Available online at www.sciencedirect.com
ScienceDirect
Journal of Electromyography and Kinesiology 17 (2007) 596–604
JOURNAL OF ELECTROMYOGRAPHY AND KINESIOLOGY
www.elsevier.com/locate/jelekin

Age-related differences in muscle activity, stride frequency and heart rate response during walking in water

Kenji Masumoto [a,*], Tomoki Shono [b], Shin-ichiro Takasugi [c], Noboru Hotta [a], Kazutaka Fujishima [a], Yukihide Iwamoto [d]

[a] Institute of Health Science, Kyushu University, 6-1 Kasuga-koen, Kasuga, Fukuoka 816-8580, Japan
[b] Department of Sports Health and Welfare, Kyushu University of Health and Welfare, 1714-1 Yoshino-machi, Nobeoka, Miyazaki 882-8508, Japan
[c] Department of Rehabilitation Medicine, Kyushu University Hospital, 3-1-1 Maidashi, Higashi-ku, Fukuoka, Fukuoka 812-8582, Japan
[d] Department of Orthopaedic Surgery, Faculty of Medicine, Kyushu University, 3-1-1 Maidashi, Higashi-ku, Fukuoka, Fukuoka 812-8582, Japan

Received 14 November 2005; received in revised form 9 May 2006; accepted 2 June 2006

Abstract

This study aimed to examine whether walking in water produces age-related differences in muscle activity, stride frequency (SF), and heart rate (HR) response. Surface electromyography (EMG) was used to evaluate muscle activities in six older and six young subjects while they walked in water immersed to the level of the xiphoid process. The trials in water utilized the Flowmill which consists of a treadmill at the base of a water flume. The measurement of maximal voluntary contraction (MVC) of each muscle was made prior to the gait analysis. The %MVCs, which refer to the surface EMG measures, from the gastrocnemius of the older subjects were significantly lower than those of the young subjects, in every experimental condition ($P < 0.05$). In contrast, the %MVCs from the rectus femoris ($P < 0.05$) and the biceps femoris ($P < 0.001$) of older subjects were significantly greater than those of young subjects in every experimental condition. Moreover, the SFs of older subjects were also significantly greater than those of young subjects ($P < 0.05$), while the HR responses of older and young subjects were similar. In conclusion, the older subjects had increased hip musculature activity and decreased ankle plantar flexor activity while walking in water, compared with the young subjects.

Keywords: Aging; Gait; Water; EMG; Underwater treadmill

1. Introduction

Water exercise programs are growing in popularity. Numerous studies have addressed the psychological (Oda et al., 1999), metabolic (Evans et al., 1978), cardiorespiratory (Di Prampero et al., 1974), and thermoregulatory (Shimizu et al., 1998) responses during various forms of water-based exercise. Quantifying muscle activity and gathering scientific evidence has been a major challenge in the research field of water exercise, because of the difficulty in fixing surface electrodes to the skin, and the complexity and sophistication of the equipment needed to transmit and to record electromyography (EMG) signals from subjects while they are immersed in water (Masumoto et al., 2004). Several investigators have evaluated muscle activities while subjects performed exercises in water. Muscle activation during maximal voluntary contraction (MVC; Clarys et al., 1985), in addition to ankle (Pöyhönen and Avela, 2002), knee (Pöyhönen et al., 1999) and shoulder (Kelly et al., 2000) exercises in water have been reported. Walking in water can be recommended for developing and maintaining cardiorespiratory and muscular fitness, and flexibility in older adults, since it involves the total

* Corresponding author. Tel.: +81 92 583 7685; fax: +81 92 592 2866.
E-mail address: masumoto@ihs.kyushu-u.ac.jp (K. Masumoto).

1050-6411/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jelekin.2006.06.006

body, and since it is both continuous and rhythmic (American College of Sports Medicine, 1998a). However, it is rare to find scientific research which evaluates muscle activity while walking in water.

Recently, Masumoto et al. (2004, 2005) successfully employed surface electrode and telemetric EMG technology to analyze muscle activities in healthy young subjects while they walked in water. They were able to demonstrate decreased muscle activity (~70%MVC of that observed on dry land), and they also demonstrated that muscle activities while walking in water tend to be greater with a water current than without (Masumoto et al., 2004). Furthermore, they demonstrated that the paraspinal muscles show dramatically greater muscle activity while subjects walk backward in water with a water current than when they walk backward on dry land, or walk backward in water without a water current (Masumoto et al., 2005). However, an extensive search of the literature has yielded no information on muscle activity in older adults while they walk in water. This lack of information regarding muscle activity in older adults led us to design this study in order to obtain basal data for this population. Such data may help us gain a better understanding of the plasticity the locomotor mechanics of aging thereby enabling an appropriate exercise prescription to be made.

Previous research has investigated physiological responses while walking or jogging in a swimming pool (Evans et al., 1978; Whitley and Schoene, 1987). However, it has been methodologically difficult to identify the physiological intensity of walking in a swimming pool (Masumoto et al., 2004, 2005). The present study was designed to utilize the Flowmill which has a treadmill at the base of a water flume. The major advantage of the Flowmill is that the speed of the underwater treadmill, the speed of the water current, depth, and water temperature can each be controlled independently, thus allowing adjustment of functional walking patterns and exercise intensity (Masumoto et al., 2004, 2005).

