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Biomechanics of Human Locomotion in Water: An Electromyographic Analysis

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Abstract and Introduction

Abstract

Quantifying muscle activity during locomotion in water is an emerging area of research. This article discusses the methods for quantifying muscle activity and summarizes key research findings of muscle activity during locomotion in water. The article is focused on comparing muscle activity during locomotion in water and on dry land.

Introduction

Water locomotion has become a common mode of exercise for inclusion in rehabilitation programs as well as in general exercise programs. The decision to include water locomotion in an exercise or rehabilitation program is generally made to take advantage of some of the unique characteristics of water environment. For example, there are fluid forces acting on the body such as buoyancy and drag forces during immersion. The buoyancy force (upward) acts in the opposite direction to the force of gravity (downward), whereas the drag force acts in the opposite direction to the movement of an object (*e.g.,* limb movement) through the water. When walking in the water immersed to the xiphoid process level, the buoyancy force will reduce weight bearing by 71% compared with being on dry land.[13] Individuals who cannot tolerate the mechanical stress associated with exercise on dry land may be able to exercise in water and thus achieve physiological responses that could provide them with health benefits.[3] Because there is a drag force when exercising in water that acts in opposition to all movements in all directions, a person is exposed to new stresses. A rehabilitation program may be purposefully designed to take advantage of the drag force, or in contrast, the drag force may be a contraindicator against the use of water exercise.

Historically, research on water locomotion has focused on cardiorespiratory responses and perceived exertion levels.[3,8,19] More recently, there is a growing body of research on biomechanical parameters during water locomotion. For example, research has been conducted to quantify muscle activity[1,2,16-24] and to understand stride characteristics,[19] kinematics,[1,2,22,23] and kinetics[1,2,22] during water locomotion. Such biomechanical data in combination with the understanding of cardiorespiratory responses to water locomotion may help the practitioner to refine the use of water locomotion within an exercise program to maximize benefits.

Measurement of common biomechanical parameters during water locomotion is complicated because most instruments are not built to operate in a water environment. For example, quantifying muscle activity through electromyography (EMG) techniques during water locomotion is challenging because of the difficulty in preventing water from interfering with the recording of the electrical signal of a muscle and because of safety concerns regarding the immersion of electrical components in water (*e.g.,* electrocution). Overcoming these challenges is worthwhile because knowledge of muscle activity is critical to the understanding of neuromuscular responses to water locomotion. In a review of the literature, it seems that measuring muscle activity during water locomotion is an emerging area of research. The purpose of this review is to discuss the methodological considerations when quantifying muscle activity during water locomotion and to summarize the key research findings of muscle activity during water locomotion. The insights gained will help to provide some direction not only for further research but also for practitioners and exercisers who use water locomotion.

Methodological Considerations for Quantifying Muscle Activity During Water Locomotion

There are several methodological considerations to bear in mind when recording EMG signals during water locomotion. The primary methodological concern for measuring EMG in water is waterproofing the EMG leads. Two general approaches to measuring muscle activity using surface EMG during water locomotion have been the following: 1) to create a localized waterproof seal around the leads (*e.g.,* references 16-20) and 2) to create a whole-body waterproof system by having subjects wear a dry suit.[21]

To create a localized waterproof seal around the EMG leads, it is common to apply a layer of adhesive waterproof tape (*e.g.,* Tegaderm™, 3M, St. Paul, MN, United States) over the electrodes. The success of this approach is partly dependent on the size of the electrodes and the size of the cable to the electrodes. To increase the chance of success with this waterproofing technique, some researchers have used waterproof tape in combination with an outer covering of a commercially available foam pad (Foam Pad, 75A; Nihon Kohden, Tokyo, Japan; Figure 1).[16-20] Studies that have used this waterproofing technique have used silver-silver chloride surface electrodes (8 mm in diameter, Mini Ag/AgCl Skin Electrode, NT-511G; Nihon Kohden) placed on the muscle of interest, with a reference electrode being placed on the acromion. Each electrode pair was covered by a combination of adhesive waterproof tape and foam pad. This combination of waterproof material served to prevent water from contacting the skin-electrode interface. Taping was done in a manner that allowed unencumbered movement of the muscles tested during exercise. When using this technique, it is important to monitor the EMG signal for changes that might indicate water leakage. Therefore, before initiating the actual trials in water, a number of submaximal EMG recordings should be repeated to establish baseline EMG characteristics. During the trials, EMG profiles should be visually inspected for changes that may be indicative of water leakage, such as a band of high-frequency noise throughout the recorded signal.

