropriate assistive or resistive torque is calculated in the central processor after the collected data is smoothed through a low-pass filter. After that, the actuator generates assistive or resistive torque on the user's hip joint side. The left and right actuators alternately provide torque proportional to the user's walking speed in the direction of hip flexion and extension.

Outcome measure

Primary outcome

[Quadriceps muscle contraction ratio]

The current investigation employed a real-time brightness mode (B-mode) ultrasound scanner (SONO 300L, Healcerion, Republic of Korea) to assess the thickness of quadriceps muscles. The transducer comprised a 10 MHz linear array and was set at 76 dB with an image depth within the linear range of 0-5. The thickness of four muscles in the quadriceps was measured during relaxation and contraction to determine the muscle contraction rate. A predetermined formula, i.e., (Thickness during contraction- Thickness during relaxation) / Thickness at rest * 100(%), was utilized to calculate the muscle contraction rate

To measure the thickness of the RF muscle in a relaxed state, the subject sat on a mat with a pillow under their knees and legs extended in a long sitting position. The thickness was measured when the subject releasedas much tension as possible as per the instructions provided. For measuring the maximum voluntary contraction thickness, the subjectwas instructed to press the knees down on the pillow in the same position to maximally contract the RF muscle. The position of the transducer was adjusted to 15 cm above the knee joint. We applied a water-based gel was applied between the skin and transducerto ensure acoustic contact and minimize misinterpretation of images caused by transducer pressure.

The thickness of the RF and VI muscles were measured in the direction perpendicular to the muscle fibers, while that of the VM and VL muscles were measured horizontally. Subsequently, ultrasound images were captured in the central part of each muscle where the ventral portion was most prominent. All muscle thickness measurements were conducted on the participant's dominant leg by a proficient physical therapist skilled in ultrasound imaging.

Secondary outcome

[SRtest]

The SRtest was measured using BS-FF (Inbody u-TOWN, Republic of Korea). The subject sits on a mat and extends their legs forward so that their feet touch the platform. Both knees are planted flat on the mat. The arms are extended horizontally at shoulder height with theirpalms facing the floor. Both hands are then placed on the meter area of BS-FF. They must then bend their upper body to push the meter as far as possible; slowly and smoothly without recoil.This position must be held for threeseconds. Linear scale method is used to gauge the measurements and the range obtainedis −20cm ~ 35cm. A total of two measurements were taken and the highest value was selected.

[Handgrip strength test]

Handgrip strength test was conductedusing a grip dynamometer (BS-HG, Inbody u-TOWN, Republic of Korea). The subject holds the dynamometer from the left hand in a standing position. They extend their arms so that their armpits and arms do not stick to the body, and squeeze hands as tightly as they can for about three seconds. It must be taken care of that force is applied only to thehands. Arms must not be lifted or moved too much. The measurements were recorded twice for both the hands, and the highest valuewas selected.

Statistical analysis

We used PASW statistics 18 (SPSS Inc., Quarry Bay, Hong Kong) to conduct allstatistical analyses. The Shapiro-Wilk test was performed to test the normality of all variable values, and as a result normality was satisfied. All data is expressed in mean (SD). Although the sample size of this study was less than 30, a parametric test was used because it satisfied normality. Therefore, we conducted apaired t-test to compare pre- and post- results outcomes of the exercise program. The statistical significance threshold was set at $P<.05$.

Results

The average values of the general characteristics of the participants are shown in Table 1.

Primary outcome

Table 2 shows the pre- and post- exercise results of muscle contraction ratio based on muscle thickness for each muscle of the quadriceps muscle. The muscle contraction rate of the RFmuscle significantly increased after exercise ($P<0.01$)(Figure 2). That of the VI muscle decreased but not significantly, while that of VM and VL uscles increased by an insignificant value (Figure 3).

Secondary outcome

Table 3 encapsulates the results of flexibility and hand grip strength tests before and after performing the exercises. The SR test for flexibility measurement showed that the average flexibility of theparticipants increased significantly after exercising($P<0.01$). Table 4 shows the results for the participants' handgrip strength test before and after performing the exercise. The two handgrip strength measurements revealed that the average of maximum handgrip strength of the participants after exercise significantly increased ($P<0.05$)(Figure 4).

Table 1. Characteristics of participants (N=17)

Sex (male / female)	12 / 5
Age (year)	35.82 (5.46)
Height (cm)	173.12 (8.63)
Weight (kg)	76.18 (17.63)
Body mass index (kg/m^2)	25.11 (3.73)

Values are presented as number or mean(SD).