To our knowledge, this investigation represents the first attempt to compare muscle activities, concurrently with the measurement of stride frequency and heart rate (HR) responses in both young and older adults while they walked in water. Based on previous findings which were observed on dry land, we hypothesized that ankle plantar flexor activity would be lower (DeVita and Hortobagyi, 2000; Judge et al., 1996; Kerrigan et al., 1998; Neptune et al., 2001; Riley et al., 2001; Winter et al., 1990), and that hip musculature activity would be greater (DeVita and Hortobagyi, 2000; Judge et al., 1996; Kerrigan et al., 1998) in older subjects than in young subjects, while walking in water. It was also hypothesized that the stride frequency of older subjects would be greater, compared with that of young subjects, while walking in water (DeVita and Hortobagyi, 2000; Kerrigan et al., 1998). Additionally, it was further hypothesized that HR responses would be similar between the two groups while walking in water (American College of Sports Medicine, 1998b).

2. Methods

2.1. Subjects

The participants in this study were six female older (mean age, 63.5 ± 3.5 yr) and six young subjects (mean age, 22.0 ± 0.6 yr). Stature, body mass, and %fat were similar between the two groups. Older subjects averaged 1.56 ± 0.26 m, 61.4 ± 1.9 kg and 25.5 ± 5.4%, while young subjects averaged 1.59 ± 0.55 m, 63.6 ± 4.1 kg and 22.3 ± 2.8% for stature, body mass and %fat, respectively. Percentage fat was estimated using the impedance method (TBF-410, Toyo Physical, Japan; Masumoto et al., 2004, 2005). The subjects recruited for this study were healthy individuals, without any known musculoskeletal, neurologic, or cardiopulmonary diagnoses. The subjects had not been participating in any exercise regularly at the time of data collection. This study was approved by the Ethical Committee of the Department of Rehabilitation Medicine at Kyushu University Hospital. All the subjects were informed about the procedures and the potential risks, and gave their written informed consent to participate in the study.

2.2. Electromyograms

The protocol for the gait analyses essentially followed the previously described methods of Masumoto et al. (2004, 2005). In order to evaluate muscle activities, the EMGs of each muscle were taken using silver–silver chloride surface electrodes (Mini Ag/AgCl Skin Electrode, NT-511G, Nihon Kohden, Japan) which were 8 mm in diameter. To keep the inter-electrode resistance low (<5 kΩ), the sites for electrode placement were prepared by shaving the hair and gently abrading the skin using a skin preparation gel (Skinpure, YZ-0019, Nihon Kohden), and then these sites were cleaned with alcohol pads in order to minimize the skin resistance. EMG signals were captured from the following muscles on the right side: the vastus medialis, rectus femoris, the long head of the biceps femoris, tibialis anterior, and the lateral head of gastrocnemius. A reference electrode was placed on the acromion. In order to minimize cross talk between the muscle groups, surface electrodes were placed 2 cm apart over the middle point of the venter. Waterproof dressings were placed over each of the electrodes. The surface electrodes were fixed with extreme care using adhesive tape (3M, USA) before being covered with foam pads (Foam Pad, 75A, Nihon Kohden) to prevent water from contacting the skin-electrode interface and to prevent electrical leakage during the tests. Taping was done in a manner that allowed unencumbered movement of the tested muscles and normal gait while performing the trials. These procedures were carried out by one particular investigator in order to ensure identical standard record keeping.

The raw EMG signal was derived with the eight-channel multitelemeter system (WEB-5000, Nihon Kohden) and was transferred to an Analogue/Digital converter (MacLab/8c, AD Instruments, USA) before being imported into a personal computer (Macintosh PowerBook 3400c, Apple Computer, USA) for later analysis. The raw EMG signal was recorded at the sampling rate of 1000 Hz and then integrated EMG (iEMG) analysis was made using the Chart v3.5/s (AD Instruments) and Scope v3.5/s software (AD Instruments). The EMG data were integrated after smoothing. The raw EMG signal was digitally filtered using second-order low-pass and high-pass filters with cut-off frequencies of 500 and 20 Hz, respectively.

MVC was used to normalize the EMG magnitude. Measurement of the MVC of each muscle, following the method of Hislop and Montgomery (1995), was made on dry land before performing gait analysis, in order to calculate the percentage of MVC (%MVC). The entire EMG activity for each muscle was expressed as a %MVC. The subjects performed a single MVC isometric contraction test for each of the tested muscles. The duration of the test was set at 5 s for each muscle. The subjects were familiarized with the testing procedure and were trained to produce the maximal force output before each measurement session.

EMG activities recorded for five randomly selected consecutive and stable gait cycles were subjected to full-wave rectification. The gait cycle was determined by event markers. This method was used because no equipment (e.g., foot-switch) is commercially available for determining gait cycles during walking in water. For each subject and each muscle, the iEMGs (mV/s) of the five randomly selected consecutive gait cycles were divided by the time required for each of the gait cycles in order to calculate the iEMGs per second (mV). Then, the iEMGs were averaged in order to yield iEMGs per gait cycle. The peak 1-s EMG signal (mV) for each of the eight muscles tested during MVC measurements was selected as a normalizing value (100%). In order to calculate the %MVC, each of the iEMGs per second (mV) was divided by the peak amplitude of MVC per second (mV) for standardization.