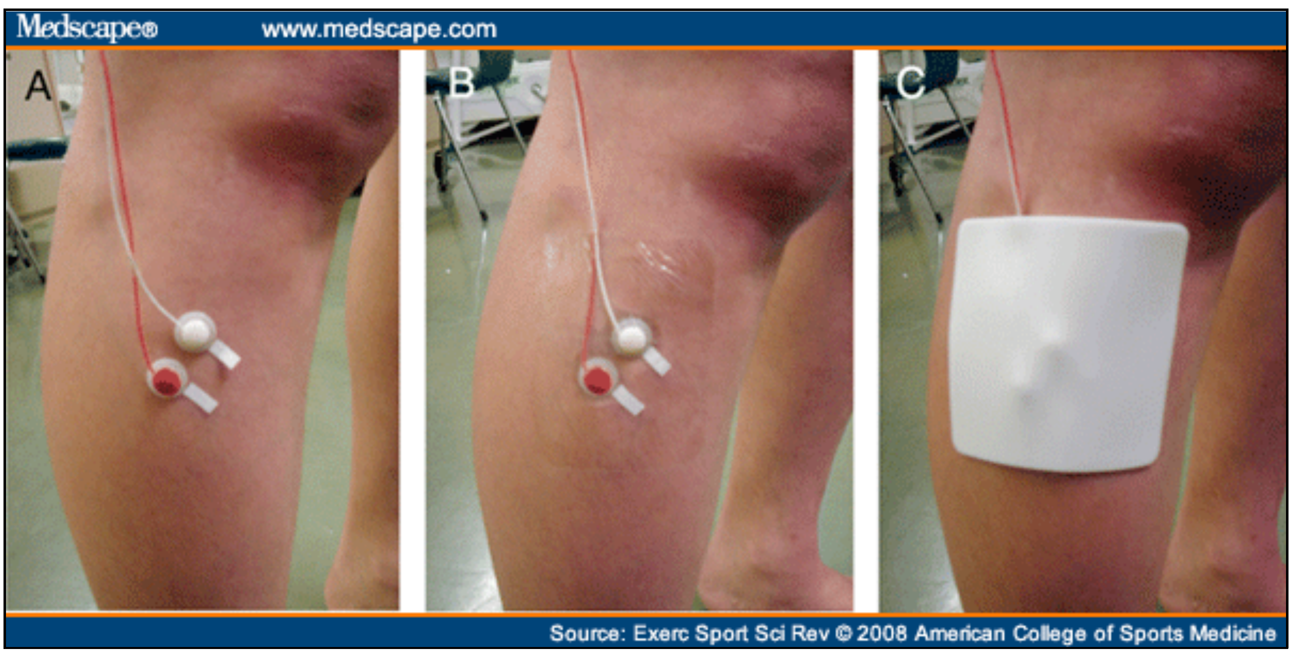

Figure 1. Waterproof dressings over each of the surface electromyography (EMG) electrodes: placed electrodes (A), covered with adhesive tape (B), and covered with foam pads (C).

One of the advantages of this waterproof technique is that only the area of interest is subject to waterproof sealing. However, there is a chance of slight irritation when removing the tape and foam pad, the subject setup time can be long, and it is always important to monitor the maintenance of each waterproof seal when multiple muscles are being measured.

To create a whole-body waterproof system, Mercer *et al.* [21] had subjects wear a dry suit. The dry suit consisted of waterproof material with the arm, leg, and neck openings tightly sealed. EMG leads were protected from the water because the body was kept dry (in contrast, a wet suit allows water inside the suit). The dry suit was designed to allow for full range of motion (ROM) during aquatic sports, such as waterskiing. To record muscle activity while using a dry suit, EMG instrumentation (Noraxon, Scottsdale, AZ, United States) followed the typical setup procedures. A subject would put on the dry suit after the leads had been placed, with the cable between the leads and the transmitting unit being run up through the neck seal. The transmitting unit should always be kept above the water.

The advantages of the dry suit technique include the fact that there is no additional setup time to waterproof the system and that it enables EMG data collection during prolonged exercise in water (*i.e.,* reduces the chance for the waterproofing to fail). The disadvantages of using the dry suit include the fact that the subject must be able to fit into the available dry suit size that a laboratory has and that the cable to the transmitting unit must run through the neck seal that creates a potential location through which water could enter. Furthermore, it is not actually known whether running movements are influenced by wearing the dry suit, although the suit was designed for dynamic activities.

Another primary concern when measuring EMG during water locomotion is the use of electronics during immersion in water. A solution to this problem is to use a telemetry versus tethered EMG system because a direct-current battery powers the transmitting unit of the telemetry system. Clarys *et al.* [4] investigated the validity of using a telemetry system during immersion exercise. In their study, muscle activity was recorded simultaneously using telemetry and tethered EMG instrumentation while subjects performed maximal voluntary contraction (MVC) in water and on dry land. It was observed that there was no difference in EMG between the two systems.[4] This led to the conclusion that muscle activity during immersion could be recorded using an EMG telemetry system.[4]

In our studies,[16-21] we have always used a telemetry system that has a transmitting unit powered by a battery (*e.g.,* 9-V battery). We have also kept the transmitting unit out of the water at all times. Furthermore, we have kept any electronic equipment powered by alternating current away from the subject. Although the risk of injury to the subject using a tethered EMG system is low, using the telemetry system further reduces the risk.

Another challenge with comparing EMG during walking in water and on dry land is the setting of exercise parameters. For example, when walking at the same speeds in water and on dry land, cardiorespiratory and perceptual responses will be higher during water locomotion compared with locomotion on dry land.[19] In addition, when walking at similar cardiorespiratory and perceptual responses in water and on dry land, walking speed will be lower in the water than on dry land.[8,19] In these cases, basic kinematic descriptors of gait (*e.g.,* stride frequency and stride length) will be different between the two different conditions.[19] Therefore, it is imperative to consider how the exercise parameters have been set when interpreting EMG observations.

EMG Analyses During MVC in Water

MVC is often used to normalize EMG data to enable the comparison of data between individuals on a relative basis (%MVC). Although this is a standard method for normalizing EMG during exercise on dry land, it is not clear whether EMG collected in water should be normalized to measurements on dry land because there seems to be differences in EMG during MVC in water and on dry land.[4,25,28] Specifically, EMG magnitude during MVC has been reported to be lower in water than on dry land.[4,25,28] However, it is presently not clear if the difference in EMG during MVC in water and on dry land is due to the methodological limitations for recording EMG in water (*e.g.,* ability to generate force in water) or due to the physiological changes that are a direct result of water immersion (*e.g.,* decreased maximal H-reflex amplitude due to reduced gravity condition).

