

Determining if muscle activity is related to preferred stride frequency during running in the water and on land

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Received: 12 January 2015 / Accepted: 1 August 2015 / Published online: 9 August 2015
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Abstract

Purpose To determine if muscle activity is related to preferred stride frequency (PSF) during deep water running (DWR) and treadmill running on dry land (TMR).

Methods Subjects ($n = 11$; 26.2 ± 4.4 years) completed TMR and DWR at their mode-specific preferred stride frequency (PSF_{mode}). They also ran at stride frequencies which were lower and higher than the PSF_{mode} (i.e., $PSF_{mode} \pm 5$, 10, and 15 %). Muscle activity from the rectus femoris (RF), biceps femoris (BF), tibialis anterior (TA), and gastrocnemius (GL), SF, and rating of perceived exertion (RPE) were measured.

Results The PSF_{mode} during DWR was significantly lower than that of TMR (i.e., 49.9 ± 11.0 versus 81.9 ± 4.8 strides/min, $P < 0.0001$). Additionally, muscle activity from the RF, TA, and GL during DWR was significantly lower than during TMR at respective PSF_{mode} (~83.6 % decrease, $P < 0.0001$). However, RPE while running at the PSF_{mode} during DWR and TMR was similar. During DWR, the RF, TA, and GL muscle activity was not different between PSF_{mode} and any other SF conditions ($P > 0.0005$). During TMR, there was no significant difference in the RF and GL muscle activity between PSF_{mode} and any other SF conditions during TMR ($P > 0.0005$).

Conclusions During DWR, subjects selected a lower PSF than during TMR even though RPE was the same. It was also determined that the relationship between muscle activity and changes in SF relative to the PSF_{mode} was unique during DWR and TMR.

Keywords Preferred stride frequency · Gait · Immersion · Electromyography

Abbreviations

BF	Biceps femoris
DWR	Deep water running
EMG	Electromyography
GL	Gastrocnemius lateralis
PSF	Preferred stride frequency
RF	Rectus femoris
RPE	Rating of perceived exertion
SF	Stride frequency
TA	Tibialis anterior
TMR	Treadmill running on dry land

Introduction

Deep water running (DWR) is a mode of exercise in which the person is suspended in the water, not being able to touch the bottom of the pool (Fig. 1). This mode of exercise can be used in rehabilitation programs for runners with overuse injuries as well as a way to supplement mileage in run training programs for healthy runners. Although there has been research on physiological (e.g., Brown et al. 1997; Frangolias and Rhodes 1995; Frangolias et al. 1996; Masumoto et al. 2009, 2014; Mercer and Jensen 1998; Phillips et al. 2008) and biomechanical (e.g., Killgore et al. 2006; Masumoto et al. 2009, 2013a, 2014; Mercer et al. 2005b,

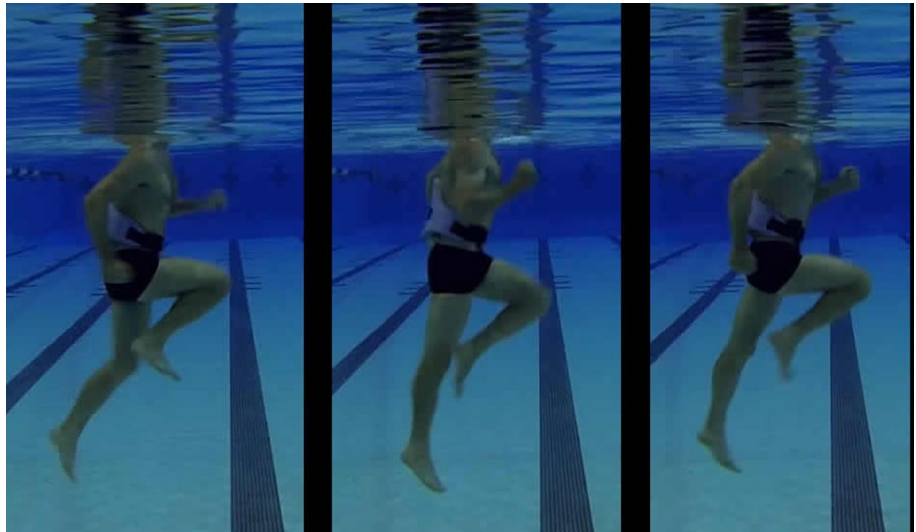
Communicated by Toshio Moritani.

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Fig. 1 A picture of an individual who is performing deep water running



2014) parameters during DWR, there are still questions about how to best prescribe the use of this mode of exercise and which features during DWR are similar to running on land.

When a person runs, either on land or in the water, he/she will select a preferred stride frequency (PSF). During DWR, the PSF is much lower than that the PSF selected during treadmill running (TMR) on dry land when using the same rating of perceived exertion (RPE) (Masumoto et al. 2009) or heart rate (Masumoto et al. 2014). For that reason, we refer to PSF as being ‘mode-specific’.

It makes sense that PSF during DWR would be lower than during TMR because the drag force that opposes the direction of limb movement and the buoyancy force provides an upward directed force on the individual (di Prampero 1986). It may be that the lower PSF during DWR is explained by lower extremity muscle activity to overcome the drag force.