2.3. Experimental procedures

Each subject completed all the exercise tests within a single day. Initially, subjects completed the MVC measurement on dry land. Verbal encouragement by the instructors was provided to motivate all the subjects into achieving their maximal contraction levels. They were then required to enter the water flume in order to perform the trials in water. Before initiating the actual measurements, a few submaximal EMG recordings were repeated to ensure accurate electrode placement, and to ensure that the electrodes had not migrated and that dampening of the signal due to water leakage had not occurred. The multitelemeter system was secured to the side of the underwater treadmill while they performed the trials in water. This set-up enabled the transmitter to be secured without placing undue tension on the leads or interfering with the gait.

The subjects walked on an underwater treadmill (Flowmill, FM-1200D, Japan Aqua Tech, Japan), immersed to the level of the xiphoid process (Masumoto et al., 2004,

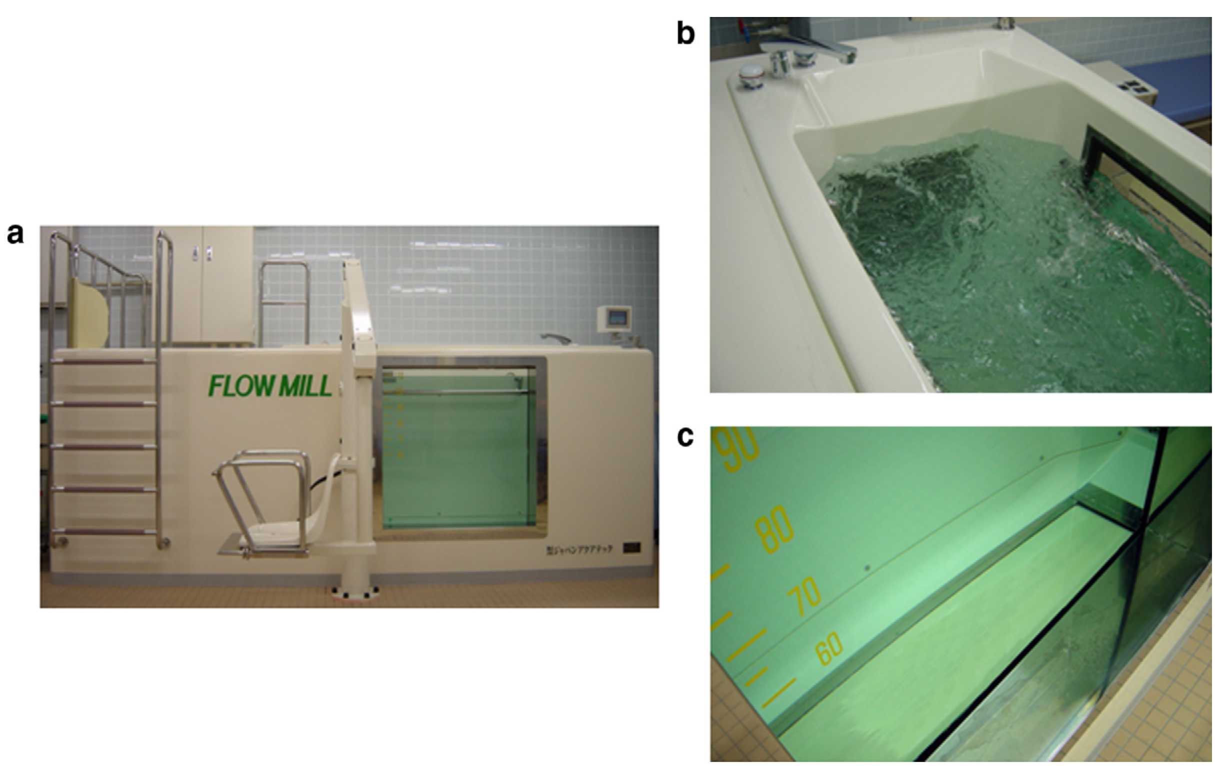

Fig. 1. (a) Side view of the underwater treadmill (Flowmill); (b) water current; (c) treadmill in water.

2005). Throughout the laboratory experiment, the water temperature of the Flowmill (Fig. 1) was maintained at 31.0 ± 0.1 °C (Evans et al., 1978; Masumoto et al., 2004, 2005), a level assumed to be thermoneutral for exercising humans (Sheldahl et al., 1984). The room temperature was maintained at 26.6 ± 0.1 °C (Masumoto et al., 2004, 2005) during the measurement days to ensure similar skin temperatures between the wet and dry conditions (Pöyhönen and Avela, 2002).

Before commencing the exercise tests, all the subjects practiced walking in water at various speeds until they felt confident enough to proceed with the actual measurements. Additional practice was performed if the subject or investigators deemed it necessary. Walking tests were carried out at three speeds (1.8, 2.4 and 3.0 km/h; Masumoto et al., 2004, 2005). The speeds of the water current were set at 1.8, 2.4 and 3.0 km/h, in line with the speeds of the underwater treadmill (Masumoto et al., 2004, 2005). These three walking speeds were chosen to represent slow, moderate and fast speeds (Masumoto et al., 2004, 2005). Each subject completed three consecutive 1-min exercise bouts, with a 1-min rest period between each of the three speed settings (Masumoto et al., 2004, 2005). The subjects wore swimsuits throughout the experimental sessions. In order to avoid potentially invoking the diving bradycardia reflex (Natelson et al., 1983), the subjects were required to keep their faces out of the water at all times.