Clarys *et al.* [4] reported that EMG was lower during MVC in water than on dry land. In their study, the main objective was to compare EMG between telemetry and tethered EMG systems during immersion and on dry land. The lower EMG during MVC was observed for both EMG systems.[4] Unfortunately, force output was not quantified, and it was not clear whether the lower EMG noted during immersion was due to a lower force output in water compared with the force output achieved on dry land. Pöyhönen *et al.* [25] measured muscle activity in water and on dry land while also measuring force output for maximal and submaximal contractions. In their study, muscle activity of the knee extensors (vastus medialis and vastus lateralis), and knee flexor (biceps femoris), was recorded during seated isometric knee extension exercises in water and on dry land. The experiment was repeated over 3 d to assess the reliability of the measurements. It was observed that muscle activity was 11%-17% lower for the vastus medialis and vastus lateralis and 17%-25% lower for the biceps femoris muscles in water than on dry land during both maximal and submaximal contractions.[25] The lower muscle activity in water compared with that on dry land was not because of force output because the isometric force measurements had similar values in both water and dry land conditions (*e.g.,* r^2 = 0.95;[25]). The intraclass correlation coefficients (ICC) and coefficients of variation (CV) of trial-to-trial (3 repetitions daily; ICC = 0.95-0.99; CV = 3.5%-11%) and day-to-day (best repetition daily; ICC = 0.85-0.98, CV = 11%-19%) reproducibility for measurements of force production and EMG during MVC in water and on dry land were high.[25] These observations led the authors to conclude that the measurements were reliable and that muscle activity was lower in water than on dry land for a similar force output.

To further explore possible explanations for the decreased muscle activity during MVC in water, Pöyhönen and Avela[28] assessed Hoffman and Achilles tendon reflexes and muscle activity of the soleus and medial gastrocnemius muscles. They had subjects perform an ankle plantar flexion MVC in water and on dry land with muscle activity recorded using surface and fine-wire EMG techniques concurrently, with force output assessed using a load cell. From this experiment, it was determined that force output decreased by approximately 13% during immersion, concurrent with an approximately 29%-35% decrease in EMG in each of the muscles studied.[28] It was also observed that the maximal H-reflex/M-wave ratio was decreased by 30% during immersion and that the EMG/force relationship was reduced during immersion.[28] Based on these observations, the authors concluded that water immersion impairs neuromuscular function and that the mechanism explaining the impairment was central and of reflex origin.[28] Specifically, the authors hypothesized that the contrived reduced gravity condition (*i.e.,* less weight-bearing force) and/or hydrostatic pressure was responsible for impairment of the neuromuscular system.[28] For example, the authors stated that immersion may lead to reduced stimulation on proprioception and may influence how vestibular system performs because immersion is similar to a reduced gravity condition.[28] Furthermore, the authors hypothesized that hydrostatic pressure could cause a decrease in leg volume, which could lead to a shift of interstitial fluid toward the upper body.[28] This change in leg volume may influence calcium ion concentration and that would influence muscle contraction and therefore influence the EMG/force relationship. Research is needed to further elucidate these hypotheses. In addition, research is needed to better understand the influence of immersion on force output because maximal force output was not different in water and on dry land for knee extension[25] but was different for plantar flexion exercise.[28] Furthermore, it has not been clearly established that the EMG/force ratio is negatively influenced during immersion. For example, during knee extension MVC, EMG was lower in water than on dry land, whereas force output was not different between the two conditions.[25] This suggests that the neuromuscular system achieved the same force output with less muscle activity. However, in the case of ankle plantar flexion exercise, both muscle activity and force output were lower in water than on dry land.[28] It is speculated that the influence of immersion is dependent upon the depth of immersion for exercising muscle. If this is the case, this would explain why the force output derived from muscles near the distal end of the lower extremity are more greatly influenced than proximally located muscles during immersion.

Based upon this review of the literature, it seems that EMG during MVC is lower when conducted in water compared with that on dry land. It is not clear at this time why EMG is lower in water, but it can be speculated that the differences in muscle activity are related to reflex and/or fluid changes caused by water immersion.

It is recommended that when research on EMG during water exercise is conducted with the intent of comparing it with EMG on dry land, a within-measures experimental design should be used. When a between-group design is required, based upon the information available to date we recommend that all EMG data should be normalized to on-land measurements because most studies reviewed (*e.g.,* references 16-20) have normalized the EMG recorded during immersion to the EMG recorded during MVC on dry land.

EMG Analyses During Human Locomotion in Water

Walking in Water and on Dry Land

Walking in Water and on Dry Land at Similar Cardiorespiratory and Perceptual Responses. Masumoto *et al.* [16-20] measured muscle activity during walking in water on an underwater treadmill (Figure 2), with subjects immersed to their xiphoid process level. The water temperature (31°C) and the air temperature (26°C) were maintained at a level considered to be thermoneutral for exercising humans. It has reported that approximately half the speed was required to walk at a similar level of energy expenditure in water, as compared with walking on dry land.[8] Therefore, the walking speed in water was set to be half the speed used on dry land (*e.g.,* 2.4 and 4.8 km·h^{-1} for water and dry land conditions, respectively;[16,17]) to induce similar cardiorespiratory responses during walking in water and on dry land. For each subject and each muscle tested, the average EMG was calculated for each gait cycle. The subjects performed a single MVC 5-s isometric contraction test on dry land for each of the tested muscles before the gait analysis. To calculate the %MVC, each of the average EMG obtained during gait was divided by the average EMG obtained during the MVC.

Figure 2. Side view of the flowmill (A), streaming water current (B), and underwater treadmill at the base of a water flume (C).

Muscle activity was lower during walking forward in water compared with walking forward on dry land in young (Figure 3)[16] and older[19] subjects at similar cardiorespiratory responses and perceptual levels. Furthermore, they observed decreased muscle activity from the lower extremity muscles during walking backward in water compared with walking backward on dry land.[17] In each of these experiments, the amount of muscle activity while walking in water was approximately 70% of that observed on dry land.[16,17,19] These observations suggest that a similar level of cardiorespiratory and perceptual responses may be obtained with decreased muscle activation during walking in water, as compared with walking on dry land.