Although there are some data on muscle activity during DWR when using the same stride frequency (SF) as used during TMR (Masumoto et al. 2013a), it is not clear if the muscle activity is optimized when running at the mode-specific PSF, since there are no published data comparing what happens when SF is intentionally manipulated around the mode-specific PSF. In this context, muscle activity would be considered to be optimized at if it were either maximized or minimized compared to using SFs other than PSF. The importance of this type of work is to gain a better understanding of the similarities and differences of DWR and TMR to best use DWR as a cross-training stimulus for on land running.

Therefore, the primary purpose of this study was to determine if muscle activity is related to PSF during DWR and TMR. To accomplish that purpose, we set out to understand the relationship between muscle activity and changes

in SF relative to the PSF selected during DWR and TMR (i.e., mode-specific PSF). We hypothesized that muscle activity is minimized while running at PSF regardless of environment (i.e., water, dry land) compared to muscle activity while using other SFs.

Methods

Subjects

Eleven subjects (6 males and 5 females: mean \pm standard deviation: age = 26.2 ± 4.4 years, height = 174.0 ± 6.5 cm, body mass = 73.0 ± 9.8 kg) participated in this study. Subjects were recreational runners. Their typical running mileage, running training duration, running training frequency, and DWR experience were 24.6 ± 19.1 km/week, 37.3 ± 13.3 min/session, 4.3 ± 1.5 sessions/week, and 0.8 ± 2.1 years, respectively. The study was approved by the University Ethics Committee. All subjects gave their written informed consent to participate.

Instrumentation

Muscle activity was recorded at the sampling rate of 1500 Hz using a telemetry electromyography (EMG) system (TeleMyo 2400T, G2, Noraxon, USA) concurrently with recording right-side knee angle using an electrogoniometer. Single-use surface electrodes with wet gel and Ag/AgCl sensor material (Ambu[®] BlueSensor N, Ambu Inc., Glen Burnie, MD, USA) were used in pairs placed over the middle point of the muscle belly longitudinally along the muscle fibers. Sensor area of 15 mm^2 with AC impedance of 600Ω with a DC offset of 0.2 mV. The customized 1.5 m cables for each EMG lead and electrogoniometer

were connected to a telemetry transmitting unit so that the transmitting unit was held above water level for all DWR conditions.

EMG data were obtained from the following muscles on the right side using dual electrodes (Dual electrodes—272, Noraxon): the rectus femoris (RF), the long head of the biceps femoris (BF), tibialis anterior (TA), and the gastrocnemius lateralis (GL) (Masumoto et al. 2009, 2013a, 2014). The sites for electrode placement were prepared by shaving the hair and abrading the skin using a skin preparation gel (Skinpure, YZ—0019, Nihon Kohden, Japan). Then, these electrode placement sites were cleaned with alcohol pads (Suzuran, Japan). The electrodes were placed over the middle point of the muscle belly longitudinally along the muscle fibers (Hermens et al. 2000) with a ground placed in combination with the RF lead as per manufacturer design. Additionally, waterproof dressings (Foam Pad, 75A, Nihon Kohden, Japan) were placed over all of the electrodes and ground leads (Masumoto et al. 2009, 2013a, 2014; Masumoto and Mercer 2008). Furthermore, subjects wore a full-body dry suit (BARE Watersports, Ultra Dry, Medium) during DWR tests (Masumoto et al. 2009, 2013a, 2014; Masumoto and Mercer 2008; Mercer et al. 2005b, 2014), to prevent water leakage. The dry suit was not worn during TMR conditions. EMG data were recorded for 30 s for each exercise bout. In addition, SF was determined by measuring the time to complete 20 strides at each condition. Furthermore, the rating of perceived exertion (RPE) was measured at the end of each exercise bout using Borg's 6–20 scale (Borg 1982).

Experimental procedures

Upon reporting to the laboratory and after giving written informed consent, subject demographics were recorded. Then, the subjects performed a self-directed warm up, such as walking and/or running on a treadmill on dry land.

Before commencing actual running tests, the subject's PSF was obtained during TMR and DWR. PSF was defined as the SF during TMR and DWR when a subject is directed to run at a comfortable pace to complete a 30-min exercise (Liebenberg et al. 2011; Masumoto et al. 2013a; Mercer et al. 2014).

To obtain the PSF during TMR, each subject was asked to run on a treadmill on dry land (C966, Precor, Woodinville, WA, USA) and to direct the investigator to increase or decrease the running speed until their most comfortable speed was obtained. The subjects were not allowed to see the actual running speeds when obtaining the PSF during TMR. The speed selected was recorded and used for subsequent TMR conditions.

To obtain the PSF during DWR, each subject was asked to run in a swimming pool and to increase or decrease the SF in water until their most comfortable pace was obtained. During DWR, a competition swim pool was used that had varying depth. The subject was never able to touch the bottom of the pool and water level was at neck level. During both DWR and TMR, PSF was determined by measuring the time to complete 20 strides. This procedure was repeated three times while measuring the subject's preferred running speed and PSF for the TMR condition and while measuring the PSF for the DWR condition. The three PSF values for each of the TMR and DWR conditions were averaged. The average PSF value for each subject was used for each of the actual baseline PSF conditions during TMR (i.e., TMR at PSF condition) and DWR (i.e., DWR at PSF condition).