For all tests, the HR responses were monitored continuously by a telemetry method (ST-30, DS-501, Fukuda-Denshi, Japan) and recorded every 10 s: the value at the middle of each exercise bout (30 s) was used for statistical analysis (Masumoto et al., 2004, 2005). Waterproof electrodes (Vitrode D-90, Nihon Koden) were used to estimate HR responses while walking in water (Masumoto et al., 2004, 2005). Furthermore, stride frequency was measured for 60 s for each exercise bout (Hall et al., 1998).

2.4. Statistical analysis

Data were expressed as mean ± standard deviation. All parameters regarding gait were analyzed using repeated measures ANOVA (factors; groups and walking speeds), with the Bonferroni correction for *post hoc* comparison tests. The anthropometrical variables were analyzed with a *t*-test. *P*-values below 0.05 were considered to indicate statistical significance.

3. Results

3.1. Anthropometry

There was no statistically significant difference in stature, body mass, or %fat between older and young subjects.

3.2. Heart rate response

Descriptive statistics for the HR responses in each experimental session can be found in Table 1. There was no significant difference in the HR response between older and young subjects, except at fast speed ($P < 0.05$). In addition, the HR responses increased as the speed increased ($P < 0.05$).

3.3. Stride frequency

Table 2 depicts the stride frequency in each experimental session. The stride frequency of older subjects was significantly greater than that of young subjects at both moderate ($P < 0.05$) and fast ($P < 0.001$) speeds, but there was no significant difference at slow speed. Additionally, it was noted that the stride frequency increased as speed increased ($P < 0.05$).

3.4. %MVC

Fig. 2 demonstrates representative raw EMG data from the muscles tested at a moderate speed. The raw EMG activity from the rectus femoris and the biceps femoris was enhanced in older subjects, when compared with that of young subjects. In contrast, however, the raw EMG activity from the gastrocnemius was reduced in older subjects compared with that observed in young subjects.

The %MVCs from each of the muscles tested while the older and young subjects walked in water are presented in Tables 3 (slow), 4 (moderate) and 5 (fast).

At slow speed, the %MVCs obtained from the rectus femoris ($P < 0.05$) and the biceps femoris ($P < 0.001$) of older subjects were significantly greater than those of young subjects, whereas those from the vastus medialis and the tibialis anterior showed no significant difference. In contrast, the %MVC obtained from the gastrocnemius of older subjects was significantly lower than that of young subjects ($P < 0.05$).

At moderate speed, the %MVCs from the rectus femoris ($P < 0.01$) and the biceps femoris ($P < 0.001$) of older sub-

Table 1
Heart rate (HR) response while walking in water (beats/min)

Speed	Young adults	Older adults	P value
Slow	78.3 ± 5.2	81.3 ± 3.9	0.288
Moderate	83.0 ± 4.9	88.3 ± 6.0	0.065
Fast	92.3 ± 2.6	99.5 ± 6.4	0.015

Values are means ± SD.

Table 2
Stride frequency while walking in water (steps/min)

Speed	Young adults	Older adults	P value
Slow	59.5 ± 5.8	59.8 ± 5.6	0.897
Moderate	61.7 ± 3.3	68.3 ± 4.2	0.015
Fast	63.2 ± 6.6	75.7 ± 4.8	<0.0001

Values are means ± SD.

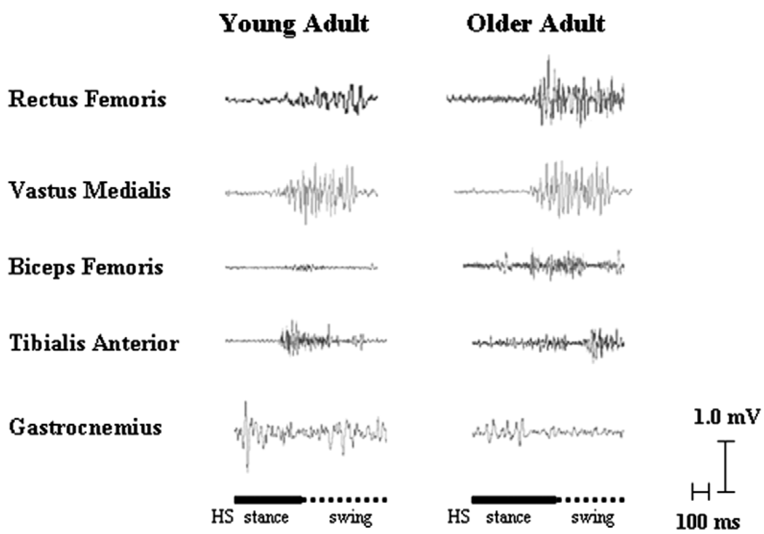

Fig. 2. Typical EMG data per gait cycle obtained from subjects performing trials at a moderate speed. HS, heel strike.