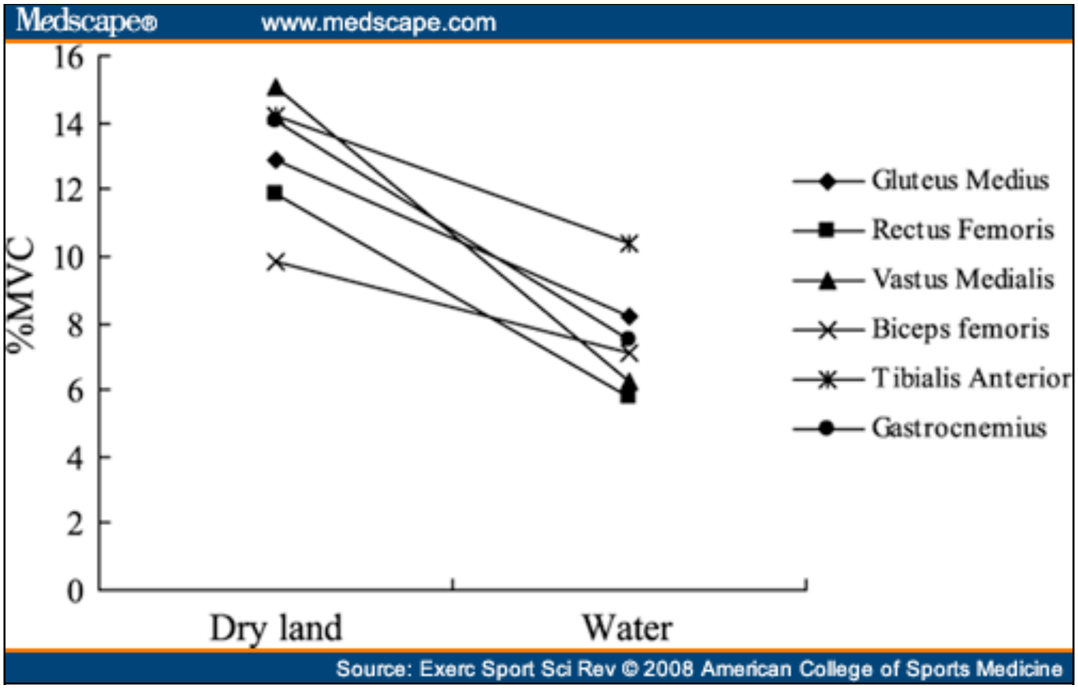

Figure 3. EMG (muscle activity) as a percentage of that obtained during maximal voluntary contraction (%MVC) while walking in water and on dry land. Dry land, walking on dry land (4.8 km·h-1); Water, walking in water (2.4 km·h-1). [Adapted from Masumoto, K., S. Takasugi, N. Hotta, K. Fujishima, and Y. Iwamoto. Electromyographic analysis of walking in water in healthy humans. J. Physiol. Anthropol. Appl. Human Sci. 23(4):119-127, 2004. Copyright © 2004 Japan Society of Physiological Anthropology. Used with permission.]

There are several explanations for the decreased muscle activity during walking in water than when walking on dry land. In the above studies,[16,17,19] subjects were free to walk with a reciprocal arm swing to maintain their proper walking position and balance in water. One explanation is that upper extremity movements may account for a greater proportion of the cardiorespiratory and perceptual responses during locomotion in water than on dry land. Therefore, when exercise intensity is matched to cardiorespiratory responses, the muscle activity from the lower extremities may not need to be as active.

Another explanation for the decreased muscle activity while walking in water compared with that on dry land is related to changes in gait characteristics. Masumoto *et al.* [19] have reported lower stride frequency (approximately 57% of that on dry land) and lower stride length while walking in water than while walking on dry land. The decreased stride frequency and stride length are primarily a result of the influence of the buoyancy and drag force present during water locomotion on limb movement. Additionally, some studies have observed a reduction in vertical ground reaction force while walking in water than when walking on dry land.[1,2,22] These biomechanical characteristics of locomotion in water correspond with the results of decreased muscle activity while walking in water. When the human body is immersed to the anatomical levels of C7, the xiphoid process or the anterior superior iliac spine, the percentage of weight bearing is 15%, 29%, and 43%, respectively.[13] The decreased muscle activity noted in water may be simply because the weight-bearing muscles do not work as hard because of the buoyancy force of water.

Another possible explanation for decreased muscle activity during water locomotion is the effect of reduced gravity and/or hydrostatic pressure on the neuromuscular system. Pöyhönen and Avela[28] reported decreased maximal H-reflex amplitude in water than on dry land. Furthermore, Dietz *et al.* [7] observed a close relationship between body weight and the magnitude of EMG after forward and backward displacements in water, although no significant correlation was observed on dry land. The authors hypothesized that the muscle activity in water may be mediated by reflexes that are activated by pressure receptors within the body.[7] These neurophysiological changes may possibly be related to the decreased muscle activity during locomotion in water.

Walking in Water and on Dry Land at Identical Speeds. Cardiorespiratory (*e.g.,* oxygen consumption and heart rate) and perceptual (*e.g.,* rating of perceived exertion) responses are higher in water than on dry land when locomotion speed is identical.[19] In an experiment[19] that required subjects to walk at identical speeds in water and on dry land (2.4 km·h^{-1}), the average muscle activity of the vastus medialis, rectus femoris, biceps femoris, and gastrocnemius in water was observed to be higher than that on dry land, whereas the muscle activity of the tibialis anterior was observed to be similar between the two conditions (Figure 4). The greater muscle activity during water locomotion is due to the need to produce an increased propulsive force to overcome the drag force while walking in water to achieve a specific speed. The authors also reported that stride frequency was lower (by 27.4 strides·min^{-1}) and that stride length was higher (by 0.15 m) in water than on dry land at the same speeds.[19] These observations suggest that muscle activity and cardiorespiratory and perceptual responses will all be higher when walking in water at the same speed as on dry land, whereas the movement pattern (*e.g.,* stride frequency) will be lower.