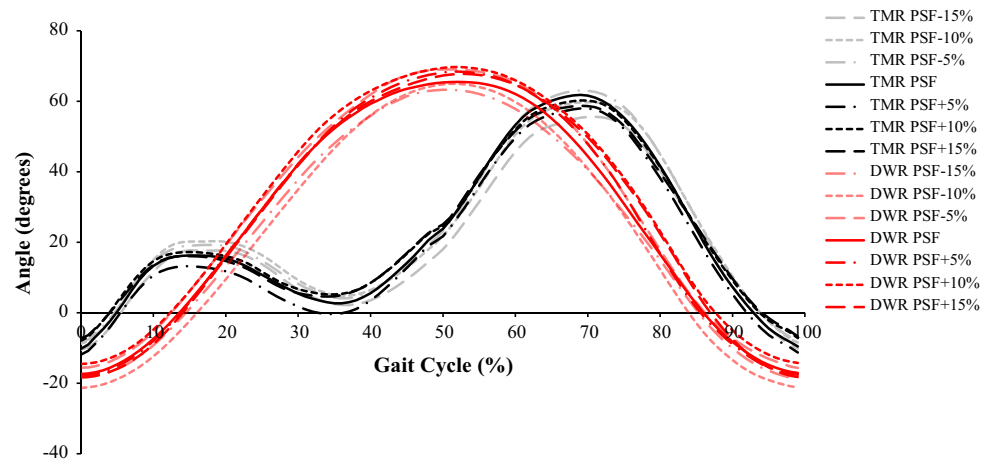
Following the PSF measurements on dry land and in water, the measurement of maximal voluntary isometric contraction of each muscle of interest was conducted on dry land (Masumoto and Mercer 2008). The duration of the maximal voluntary isometric contraction test was set at 5 s for each tested muscle. The subjects performed a single maximal voluntary isometric contraction test for each of the tested muscle. The subjects were asked to produce the maximal force output before each maximal voluntary isometric contraction measurement with a research team member providing resistance to maintain the isometric contraction.

Subjects then completed actual running trials. The SF conditions consisted of running at prescribed SF during TMR and DWR which were set based upon the mode-specific PSF. The SF conditions consisted of both DWR and TMR at PSF – 5, PSF – 10, PSF – 15, PSF, PSF + 5, PSF + 10, and PSF + 15 %.

A digital audio metronome was used to control each SF condition. Running speed during TMR was set to the self-selected speed used when determining PSF (11.4 ± 2.0 km/h). Actual data collection was commenced after ensuring that the subjects could maintain the targeted SF condition.

During DWR and TMR tests, the water temperature and room temperature were 28 and 26 °C, respectively. The subjects were immersed to their shoulder level during DWR with the flotation device (Aqua Jogger, Excel Sport Science, USA). During DWR conditions, the subjects were instructed to use high-knee DWR style which is similar to stair stepping or marching in place and were asked to maintain upright posture in a 25-yard swimming pool, where no foot contact with the bottom of the pool can be made. The subjects did not wear any shoes during DWR; however, they ran in their own running shoes for all TMR conditions.

Fig. 2 Knee angle data during treadmill running on dry land (a) and deep water running (b). PSF, preferred stride frequency



Data reduction

EMG data were normalized to the greatest 1-s average EMG during maximal voluntary isometric contraction. Knee angle was used to identify 10 stride patterns by selecting times of maximum knee extension defining a stride. Average EMG and root mean square were calculated for each muscle across the 10 strides after removing any zero offset and full-wave rectifying the signal. To describe the muscle activity patterns, EMG data were further processed by using a fourth-order, Butterworth, zero-phase lag low pass filter (cutoff frequency = 4 Hz) to smooth the data set. To create ensemble muscle activity patterns per condition, 11 consecutive maximum knee extension discrete events were identified (Fig. 2). EMG data were extracted between the consecutive maximum knee extension occurrences to yield data for 10 consecutive strides with stride time normalized to 100 %.

Statistical analyses

For all data, the assumption of normal distribution was checked using a Kolmogorov–Smirnov test. All dependent variables (Average EMG and root mean square of each muscle, RPE, and SF) were analyzed using a 2 (mode) \times 7 (SF) repeated measures analysis of variance ($\alpha = 0.05$). SF was considered a dependent variable to establish that the SF conditions were different from each other. Where Mauchly's tests indicated a violation of assumed sphericity, the Greenhouse–Geisser corrected test estimates were reported. Partial eta squared (η^2) was reported. When an interaction effect was identified, Bonferroni corrected post hoc tests were used to detect differences between conditions (i.e., simple main effect: $\alpha = 0.0005$). Furthermore, muscle activity patterns during DWR and TMR at each SF conditions were qualitatively described (Fig. 6).

Results

SF and RPE during DWR and TMR in each condition are presented in Fig. 3. SF ($P < 0.001$, partial $\eta^2 = 0.555$) and RPE ($P < 0.001$, partial $\eta^2 = 0.633$) were each influenced by the interaction of mode and SF condition.