Table 3
Muscle activity while walking in water at slow speed (%MVC)

Muscle	Young adults	Older adults	*P* value
Vastus medialis	3.9 ± 1.9	6.5 ± 1.5	0.166
Rectus femoris	5.0 ± 2.2	7.7 ± 2.1	0.048
Biceps femoris	5.7 ± 1.7	10.4 ± 1.9	0.0004
Tibialis anterior	6.8 ± 2.8	6.3 ± 2.9	0.772
Gastrocnemius	8.1 ± 2.3	4.9 ± 1.6	0.037

Values are means ± SD.

Table 4
Muscle activity while walking in water at moderate speed (%MVC)

Muscle	Young adults	Older adults	*P* value
Vastus medialis	6.8 ± 3.3	8.0 ± 2.9	0.520
Rectus femoris	7.9 ± 2.0	11.9 ± 2.9	0.004
Biceps femoris	7.9 ± 1.8	13.9 ± 2.0	<0.0001
Tibialis anterior	13.9 ± 2.1	12.3 ± 2.5	0.326
Gastrocnemius	15.3 ± 3.1	10.7 ± 1.6	0.035

Values are means ± SD.

Table 5
Muscle activity while walking in water at fast speed (%MVC)

Muscle	Young adults	Older adults	*P* value
Vastus medialis	10.4 ± 4.3	13.5 ± 3.4	0.099
Rectus femoris	13.2 ± 2.6	18.2 ± 2.1	0.0007
Biceps femoris	15.5 ± 2.3	20.7 ± 2.8	0.0001
Tibialis anterior	16.8 ± 3.1	14.4 ± 3.0	0.134
Gastrocnemius	22.5 ± 3.3	16.9 ± 3.7	0.0007

Values are means ± SD.

jects were significantly greater than those of young subjects, although there was no significant difference in muscle activities from the vastus medialis or the tibialis anterior. In contrast, the %MVC obtained from the gastrocnemius of older subjects was significantly lower than that of young subjects ($P < 0.05$).

At fast speed, the %MVCs from the rectus femoris ($P < 0.001$) and the biceps femoris ($P < 0.001$) of older subjects were significantly greater than those of young subjects, although there was no significant difference in the muscle activities from the vastus medialis or the tibialis anterior. In contrast, the %MVC obtained from the gastrocnemius of older subjects was significantly lower than that of young subjects ($P < 0.001$). In addition, it was noted the %MVCs from the tested muscles increased as the speed increased ($P < 0.05$).

4. Discussion

The primary interest of this investigation was to test for differences in the %MVC, which is relative to the amplitude of the EMG, of each tested muscle while young and older subjects walked in water. Water temperature was kept within the thermoneutral range (Pöyhönen and Avela, 2002; Sheldahl et al., 1984). In the case of the present study, it therefore follows that immersion-related changes in electromechanical factors that affect the measurement techniques or detected signal can also be assumed to be negligible. The major new finding of this study was that the %MVC from the gastrocnemius in older subjects was significantly lower than that of young subjects in every experimental condition (Tables 3–5). Furthermore, the %MVCs from the rectus femoris and biceps femoris in older subjects were significantly greater than those of young subjects in every experimental condition (Tables 3–5). Possible explanations for differences in %MVCs, stride frequencies, and HR responses of older and young subjects while walking in water can only be considered based on previously reported findings on dry land and the current findings in water, because there have not been any previous studies comparing these variables while older and young subjects walk in water.

Our finding of decreased muscle activity from the gastrocnemius in older subjects while walking in water is in agreement with previous analyses conducted on dry land (DeVita and Hortobagyi, 2000; Judge et al., 1996; Kerrigan et al., 1998; Riley et al., 2001; Winter et al., 1990). It has been reported that ankle plantar flexors have larger physiological and biomechanical deficits compared with the other muscle groups in the elderly in contrast to young adults (DeVita and Hortobagyi, 2000). From physiological perspectives, it has been shown that the rate of decline in maximal voluntary isometric force between the ages of 25 and 74 yr is the largest in the plantar flexors, compared the five other muscle groups (Christ et al., 1992), and that the rate of decline in plantar flexor strength is actually fourfold that of other muscle groups, based on a longitudinal study of the elderly (Winegard et al., 1996). It has also been reported that there is a 25% decline in citrate synthase activity in the gastrocnemius of subjects between the ages of 18 and 80 yr, whereas no decline has been observed in the vastus lateralis (Houmard et al., 1998). Furthermore, Coggan et al. (1992) reported 13–31% reductions in type IIa and IIb fiber areas and a 25% reduction in mitochondrial enzyme activity in the gastrocnemius of elderly adults, compared with young adults. From biomechanical perspectives, reduced plantar flexor function could affect forward progression of the leg into the swing phase, swing initiation and trunk progression in late stance, or trunk stabilization in early stance (Judge et al., 1996; Neptune et al., 2001; Riley et al., 2001). Furthermore, Porter et al. (1997) found reduced concentric ankle plantar flexor strength in the elderly, even though the eccentric strength in this population was well preserved. Likewise, rapid ankle torque generation capacity decreases with age, and this represents a potential limiting impairment in the elderly (Thelen et al., 1996). Although functional decline with age is larger in the plantar flexors than in the other muscle groups, the elderly retain 60% of their maximal isometric and concentric torque at age 80 yr (Christ et al., 1992; Gajdosik et al., 1999). The mean age of the older subjects of the present study was only 63 yr, and because of this they could have walked with presumably greater plantar flexor power. Accordingly, the older subjects of this study may have had some remaining power-generating capability in their plantar flexors which they did not use. It can be speculated that the reduction in physiological and biomechanical properties of human plantar flexors that comes with age actually causes older subjects to use less power from the gastrocnemius compared with young subjects while they are walking in water, even though the older subjects still have the capability to generate the same amount of power as that used by young subjects while walking in water.