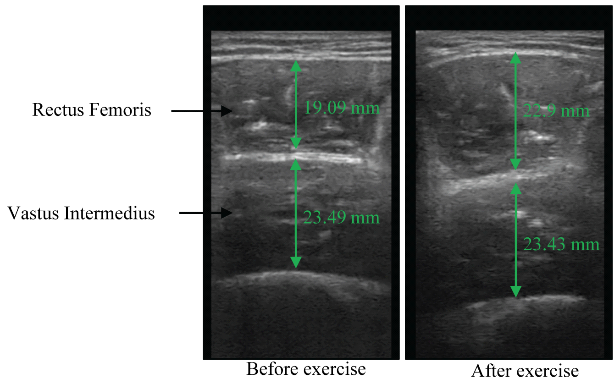

Figure 2. Rectus Femoris and Vastus Intermedius muscle thickness

Table 2. Quadriceps muscle contraction ratio (N=17)

	Pre	Post
Rectus femoris (%)	37.97 (23.24)	57.21**(21.21)
Vastus intermedius (%)	73.77 (25.37)	66.34 (22.16)
Vastus medialis (%)	15.58 (15.21)	18.47 (21.62)
Vastus lateralis (%)	53.78 (21.32)	59.82 (20.19)

Values are presented as mean (SD).
**: $P<0.01$

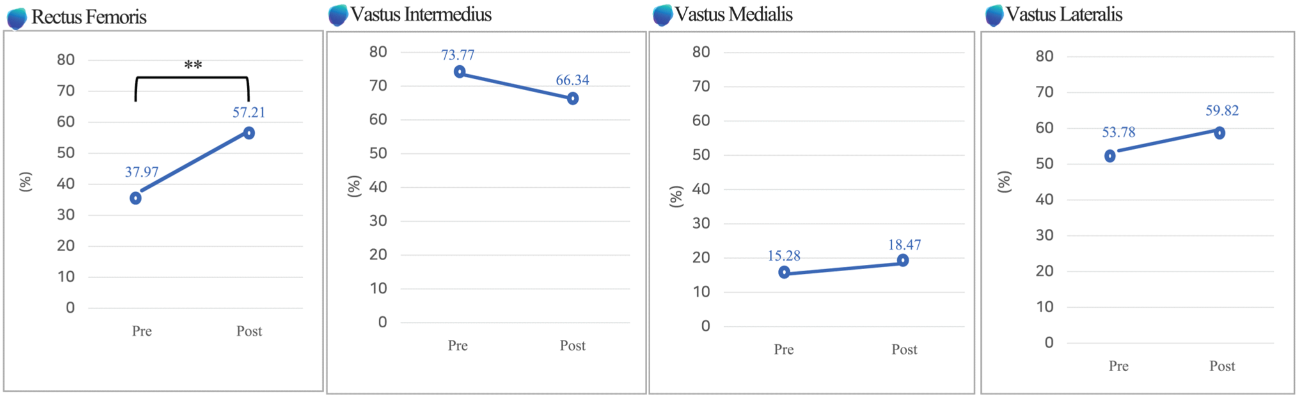

Figure 3. Quadriceps muscle contraction ratio
**: $P < 0.01$

Table 3. Sit and reach (SR) test (N = 17)

Variable	Pre	Post
Flexibility (cm)	0.54 (9.11)	6.06** (9.12)

Values are presented as mean (SD).
**: $P < 0.01$

Table 4. Handgrip strength test (N = 17)

Variable	Pre	Post
Handgrip strength (kg)	34.72 (11.14)	37.92*(11.95)

Values are presented as mean (SD).
*: $P < 0.05$

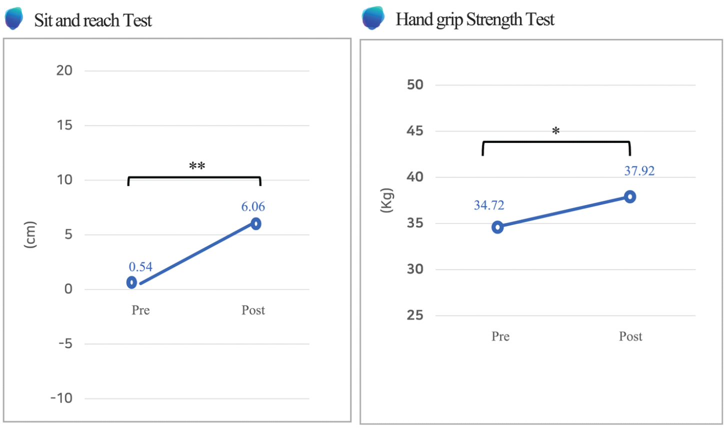

Figure 4. Flexibility and Hand grip strength
**: $P < 0.01$, *: $P < 0.05$

Discussion

This study aimed to confirm the morphological changes of quadriceps muscle, flexibility, and hand grip strength after exercise program using EX1 for young adults. It is an exoskeleton robot which provides assistive or resistive torque around the hip joint.