SF during DWR was significantly lower than that of TMR at each %PSF condition (e.g., 81.9 ± 4.8 strides/min versus 49.9 ± 11.0 strides/min for TMR and DWR at mode-specific PSF, respectively, $P < 0.0001$). RPE, however, was not different during DWR and TMR when running at PSF (i.e., 12.2 ± 1.5 versus 11.3 ± 2.0 for TMR and DWR at mode-specific PSF, respectively, $P > 0.0005$) or when using PSF + 5, PSF + 10, or PSF + 15 % ($P > 0.0005$). RPE was lower during DWR versus TMR during PSF-15 and PSF-10 % ($P < 0.0001$). Interestingly, RPE was not different across SF conditions during TMR ($P > 0.0005$), but did increase across slow to fast SF during DWR ($P < 0.0001$).

Muscle activity during DWR and TMR in each condition is presented in Fig. 4 (Average EMG) and Fig. 5 (root mean square). Average EMG from the RF, TA, and GL (RF, $P < 0.05$, partial $\eta^2 = 0.278$; TA, $P < 0.001$, partial $\eta^2 = 0.570$; GL, $P < 0.05$, partial $\eta^2 = 0.301$) and root mean square from the RF, TA, and GL (RF, $P < 0.01$, partial $\eta^2 = 0.458$; TA, $P < 0.001$, partial $\eta^2 = 0.696$; GL, $P < 0.01$, partial $\eta^2 = 0.378$) were influenced by the interaction of mode and SF condition.

Using planned comparisons, our first focus was comparing muscle activity during DWR and TMR at the mode-specific PSF. It was determined that RF, TA, and GL were less active during DWR than TMR while running at the mode-specific PSF (i.e., 65.1–83.6 % decreases in average EMG and root mean square, $P < 0.0001$).

Our next focus was on comparing muscle activity within DWR or TMR during the mode-specific PSF to each of the SF conditions per mode. For example, muscle

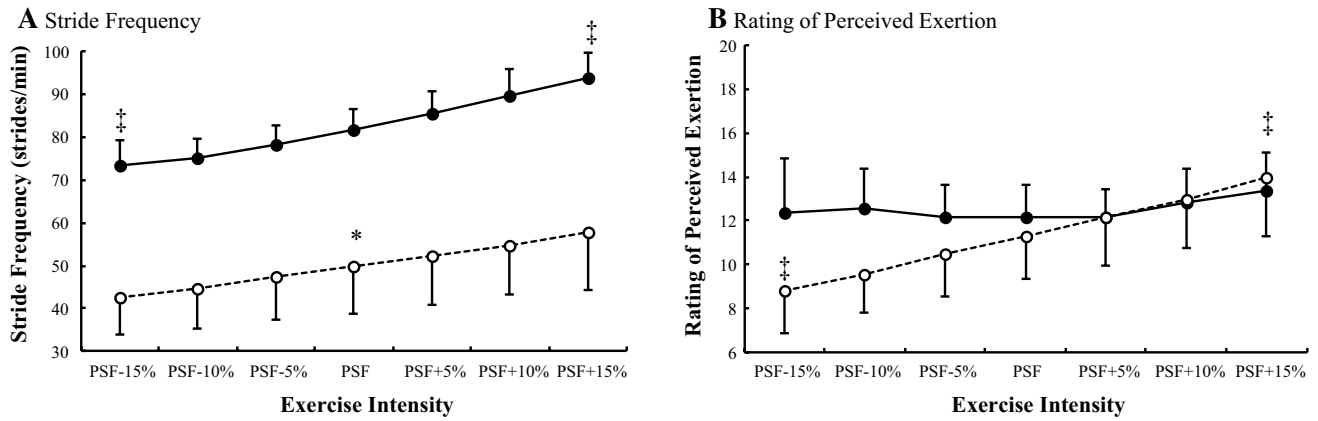


Fig. 3 Stride frequency (a) and rating of perceived exertion (b) during deep water running (DWR dashed line; open symbols) and treadmill running on dry land (TMR solid line; closed symbols). PSF, preferred stride frequency. Data are presented as mean ± standard

deviation. * $P < 0.0005$, Significant difference between deep water running and treadmill running on dry land at the PSF. ‡ $P < 0.0005$, Significant difference between PSF and each of the stride frequency conditions