The increased muscle activities from the rectus femoris and biceps femoris in older subjects while walking in water are consistent with earlier observations which found an increase in hip musculature power during gait on dry land (DeVita and Hortobagyi, 2000; Judge et al., 1996; Kerrigan et al., 1998). Judge et al. (1996) reported that more hip flexor power was used by elderly subjects compared with young subjects, and that elderly subjects increased their hip flexor power when increasing their gait velocity. While walking at identical speed, elderly subjects created more hip flexion, and they used a greater range of motion (ROM) at the hip compared with young subjects (DeVita and Hortobagyi, 2000). Increased hip flexion may be a postural adjustment to further stretch the hip extensor muscles, thereby enabling them to produce larger amounts of torque and power during the stance phase compared with young subjects (DeVita and Hortobagyi, 2000). It has also been shown that the function of the hip flexor moment at the late stance during gait is to pull the thigh forward and upward (Winter, 1990). On the other hand, DeVita and Hortobagyi (2000) and Kerrigan et al. (1998) identified increased output from the hip extensor muscles in elderly subjects, compared with young subjects. Elderly subjects produced a larger extensor torque and more work at the hip during the first half of the stance than young subjects (DeVita and Hortobagyi, 2000). Furthermore, elderly subjects may use the hip extensors, in addition to enhancing trunk stability, to assist in advancing the contralateral leg into the swing phase (DeVita and Hortobagyi, 2000; Kerrigan et al., 1998). Therefore, increased hip musculature activity in older subjects while walking in water may possibly result in providing trunk stability with hip extensors, pulling the thigh forward and upward at the late stance with hip flexors, and assisting with leg swing initiation via hip flexors and possibly with hip extensors as well. However, the present study did not determine the actual mechanisms of the increased hip musculature activity in older adults while walking in water. In addition, it is thought that different hip actions could exist for different reasons. Future studies are warranted to address the possible mechanisms of these differences.

It is of interest to note that the %MVCs from the tested muscles increased with increasing speed. In fact, the level of muscle activity while walking in water at moderate and fast speeds showed an approximately 67% and 150% increase over that observed at slow speed, respectively. This is in agreement with our previous investigation (Masumoto et al., 2005). Resistance in water is related to the speed of movement, and it increases as the square of speed (Hall et al., 1998). The increased %MVCs may be related to the muscle masses which are activated to maintain the pace as speed increases, or they may simply be a reflection of the greater resistance to movements encountered in water (Hall et al., 1998; Masumoto et al., 2005).

The stride frequencies of older subjects were significantly greater than those of young subjects while walking in water (Table 2). This is in general agreement with earlier studies performed on dry land (DeVita and Hortobagyi, 2000; Kerrigan et al., 1998). One possible explanation for this is that the elderly subjects matched the gait speed by increasing their stride frequencies to compensate for their shorter step length (DeVita and Hortobagyi, 2000), or it may be related to the decrease in plantar flexor power (Judge et al., 1996; Kerrigan et al., 1998; Riley et al., 2001; Winter et al., 1990). In addition, the increased stride frequency noted in older subjects in this study may be related to a longer relative stance time (DeVita and Hortobagyi, 2000; Finley et al., 1969; Murray et al., 1969; Winter et al., 1990) and a shorter absolute swing time (DeVita and Hortobagyi, 2000). The absolute stride frequency values observed in this study were approximately half of the previously reported values on dry land (DeVita and Hortobagyi, 2000; Kerrigan et al., 1998; Riley et al., 2001; Winter et al., 1990). Lower levels of stride frequency have been previously shown in water (Frangolias and Rhodes, 1995; Hall et al., 1998; Newman et al., 1994). An alternative explanation for this could be that the viscosity friction of the water influences running style by reducing dependency on the postural muscles (Wilder and Brennan, 1993), or the reduced stride frequency may be related to a reduction in ground reaction force (Newman et al., 1994), or may be due to the decrease in weight-bearing (e.g., 70% weight-bearing at the level of the xiphoid process; Harrison et al., 1992). It is possible that kinematically different movements may be a reason for the lower absolute stride frequency values in water than on dry land.

HR responses are known to be affected by water temperature (Craig and Dvorak, 1968). However, in this study, the water temperature was kept at a level assumed to be thermoneutral for exercising humans (Pöyhönen and Avela, 2002; Sheldahl et al., 1984). The HR responses of older and young adults have been shown to be similar at the same absolute work rate (e.g., the same walking speed; American College of Sports Medicine, 1998b). In the present study, the HR responses of older and young subjects were similar while walking in water (Table 1). This may be because the subjects performed the tests at an identical gait velocity. Additionally, it was noted that the HR increased as speed increased. This is in accordance with previous reports (Hall et al., 1998; Masumoto et al., 2005). However, further investigations to evaluate cardiorespiratory response while walking in water in older adults would be a noteworthy assignment, before any definitive conclusion can be derived.