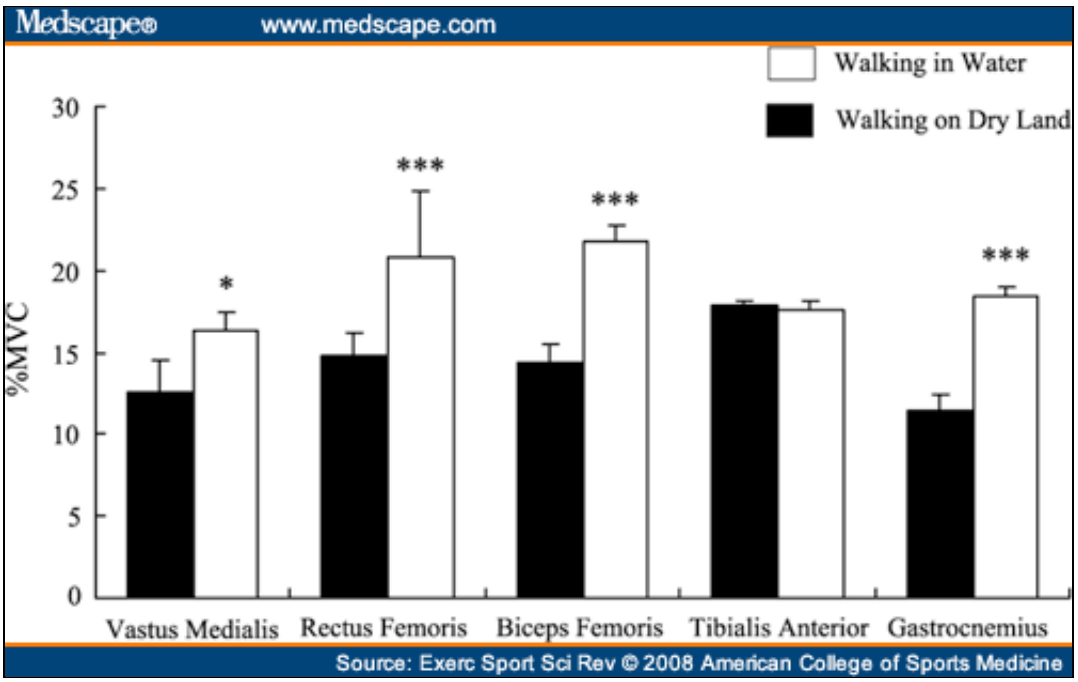

Figure 4. EMG (muscle activity) as a percentage of that obtained during maximal voluntary contraction (%MVC) in older adults while walking in water and on dry land at the same speeds (2.4 km·h-1). *P < 0.05, ***P < 0.001, walking in water versus walking on dry land. [Adapted from Masumoto, K., T. Shono, N. Hotta, and K. Fujishima. Muscle activation, cardiorespiratory response, and rating of perceived exertion in older subjects while walking in water and on dry land. J. Electromyogr. Kinesiol. (in press). Copyright © 2007 Elsevier Ltd. Used with permission.]

Walking in Water and on Dry Land at Subjects' Self-selected Speeds. Some research on muscle activity during walking in water and on dry land at subjects' self-selected speeds has been conducted.[1,2,22] In each of these studies, the subjects walked on a walkway on dry land and in water, immersed either to the xiphoid process level[1,2] or to a depth that resulted in body weight of 80% (axillae level; (22)). Muscle activity from the lower extremity and the trunk muscles has been recorded and analyzed.[1,2,22] The speed at which subjects chose to walk in water was always lower than that on dry land[1,2,22] (*e.g.,* 33.2 and 63.1 m·min^{-1}, for water and dry land conditions, respectively;[22]).

Two general approaches have been taken to compare muscle activity between these conditions: 1) compare peak and/or average EMG within a gait cycle and 2) compare EMG patterns. It was reported that the peak muscle activity (trunk muscles and lower extremity muscles) at self-selected walking speed was lower in water than on dry land in both young[1] and older[2] adults, although the gastrocnemius activity was similar between the two conditions. In examining average muscle activity within a gait cycle, it was reported that the biceps femoris activity while walking in water was higher than that while walking on dry land at self-selected speed.[22] The increased biceps femoris activity in water may be related to the increased propulsive force needed to overcome drag force in water.

The muscle activation pattern has been observed to be different during walking in water and on dry land.[1,2] For example, well-defined peaks of muscle activity (*e.g.,* phasic pattern) were observed while walking on dry land; however, a flatter muscle activation pattern (*e.g.,* tonic pattern) was observed while walking in water.[1,2] This may be due to the continuous muscle activation needed to resist the drag force while walking in water. However, given that the subjects' self-selected walking speed was lower in water than on dry land in those studies[1,2] (*e.g.,* 0.50 and 1.39 $m \cdot s^{-1}$, for water and dry land conditions, respectively;[1]), it is not clear if the changes in muscle activity patterns were due to the interaction of conditions (*e.g.,* water vs dry land) and walking speed.

Taken together, these results indicate that walking in water at subjects' self-selected speeds elicits lower peak muscle activity than when walking on dry land. However, walking in water may also produce higher average muscle activity and a flatter muscle activation pattern than when walking on dry land.

Walking Backward in Water

Walking Backward in Water and Walking Forward in Water. In most cases of water locomotion, movement is not only in a forward direction but also in various other directions. For example, backward locomotion has been used for rehabilitation after lower-extremity injuries and for injury prevention.[9,11] A reason for using backward locomotion in a rehabilitation program is that it reduces the peak patellofemoral joint compressive forces.[11] In addition, backward locomotion results in an increase in muscle activity from the rectus femoris and vastus medialis when compared with forward locomotion.[10] Furthermore, it has been reported that backward locomotion produced higher cardiopulmonary responses than forward locomotion at identical locomotion speeds (*e.g.,* an increase of 78% in oxygen consumption;[9]). Based on these observations on dry land, it seems that backward locomotion could be a beneficial adjunct to rehabilitation and exercise programs for patellofemoral pain syndrome and anterior cruciate ligament injuries and for maintaining cardiovascular conditioning.

Compared with walking forward in water, walking backward in water resulted in a significantly higher average muscle activation of the paraspinal muscles (an increase of 61%), vastus medialis (an increase of 83%), and tibialis anterior (an increase of 47%), although there was no significant difference in muscle activity of the rectus femoris, gluteus medius, biceps femoris, and gastrocnemius.[20] Increased muscle activity from the paraspinal muscles is likely due to the greater resistance of movement encountered by the upper body while walking backward in water. The increased vastus medialis activation is because this muscle is responsible for generating the force necessary for propulsion when walking backward in water. The increased tibialis anterior activation may be related to the difference in ankle joint movement during backward and forward locomotion. Based on these observations, walking backward in water may be a good choice of exercise in a rehabilitative or exercise program to facilitate paraspinal muscle, vastus medialis muscle, and tibialis anterior muscle activation.