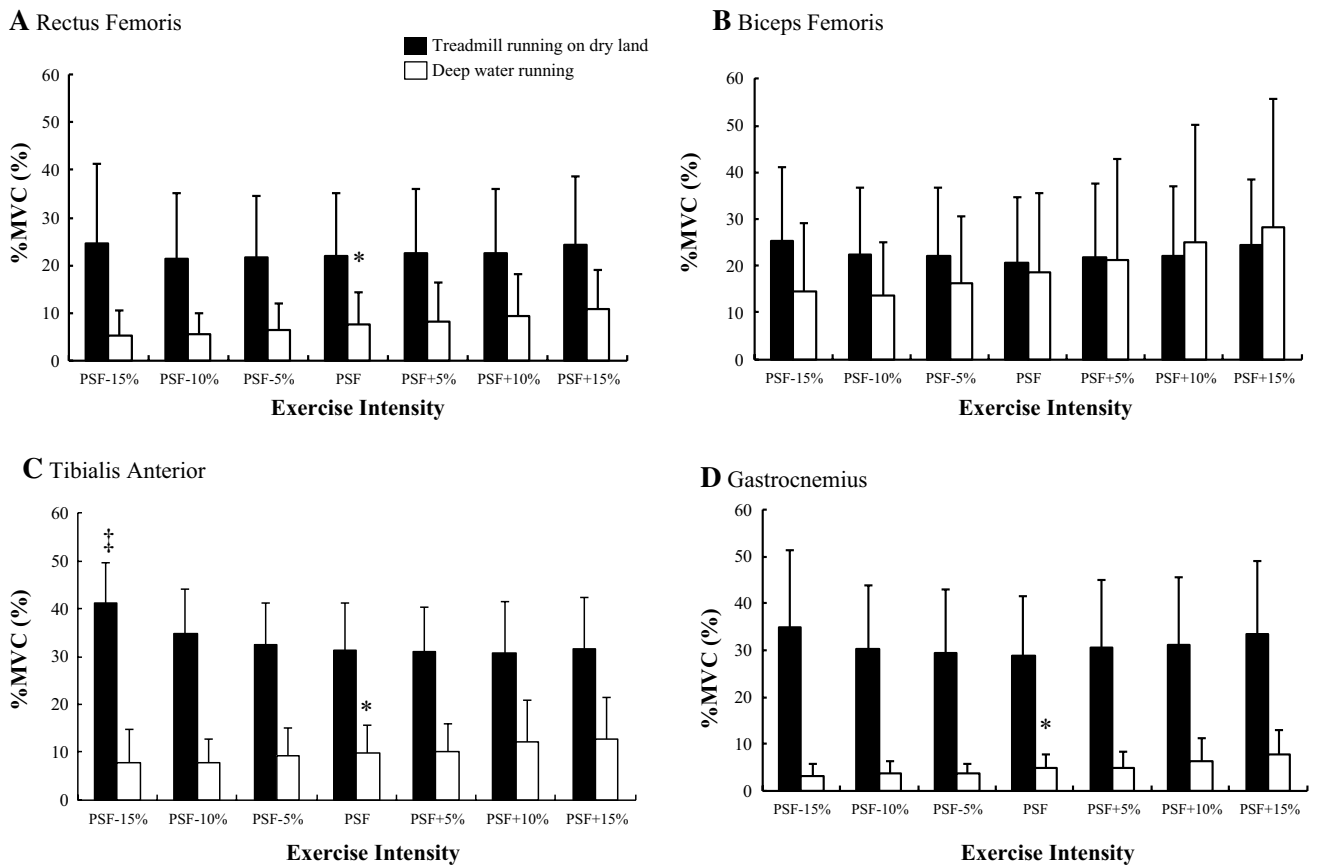


Fig. 4 Average muscle activity as a percentage of that observed during maximal voluntary contraction (%MVC) from the rectus femoris (a), biceps femoris (b), tibialis anterior (c), and gastrocnemius (d) during deep water running (DWR white bars) and treadmill running on dry land (TMR black bars). PSF preferred stride frequency. Data

are presented as mean ± standard deviation. * $P < 0.0005$, Significant difference between deep water running and treadmill running on dry land at the PSF. ‡ $P < 0.0005$, Significant difference between PSF and each of the stride frequency conditions

activity during DWR during mode-specific PSF vs. mode-specific PSF + 5 %, mode-specific PSF vs. mode-specific PSF + 10 %, etc. Using those planned comparisons, it was

determined that muscle activity was largely unaffected by the SF manipulations around PSF (Figs. 4, 5) other than some comparisons between PSF and extreme conditions.