5. Conclusions

We have demonstrated that older subjects have increased hip musculature activity and decreased ankle plantar-flexor activity while walking in water. However, since this study employed the same walking speed for both older and young subjects, further research at a subject's self-selected speed may be imperative, in order to explore whether similar results can still be observed. Furthermore, the methodology presented in the current study should enable a comparison of normal and pathological gait patterns in water. This is perhaps a possible pointer for further research in the field of electromyography and kinesiology.

Acknowledgements

The authors acknowledge all the subjects for their voluntary involvement in the present study thereby making the project a success. The English used in this article was revised by Katherine Miller (Royal English Language Centre, Fukuoka, Japan).

References

American College of Sports Medicine Position Stand. The recommended quantity and quality of exercise for developing and maintaining cardiorespiratory and muscular fitness, and flexibility in healthy adults. Med Sci Sports Exerc 1998a;30(6):975–91.

American College of Sports Medicine Position Stand. Exercise and physical activity for older adults. Med Sci Sports Exerc 1998b;30(6):992–1008.

Christ CB, Boileau RA, Slaughter MH, Stillman RJ, Cameron JA, Massey BH. Maximal voluntary isometric force production characteristics of six muscle groups in women aged 25 to 74 years. Am J Hum Biol 1992;4(4):537–45.

Clarys JP, Robeaux R, Delbeke G. Telemetered versus conventional EMG in air and water. In: Winter D, Norman R, Hayes R, Patla A, editors. Biomechanics IX-B. Champaign, IL: Human Kinetics; 1985. p. 286–90.

Coggan AR, Spina RJ, King DS, Rogers MA, Brown M, Nemeth PM, et al.. Histochemical and enzymatic comparison of the gastrocnemius muscle of young and elderly men and women. J Gerontol 1992;47(3):B71–6.

Craig Jr AB, Dvorak M. Thermal regulation of man exercising during water immersion. J Appl Physiol 1968;25(1):28–35.

DeVita P, Hortobagyi T. Age causes a redistribution of joint torques and powers during gait. J Appl Physiol 2000;88(5):1804–11.

Di Prampero PE, Pendergast DR, Wilson DW, Rennie DW. Energetics of swimming in man. J Appl Physiol 1974;37(1):1–5.

Evans BW, Cureton KJ, Purvis JW. Metabolic and circulatory responses to walking and jogging in water. Res Q Exerc Sport 1978;49(4):442–9.

Finley FR, Cody KA, Finizie RV. Locomotion patterns in elderly women. Arch Phys Med Rehabil 1969;50(3):140–6.

Frangolias DD, Rhodes EC. Maximal and ventilatory threshold responses to treadmill and water immersion running. Med Sci Sports Exerc 1995;27(7):1007–13.

Gajdosik RL, Vander Linden DW, Williams AK. Concentric isokinetic torque characteristics of the calf muscles of active women aged 20 to 84 years. J Orthop Sports Phys Ther 1999;29(3):181–90.

Hall J, Macdonald IA, Maddison PJ, O'Hare JP. Cardiorespiratory responses to underwater treadmill walking in healthy females. Eur J Appl Physiol Occup Physiol 1998;77(3):278–84.

Harrison RA, Hillman M, Bulstrode S. Loading of the lower limb when walking partially immersed: implications for clinical practice. Physiotherapy 1992;78(3):164–6.

Hislop HJ, Montgomery J. Daniel's and Worthingham's muscle testing: techniques of manual examination. 6th ed. Philadelphia: WB Saunders; 1995.

Houmard JA, Weidner ML, Gavigan KE, Tyndall GL, Hickey MS, Alshami A. Fiber type and citrate synthase activity in the human gastrocnemius and vastus lateralis with aging. J Appl Physiol 1998;85(4):1337–41.

Judge JO, Davis RB, Ounpuu S. Step length reductions in advanced age: the role of ankle and hip kinetics. J Gerontol A-Biol Sci Med Sci 1996;51(6):M303–12.

Kelly BT, Roskin LA, Kirkendall DT, Speer KP. Shoulder muscle activation during aquatic and dry land exercises in nonimpaired subjects. J Orthop Sports Phys Ther 2000;30(4): 204–10.