Walking Backward in Water and Walking Backward on Dry Land. Recently, Masumoto *et al.* [17] investigated muscle activity during backward walking in water and on dry land. In this study, the walking speeds in water were set to be half of those on dry land (*e.g.,* 3.0 and 6.0 $km \cdot h^{-1}$ for water and dry land conditions, respectively). The speeds of a water current were set at the same speeds as the speeds of the underwater treadmill. In this study,[17] muscle activity from the trunk muscles and lower extremity was measured. Before commencing actual trials, the subjects performed MVC measurements for each of the muscles tested on dry land. EMG data were normalized to MVC on dry land

(%MVC). The authors reported that the paraspinal muscles were more active while walking backward in water with a water current than when walking backward on dry land or walking backward in water without a water current (*e.g.,* 19%MVC, 13%MVC, and 13%MVC for backward walking in water with a current, backward walking on dry land, and backward walking in water without a current, respectively). The increased paraspinal muscle activity is probably a reflection of the greater resistance of movement encountered in water with a current that was streaming against the subject's back.

Age-Related Difference in Muscle Activity During Walking in Water

Because water locomotion is used by individuals of a variety of ages, Masumoto *et al.* [18] investigated whether muscle activity during water locomotion was influenced by age. Older and young subjects walked in water while immersed to the xiphoid process level at the three speeds (1.8, 2.4, and 3.0 km·h^{-1}). Muscle activity was recorded from the following muscles on the right side: the vastus medialis, rectus femoris, biceps femoris, tibialis anterior, and gastrocnemius. Average EMG over a gait cycle for each of the muscles investigated was calculated and analyzed for each speed condition. It was observed that hip flexor/extensor (rectus femoris and biceps femoris) activity was approximately 56% higher, and ankle plantar flexor (gastrocnemius) activity was approximately 31% lower for older subjects (63.5 ± 3.5 yr) compared with younger subjects (22.0 ± 0.6 yr), although no significant difference was observed in vastus medialis and tibialis anterior activations (Figure 5;[18]). There is no evidence available that compares biomechanical parameters that occur during walking in water in older and young subjects. Therefore, the difference in muscle activation of older and young subjects while walking in water can only be discussed based on previously reported findings on dry land.

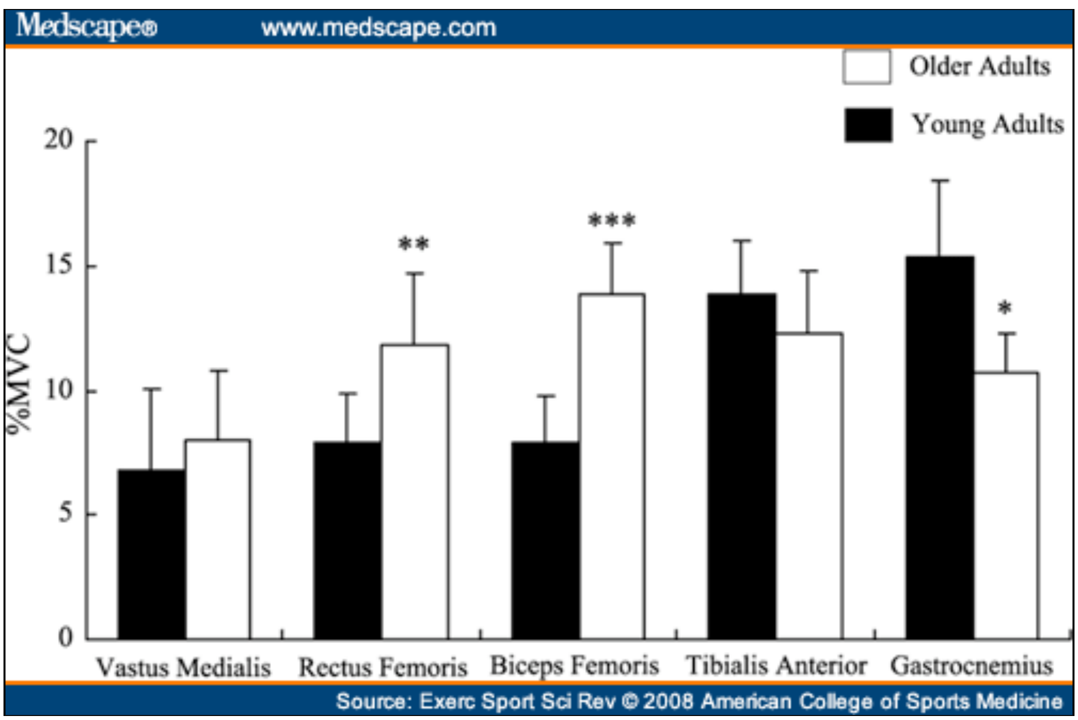

Figure 5. EMG (muscle activity) as a percentage of that obtained during maximal voluntary contraction (%MVC) in older adults and young adults during walking in water at 2.4 km·h-1. *P < 0.05, **P < 0.01, ***P < 0.001, older adults versus young adults. [Adapted from Masumoto, K., T. Shono, S. Takasugi, N. Hotta, K. Fujishima, and Y. Iwamoto. Age-related differences in muscle activity, stride frequency and heart rate response during walking in water. J. Electromyogr. Kinesiol. 17:596-604, 2007. Copyright © 2006 Elsevier Ltd. Used with permission.]