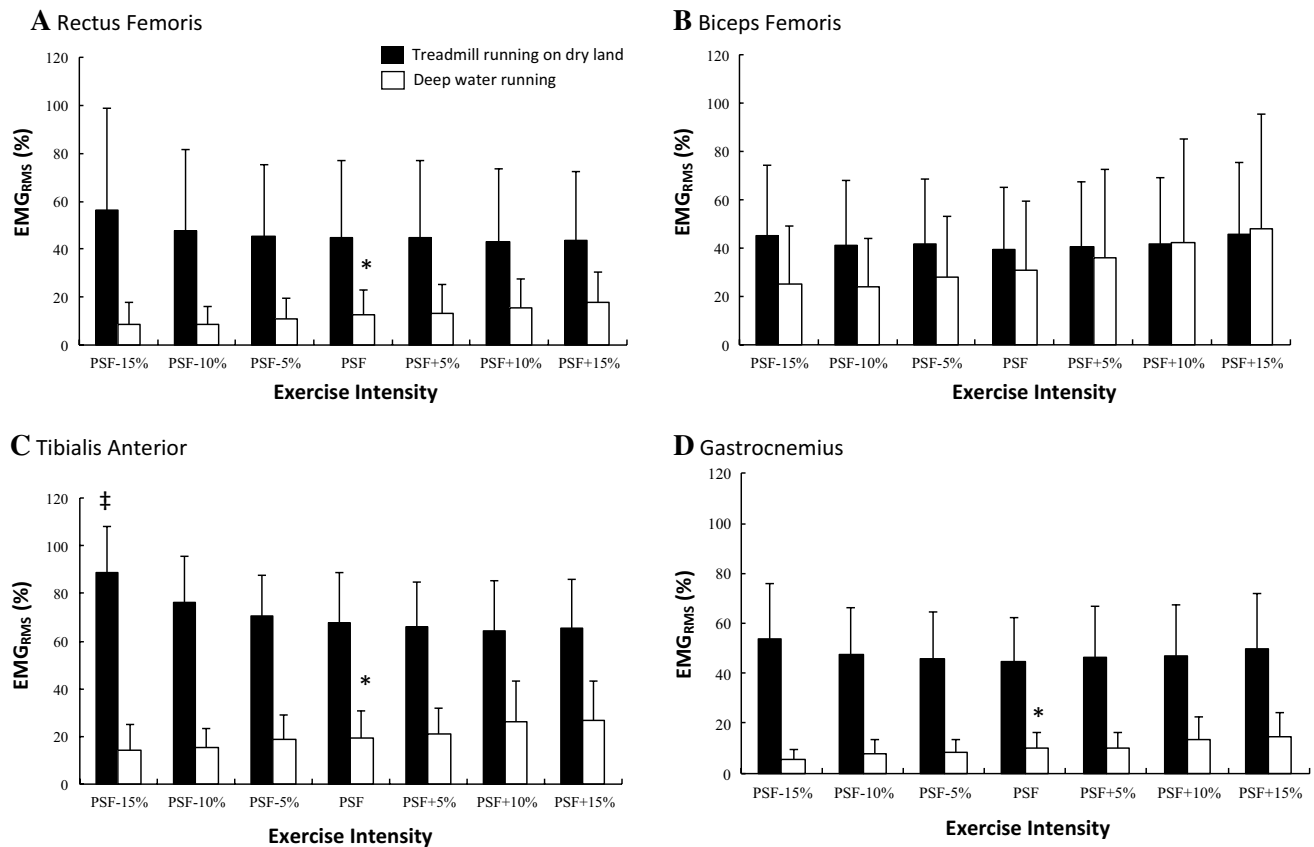


Fig. 5 Root mean square [EMG_{RMS} (%)] from the rectus femoris (a), biceps femoris (b), tibialis anterior (c), and gastrocnemius (d) during deep water running (DWR white bars) and treadmill running on dry land (TMR black bars). PSF preferred stride frequency. Data are pre-

sented as mean \pm standard deviation. * $P < 0.0005$, Significant difference between deep water running and treadmill running on dry land at the PSF. † $P < 0.0005$, Significant difference between PSF and each of the stride frequency conditions

Discussion

The main observations from this experiment were that the relationship between RF, TA, and GL muscle activity and changes in SF largely had little influence on average muscle activity during either DWR or TMR. However, there were some unique changes in muscle activity during extreme SF conditions within each mode. Nevertheless, it does not appear that muscle activity was maximized or minimized at the mode-specific PSF during DWR or TMR. In contrast, BF muscle activity was comparable between modes of exercise. It was also interesting to observe that SF manipulations did not influence RPE during TMR, but did influence RPE during DWR.

There is a paucity of data on the influence of SF on muscle activity relative to the mode-specific PSF during DWR. In previous work, participants exercised at the same RPE during DWR and TMR (Masumoto et al. 2009) which subsequently yielded different SF used during each mode of exercise. In that experiment, participants exercised at RPE levels of 11, 13, and 15 during DWR and TMR. Since

the intensity of DWR can be manipulated by changing SF and/or range of motion, the resulting SF during DWR increased across RPE levels (35.4, 45.5, and 51.7 strides/min). Interestingly, RF and BF muscle activity increased with increases in RPE levels (but TA and GL did not)—which is in contrast to what was observed in the present study. The main difference between the two studies is that Masumoto et al. (2009) had participants exercise while tethered in place whereas in the present study participants were allowed to move forward (untethered). It may be that the mechanics of movement to achieve higher intensities during tethered DWR (or change SF) may explain the difference in response compared to freely moving DWR. It would be beneficial if future studies evaluated the effect of SF on kinematic variables during tethered versus non-tethered DWR.

Previously, Masumoto et al. (2014) compared muscle activity during DWR and TMR when exercising at the same heart rate. To obtain the same heart rate levels during DWR vs. TMR, participants used SF ranging from about 55 strides/min to 70 strides/min during DWR but around 80 strides/