Kerrigan DC, Todd MK, Della Croce U, Lipsitz LA, Collins JJ. Biomechanical gait alterations independent of speed in the healthy elderly: evidence for specific limiting impairments. Arch Phys Med Rehabil 1998;79(3):317–22.
Masumoto K, Takasugi S, Hotta N, Fujishima K, Iwamoto Y. Electromyographic analysis of walking in water in healthy humans. J Physiol Anthropol Appl Human Sci 2004;23(4):119–27.
Masumoto K, Takasugi S, Hotta N, Fujishima K, Iwamoto Y. Muscle activity and heart rate response during backward walking in water and on dry land. Eur J Appl Physiol 2005;94(1-2):54–61.
Murray MP, Kory RC, Clarkson BH. Walking patterns in healthy old men. J Gerontol 1969;24(2):169–78.
Natelson BH, Nary CA, Curtis GA, Creighton D. Roles of stress and adaptation in the elicitation of face-immersion bradycardia. J Appl Physiol 1983;54(3):661–5.
Neptune RR, Kautz SA, Zajac FE. Contributions of the individual ankle plantar flexors to support, forward progression and swing initiation during walking. J Biomech 2001;34(11):1387–98.
Newman DJ, Alexander HL, Webbon BW. Energetics and mechanics for partial gravity locomotion. Aviat Space Environ Med 1994;65(9):815–23.
Oda S, Matsumoto T, Nakagawa K, Moriya K. Relaxation effects in humans of underwater exercise of moderate intensity. Eur J Appl Physiol Occup Physiol 1999;80(4):253–9.
Porter MM, Vandervoort AA, Kramer JF. Eccentric peak torque of the plantar and dorsiflexors is maintained in older women. J Gerontol A-Biol Sci Med Sci 1997;52(2):B125–31.
Pöyhönen T, Avela J. Effect of head-out water immersion on neuromuscular function of the plantarflexor muscles. Aviat Space Environ Med 2002;73(12):1215–8.
Pöyhönen T, Keskinen KL, Hautala A, Savolainen J, Mälkiä E. Human isometric force production and electromyogram activity of knee extensor muscles in water and on dry land. Eur J Appl Physiol Occup Physiol 1999;80(1):52–6.
Riley PO, Della Croce U, Kerrigan DC. Effect of age on lower extremity joint moment contributions to gait speed. Gait Posture 2001;14(3):264–70.
Sheldahl LM, Wann LS, Clifford PS, Tristani FE, Wolf LG, Kalbfleisch JH. Effect of central hypervolemia on cardiac performance during exercise. J Appl Physiol 1984;57(6):1662–7.
Shimizu T, Kosaka M, Fujishima K. Human thermoregulatory responses during prolonged walking in water at 25, 30 and 35 °C. Eur J Appl Physiol Occup Physiol 1998;78(6):473–8.
Thelen DG, Schultz AB, Alexander NB, Ashton-Miller JA. Effects of age on rapid ankle torque development. J Gerontol A-Biol Sci Med Sci 1996;51(5):M226–32.
Whitley JD, Schoene LL. Comparison of heart rate responses: water walking versus treadmill walking. Phys Ther 1987;67(10):1501–4.
Wilder RP, Brennan DK. Physiological responses to deep water running in athletes. Sports Med 1993;16(6):374–80.
Winegard KJ, Hicks AL, Sale DG, Vandervoort AA. A 12-year follow-up study of ankle muscle function in older adults. J Gerontol A-Biol Sci Med Sci 1996;51(3):B202–7.
Winter DA. Biomechanics and motor control of human movement. New York: John Wiley & Sons Inc; 1990, p. 11–102.
Winter DA, Patla AE, Frank JS, Walt SE. Biomechanical walking pattern changes in the fit and healthy elderly. Phys Ther 1990;70(6):340–7.

Kenji Masumoto, Ph.D. received his B.S. in Exercise Physiology at the National Institute of Fitness and Sports in Kanoya in 1999, his M.S. in Health Science at Kyushu University in 2001, and his Ph.D. in Medical Sciences at Kyushu University in 2005. His prior research addressed the biomechanical and physiological responses during exercise in water. Currently he is conducting research as a Japan Society for the Promotion of Science Research Fellowship for Young Scientists. At present his scientific activity is focused on neuromuscular and metabolic physiology and biomechanics of human movement.

Tomoki Shono, Ph.D. received his Ph.D. in Human Environmental Studies at Kyushu University in 2003. He is now an Associate Professor of Kyushu University of Health and Welfare, Miyazaki, Japan. His research interest includes exercise prescription regarding swimming and water exercises for a wide range of age groups (from young children to people of an advanced age).

Shin-ichiro Takasugi, M.D., Ph.D. received his M.D. in 1983 and his Ph.D. in 1989 at Kyushu University. He is now an Assistant Professor of the Department of Rehabilitation Medicine, Kyushu University Hospital, Fukuoka, Japan. He has been selected as a Fellow of the Japanese Orthopaedic Society for Sports Medicine. His current research interests include therapeutic modalities and therapeutic exercises.

Noboru Hotta, M.S. received his M.S. in Exercise Physiology at Juntendo University in 1981. He has been an Associate Professor of the Institute of Health Science at Kyushu University since 1990. His research has primarily been focusing on aging physiology, biochemical responses during exercise using both in vivo and in vitro experimental conditions, and exercise prescription for the elderly.

Kazutaka Fujishima, Ph.D. received his Ph.D. at the Medical Institute of Bioregulation, Kyushu University in 1986. He has been a Professor of the Institute of Health Science at Kyushu University since 1989, and currently serves as a Professor Emeritus of Kyushu University, Fukuoka, Japan. His primary research interests include environmental physiology and thermoregulation during exercise in water.

Yukihide Iwamoto, M.D., Ph.D. is a Professor and the Chairman of the Department of Orthopaedic Surgery, Graduate School of Medical Sciences, Kyushu University, Fukuoka, Japan. He has served as Director of the Japanese Orthopaedic Society for Sports Medicine, and has also served as Director of the Japanese Society for Clinical Biomechanics.