The increased hip musculature activity in older subjects compared with young subjects while walking in water is congruent with earlier observations of increased hip power in the older population during locomotion on dry land.[6,14] It has been reported that elderly subjects produced higher hip flexion power compared with young subjects during locomotion.[14] On the other hand, elderly subjects have been shown to produce increased hip extensor moment compared with young subjects during locomotion.[6] However, it is not clear if these mechanisms explain the results reported by Masumoto *et al.*.[18] Future studies are needed to better understand the reason for the increased hip musculature activity in older adults versus young adults while walking in water.

The decreased plantar flexor activity in older subjects compared with young subjects while walking in water is in accordance with previous findings of decreased plantar flexor work in an older population during locomotion on dry land.[6,14] It is speculated that the physiological (*e.g.,* decreased Type II fiber area;[5]) and biomechanical (*e.g.,* decreased plantar flexor power;[6,14]) deficits of plantar flexors that come with age actually cause older subjects to select a movement pattern that requires less gastrocnemius activation.

Effects of Walking Speed, Weight Loading, and a Water Current on Muscle Activity During Walking in Water

There are several studies that have investigated muscle activity during walking in water at different speeds.[22,23] In these studies, the subjects walked at self-selected speeds, immersed to their axillae level. Muscle activity was recorded from the lower extremity, such as the biceps femoris and gluteus maximus[23] and the medial gastrocnemius, tibialis anterior, biceps femoris, and rectus femoris.[22] Average EMG was calculated and analyzed for each speed condition.[22,23] It was observed that muscle activity from the biceps femoris increased with increasing walking speed in water, whereas the gluteus maximus increased only slightly.[23]

Miyoshi *et al.* [22] investigated how muscle activity changes across speed during walking in water compared with walking on dry land. In this study, the subjects walked at self-selected speeds on dry land and in water, immersed to the axillae level. It was observed that muscle activity from the medial gastrocnemius and biceps femoris increased with increasing walking speed in water.[22] Interestingly, biceps femoris activity did not increase significantly with increasing speed on dry land, although in contrast, medial gastrocnemius activity did increase with increasing speed.[22] Walking speed on dry land was approximately 77% (comfortable speed) and 140% (fast speed) faster than the slow speed.[22] On the other hand, the walking speed in water was approximately 30% (comfortable speed) and 123% (fast speed) faster than the slow speed.[22] These observations suggest that greater changes in selected muscle activity can be elicited with small changes in walking speed in water than can be elicited on dry land. This may be due to the exponential increase in drag force with an increase in movement speed during water locomotion (*e.g.,* drag force increases as velocity squared (v^2);[27]).

In addition to studying the influence of walking speed on muscle activity, Miyoshi *et al.* [24] also investigated the effects of weight loading and walking speed on ankle plantar flexor activity (soleus and medial gastrocnemius) during water locomotion. The subjects walked in water under three different load conditions (no load, and 4 and 8 kg) and four different speed conditions (self-determined comfortable, slow, fast, and fastest). Average EMG of the plantar flexors at the stance phase was calculated. The authors reported that the medial gastrocnemius activity was more dependent upon walking speed, whereas the soleus activity was dependent upon weight loading.[24] Because the medial gastrocnemius activity was closely related to walking speed, the authors hypothesized that the main role of the medial gastrocnemius is to produce a propulsive force while walking in water.[24] Additionally, the authors hypothesized that the closer relation of the soleus to the load magnitude during walking in water may be because the load-related somatosensory input has a greater effect on the soleus motor neuron than on the medial gastrocnemius motor neuron.[24]

Masumoto *et al.* [16,17] further evaluated the influence of a water current on muscle activity during walking in water. Subjects in this study walked on an underwater treadmill with and without a water current immersed to their xiphoid process level. The speeds of the water current were set at 1.8, 2.4, and 3.0 $km \cdot h^{-1}$. MVC measurement (5-s isometric contraction) was performed on dry land, before starting the gait analysis. Average EMG for each muscle was calculated and analyzed on a relative basis (%MVC). It was reported that the muscle activity from the trunk muscles and the lower extremity muscles that tended to be higher with a water current than without a water current during forward[16] and backward[17] walking in water (*e.g.,* 40% at 2.4 km·h^{-1} and 80% at 3.0 km·h^{-1}) increased over that observed at 1.8 km·h^{-1};[17]). The higher muscle activity during walking in water when there is a current than when there is no current may be related to the greater drag force to movement encountered in water.

Based on these observations, muscle activity can be increased by increasing walking speed or through the addition of a water current during walking in water. Furthermore, ankle plantar flexors (soleus and medial gastrocnemius) act in an independent manner (weight loading and walking speed) during walking in water.

Shoulder Exercises in Water

To the best of our knowledge, there is no study that has reported muscle activity of the upper extremity during water locomotion. However, Fujisawa *et al.* [12] and Kelly *et al.* [15] investigated muscle activity during shoulder exercises in water. Fujisawa *et al.* [12] evaluated upper extremity (*e.g.,* supraspinatus, infraspinatus, subscapularis, pectoralis, deltoid, and latissimus dorsi) muscle activity at specific shoulder joint positions while subjects were in water and on dry land. Muscle activity was recorded while subjects held their shoulder in nine different static positions consisting of different combinations of shoulder flexion and abduction. Muscle activity was recorded using both surface and indwelling leads while subjects held a position for 5 s. It was observed that muscle activity for all muscles during immersion was approximately 1%-20% that of muscle activity during dry land conditions. Given the static nature of the conditions, the large difference in muscle activity between immersion and on-land conditions was due to the buoyancy force of water.

Kelly *et al.* [15] investigated upper extremity (supraspinatus, infraspinatus, subscapularis, anterior deltoid, middle deltoid, and posterior deltoid) muscle activity during dynamic shoulder exercises during immersion and dry land conditions. In their experiment, subjects performed humeral abduction about the shoulder at controlled rates (30, 45, and 90 degrees·s^{-1}) while immersed in water (neck level) or on dry land. It was observed that muscle activity was lower during immersion versus dry land conditions at the slower movement speeds (*e.g.,* 30 and 45 degrees·s^{-1}). In contrast, muscle activity for five of the six muscles studied was not different between immersion and on dry land at the faster movement speed (*i.e.,* 90 degrees·s^{-1}). The authors suggested that the faster movement speed during immersion resulted in a balance between the buoyancy and resistive forces in such a way that muscle activity was matched to dry land levels.