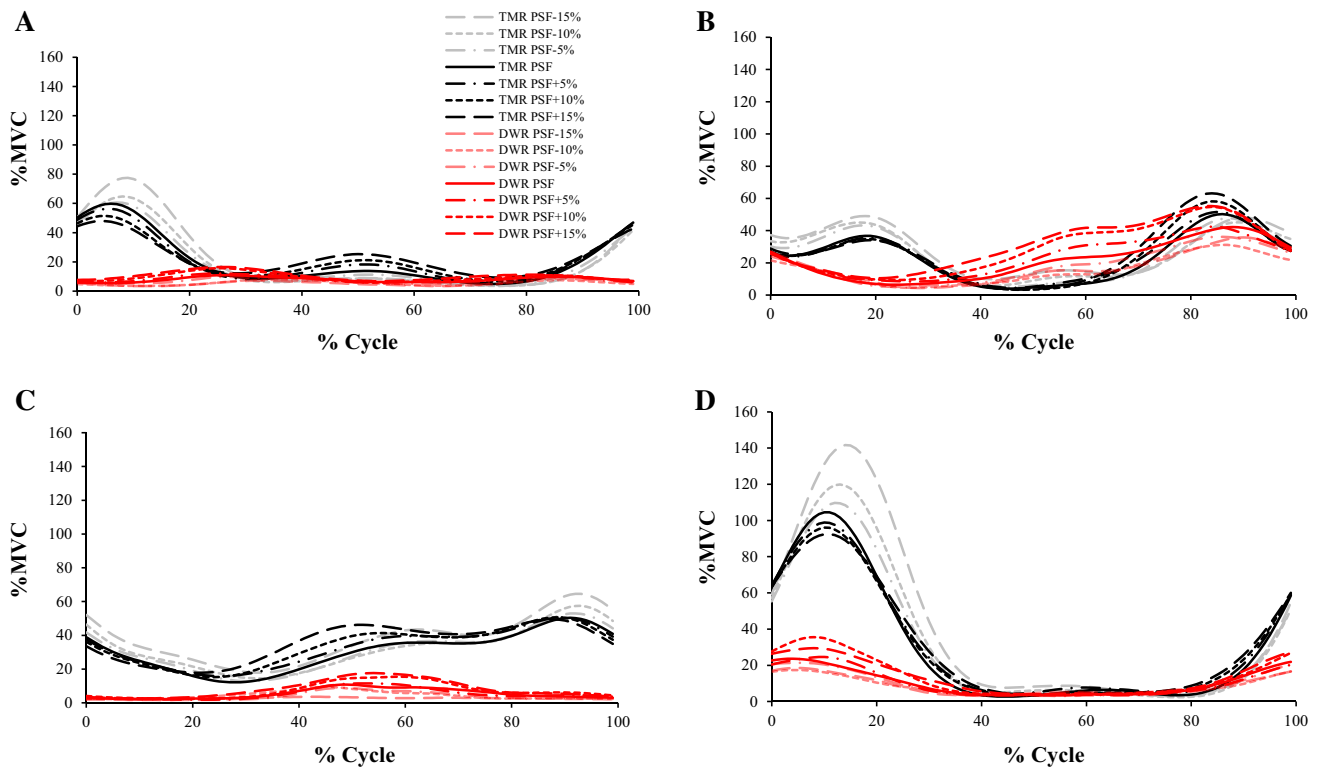


Fig. 6 Average muscle activity patterns from the rectus femoris (a), biceps femoris (b), tibialis anterior (c), and gastrocnemius (d) during deep water running (DWR) and treadmill running on dry land (TMR).

%MVC, average muscle activity as a percentage of that observed during maximal voluntary contraction

min to 83 strides/min (regardless of level of intensity) during TMR. In that experiment, muscle activity increased across these different levels of intensity (and therefore across SF). Furthermore, it has been reported that RF, BF, GL, and TA muscle activity during DWR increased when SF was increased from 70.0 strides/min to 92.0 strides/min (Masumoto et al. 2013a). However, in the present experiment, we observed that muscle activity was largely unaffected by the change in SF. In this experiment, the SFs used were low compared to other research (i.e., 42.5–57.8 strides/min). Since the drag force increases as a function of speed of movement (i.e., $D = kv^2$; di Prampero et al. 1986), the different observations of an increase in muscle activity with increasing SF between the previous studies (Masumoto et al. 2013a, 2014) and the current study may be related to the amount of drag force exerted on lower extremity during DWR. Combining the observations from all these studies, it is hypothesized that there is a non-linear relationship between muscle activity and SF during DWR.

By manipulating SF around the mode-specific PSF, we had set out to understand if muscle activity could be a criterion explaining PSF. However, muscle activity was neither maximized nor minimized during either DWR or TMR indicating that this, by itself, does not explain PSF. Previously, evidence has been presented to test the hypothesis that

minimizing metabolic cost is a contributing factor during running on land (Hamill et al. 1995; Masumoto et al. 2013b; Mercer et al. 2008; Minetti et al. 1995) and in an aquatic environment (shallow water locomotion) (Masumoto et al. 2013b). There seems to be a large range of SF that can be used in which metabolic cost is not negatively influenced (Mercer et al. 2008)—suggesting the factors determining PSF go beyond simply metabolic cost. Other research has considered whether impact magnitude is an optimality criterion (Hobara et al. 2012; Mercer et al. 2005a). For example, Mercer et al. (2005a) had subjects run (overground) at a variety of speeds in which the SF-stride length combinations were manipulated and it was reported that the impact peak is neither maximized nor minimized while running at the PSF. From our present work, we have further demonstrated that average muscle activity does not explain the selection of PSF during either DWR or TMR. That being said, there may be mechanical advantages to changing SF during running on land. For example, it has been reported that a 10 % decrease in preferred stride length (i.e., a 10 % increase in SF from the PSF) during running on dry land may decrease stress on lower extremity (e.g., vertical ground reaction force (Heiderscheit et al. 2011), patellofemoral forces (Lenhart et al. 2014), and probability of tibial stress fracture (Edwards et al. 2009). In any case, it is not clear if the

optimality criterion determining PSF is physiologically or mechanically based (or some combination thereof).