The exoskeleton characteristics of EX1 were expected to significantly impact the quadriceps muscle; as confirmed by the experiment results. Muscle thickness was measured through ultrasound; however, comparing muscle thickness yields a slight difference during rest and contraction. Sarcoplasmic hypertrophy increases the muscle thickness during rest by increasing the amount of fluid in the muscle. Sarcoplasm is the cytoplasm of the muscle cellfilled with glycogen, water, and mineral ions. Conversely, hypertrophy of myofibrils increasesthe muscle thickness during contraction by increasing the number of fibers thatcontract the actual muscle, thereby increasingthe density of the muscle and its strength[37, 38]. Therefore, to confirm whether muscle strength has actually improved, the muscle contraction ratio should be calculated during rest and contraction.

Among the four muscles which make up the quadriceps muscle, the RF showed the greatest increase in muscle contraction ratio. Itis the only two-joint muscle among the four that is also involved in the movement of the hip joint[39]. Because EX1 provides torque centered on the hip joint, RF is the only muscle that exhibiteda significant change ($P < 0.01$). Muscle contraction ratio of other muscles also increased after exercise; however, VI showed a slight decrease. It suggested that the positional characteristics of the EX1's actuator, which assists the action of the hip joint rather than the direct action of the knee joint shows the different muscle contraction increase results of RF and VI[39].

Flexibility of trunk increased significantly after performing the exercise. We conducted the SR test to evaluate flexibility of the hamstring. According to previous study, the correlation between hamstring flexibility and SR test was moderate ($r = 0.64$) and the correlation with low back flexibility was low ($r = 0.28$)[40]. The exercise program using EX1 involved various motions that stretch the hamstrings during anaerobic exercise; it is expected that the flexibility of the hamstrings increased during these types of exercise, resulting in a significant increase in the value obtained through the SR test ($P < 0.01$). Similarly, in another study, as a result of retro walking exercise for 4 weeks, the flexibility of the hamstring significantly increased. These results also revealed that it can increase jumping height or reduce low back pain[41]. Additionally, in the walking exercise, the assistive mode induces the eccentric contraction of the hamstring at the end of the swing for knee stability and deceleration control[42]. Since this eccentric contraction exercise is concurrently performed, it can be expected that the increase in flexibility can occur with the increase in muscle strength. Also, In gait, clinically, the first resistance to the hamstring is related to the possibility of extension of the knee joint, therefore, when the flexibility of the hamstrings is limited, the dynamic knee extension is also limited at terminal swing phase[43].

One of the indices which can be easily and indirectly evaluated for physical limitation, movement restriction, and lower extremity muscle strength is the hand grip strength[23, 24]. In this study, as in previous studies, the strength and flexibility of the lower extremities improved significantly after performing the exercise ($P < 0.05$). In the exercise program using EX1, the strength exercise focusing on the lower extremity and core muscles had an indirect positive effect on the improvement of hand grip strength. Increased hand grip strength is clinically used as a tool to predict and evaluate metabolic disease, cognitive impairment, sarcopenia, mental health, and cardiopulmonary disease in older adults[44]. In addition, the participants of this study were young adults, and previous study revealed that the increase in hand grip strength in young adults was correlated with mobility, quality of life, and physical activity[45].

This study has several limitations. First, owing to the small sample size, the results cannot be generalized. Second, although we included walking exercise in this exercise program, the cardiopulmonary endurance was not measured. Therefore, we recommend that future studies should confirm changes in muscle strength in core muscle and other lower extremity muscles and cardiopulmonary endurance through a larger sample size.

Conclusion

The results obtained suggest that 10 times combined exercise program using EX1 positively contributes to morphological changes of the quadriceps muscle, hand grip strength, and flexibility of the hamstring muscle in young adults. Therefore, healthy young adults can effectively perform various exercises routinely performed using EX1.

Conflict of interest

The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this paper.

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