Knee Exercises in Water

Water locomotion is one example of the variety of exercises that can be performed within water. In addition to water locomotion, water aerobics or aquatic exercises are very commonly included within an aquatic exercise program. Because water aerobics involves a variety of whole body movements, it is difficult to analyze muscle activity during a typical exercise routine. However, research has been undertaken on muscle activity during single joint movements such as knee extension-flexion exercise.[26,27]

Single and Repeated Knee Exercises in Water. To understand how muscles are activated during knee exercise while a person is immersed in water, Pöyhönen *et al.* [27] had subjects sit in a poolside patient elevator chair. The chair was lowered so that the subject was immersed to the midsternum level while muscle activity was recorded for the quadriceps (vastus medialis and vastus lateralis) and hamstring (biceps femoris and semitendinosus) muscles. Subjects completed three conditions: 1) single knee extension exercise, 2) single knee flexion exercise, and 3) repeated knee extension-flexion exercise. EMG data were averaged across 10° epochs during the ROM in order for the magnitude and temporal aspect of peak EMG to be determined.

It was observed that during the single knee exercises (*e.g.,* either extension or flexion), the agonist activity was high during precontraction and the initial phases of the movement, whereas the antagonist activity was dramatically quiet during the entire ROM. In contrast, during repeated knee extension-flexion exercise, the quadriceps and hamstrings had alternating activation patterns with the result that the quadriceps had peak muscle activity concurrent with low hamstring activity. Additionally, there were periods within the ROM when both muscles were active, indicating that there were distinct phases of eccentric muscle contraction when a muscle was functioning as an antagonist.

Based on these observations,[27] single knee extension or flexion exercises in water can be used to isolate muscle activity. Furthermore, when repeated extension-flexion exercises are performed in water, the amount of eccentric activation is greater than that during single extension or flexion exercises.

Knee Exercises on Dry Land and in Water While Wearing or Not Wearing a Resistive Device. There is a plethora of accessories that can be used during water exercise that are designed to provide flotation assistance or increased resistance to movement. Pöyhönen *et al.* [26] investigated the influence of wearing one such device (Hydro Boot) during knee extension-flexion exercises on muscle activity. In this study, subjects completed three knee extension-flexion conditions: 1) barefoot, 2) wearing a resistive device, and 3) isokinetic (dry land condition). During the barefoot and resistive device conditions, subjects were seated in a poolside patient chair that was lowered so that each subject was immersed to the midsternum level. All conditions were maximal effort; the speed of the isokinetic condition was set to 180 degrees$\cdot$s^{-1} (speed was not constrained during water conditions). Muscle activity was recorded for quadriceps (vastus medialis and vastus lateralis) and hamstring (biceps femoris) muscles. EMG data were reduced to yield the following: 1) peak EMG (determined as the greatest EMG observed during concentric phase) and 2) EMG_{90} (the peak EMG at 90 degrees of flexion). Velocity of movement was determined through video analysis.

It was observed that muscle activity patterns during knee extension-flexion exercise completed in the water were similar between the barefoot and wearing a resistive device conditions. It was also observed that, in general, when a muscle was acting as an agonist, it was active through approximately the first 50%-60% of the ROM. When a muscle was acting as an antagonist, muscle activity was apparent at about the last 50%-60% of the ROM. In contrast to the EMG pattern during the immersion conditions, during the isokinetic (dry land) condition, there was very little antagonistic muscle activity, whereas agonist activity was apparent throughout the entire ROM. Taken together, it seems that the muscle activity patterns during knee exercises in water are not consistent with isokinetic muscle activity patterns on dry land. In particular, there is a greater period of eccentric muscle contraction during water versus dry land exercise as evident by the greater antagonistic muscle activity. It is of interest to note that the exercises with a resistive device extended the duration of agonistic activity compared with that of the barefoot condition in both knee extension and flexion exercises in water. The magnitudes of EMG were generally similar between the water conditions. Although the drag force was greater while subjects wore the resistive device, the velocity of movement was lower than that used during the barefoot condition. Compared with the isokinetic (dry land) condition, hamstring maximal EMG was greater during the resistive water condition but similar to the barefoot condition. The quadriceps maximal EMG was similar between isokinetic and each of the water conditions. The EMG_{90} was greater during isokinetic versus each of the water conditions for each muscle. Comparing EMG during the water and dry land conditions is complicated by the differences in angular velocities between the conditions. The angular velocity of the isokinetic condition was set at 180 degrees$\cdot$s^{-1}, whereas the angular velocities achieved during the water conditions ranged from 168 degrees$\cdot$s^{-1} (angular velocity during flexion, resistive device worn, female subjects) to 360 degrees$\cdot$s^{-1} (angular velocity during knee extension, barefoot, male subjects). The authors conjectured that the observation of similar EMG magnitudes achieved at different velocities was due primarily to the force-velocity relationship of muscle contraction. A similar experiment conducted at the same angular velocity could result in different findings. Further clarification regarding this point would be a noteworthy assignment.

Summary and Conclusions

In this article, we have discussed methodological approaches used to quantify muscle activity during locomotion in water, and we have presented factors that influence muscle activity during water locomotion and discussed how the magnitude and patterns compare with observations made during locomotion on dry land. Based on the literature reviewed, it seems that, in general, muscle activity during human locomotion in water is influenced by the direction of walking, walking speed, and the existence of a water current. It also seems that muscle activity during water locomotion was different for younger and older individuals. Furthermore, in general, muscle activity tends to be lower in the water versus on dry land during MVC and when locomotion speed is self-selected. Further research is needed to understand why muscle activity is lower in water versus on dry land during MVC and how the pattern of muscle activity compares during locomotion in water and on dry land. Insights from these areas of research may help us gain a better understanding of the important biomechanical aspects of water locomotion that are important for an exercise and/or rehabilitation program.

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