Another novel observation of this study was that muscle activity from the RF, TA, and GL during DWR was 65.1–72.0, 68.9–71.3, and 77.4–83.6 % lower than that of TMR at mode-specific PSF, respectively. Some of the changes in muscle activity were expected since there are obvious mechanical differences during DWR and TMR. Even though DWR and TMR are considered “running” movements, comparing these activities is difficult since there are some distinct differences in movements. For example, during TMR, the foot is in contact with the ground during the stance phase of the stride. Therefore, muscle activity during stance results in the person is pushing on the ground (and the ground back on the person). During DWR, there is no stance phase since the foot never contacts the ground. However, there is always resistance to direction of movement due to the drag force that is applied to both upper and lower body movements. Since there was no foot contact with the ground during DWR, there was 100 % body weight support during DWR. In a parallel line of research, it has been reported that muscle activity (RF, TA, and GL) is influenced by the amount of body weight support provided during running on a lower body positive pressure (LBPP) treadmill (i.e., on dry land) (Liebenberg et al. 2011; Mercer et al. 2013). Therefore, the decreased muscle activity from the RF, TA, and GL during DWR when compared to that of TMR at the mode-specific PSF is likely related to body weight support nature of DWR (provided by the buoyancy force). Interestingly, when running at the mode-specific PSF, it seems that the drag force during DWR was not sufficient to produce enough resistance so muscle activity would be similar to TMR.

The relationship between BF muscle activity and SF seems rather unique as compared to the other muscles. For example, there were no differences in muscle activity during DWR and TMR at the mode-specific PSF. These observations suggest that DWR may provide sufficient stress to the BF such that muscle activity is matched to TMR. It is speculated that the BF muscle activity may be an important factor for determination of PSF during DWR.

Recently, Mercer et al. (2014) reported that relative decrease in lower extremity muscle activity was not equal to the relative increase in body weight support during running on dry land. For example, the authors reported that muscle activity from lower extremity was 43, 51, and 52 % less active when weight bearing was reduced to 40, 30, and 20 % of body weight, respectively (Mercer et al. 2014). Clarification of the definitive contribution of weightlessness (i.e., microgravity conditions) on physiological and biomechanical responses during running will require additional research. During running in water, there is always resistance to movement via the drag force that is applied at

both lower and upper extremities. There may be some value in understanding muscle activity during running in water by including a 100 % body weight support condition on dry land (e.g., suspending the subject who would be simulating a running action).

We recognize that investigating average muscle activity over a large period of time has limitations. Figure 6 is an illustration of the muscle activity patterns and it is clear that the peak muscle activity increases with faster SF. However, the time to complete a stride is reduced as SF is increased—that observation is not illustrated well when the x-axis is normalized to 100 % (to calculate ensemble patterns). Thus, in the present study, average muscle activity over a large period of time may be masking some of the key changes in peak muscle activity. Inspecting the ensemble patterns (i.e., Fig. 6), it seems that the higher SFs (and higher intensities) are being achieved by greater peak muscle activity (versus average muscle activity). Since average muscle activity is largely unaffected, it may be that the greater drag force applied to the limbs (via increased velocity of the limbs) is overcome by reducing the stride time and/or range of motion of the limbs.

A challenge with investigating muscle activity during DWR is that there are different DWR styles used by runners (e.g., high-knee and cross-country styles of DWR). We had subjects use the high-knee style of DWR in this study and recognized that the style of DWR may influence the preferred movement patterns (e.g., PSF during DWR). In fact, it has been reported that lower extremity kinematics (Killgore et al. 2006) and muscle activity (Masumoto et al. 2013a) are influenced by the style of DWR (i.e., high-knee and cross-country styles of DWR). Since there are no data regarding the preferred movement patterns during the different styles of DWR, we selected one style. In our study, subjects completed a DWR practice session before starting the actual measurements. They were familiar with DWR but not necessarily trained using this mode of exercise. We recognize that familiarity to task may influence initial choice of movement frequency (Dean 2013) and it has been reported that familiarity to an aquatic environment influenced physiological responses during DWR (Frangolias et al. 1996). We do not know if to what extent familiarity with water locomotion influences preferred gait pattern. Future studies may be required to confirm the current observations in individuals who have used water locomotion extensively.

To measure muscle activity during DWR, it was necessary for subjects to wear a dry suit (this was worn only during DWR conditions). The dry suit is constructed for dynamic activities in water (e.g., water skiing, windsurfing). However, unfortunately, it is not clear whether the water resistance is influenced by wearing the dry suit during DWR. It would seem the use of the dry suit would

increase drag force. Future study should investigate the influence of wearing dry suit on muscle activity during DWR.

In addition, it has been reported that wearing shoes may influence physiological responses during locomotion in water (e.g., Rife et al. 2010). However, in most of the previous studies on muscle activity during DWR, subjects did not wear shoes (i.e., barefoot) during DWR (e.g., Mercer et al. 2005b; Masumoto et al. 2009, 2013a, 2014). Therefore, we did not ask our subjects to wear shoes during DWR tests in this study. To our knowledge, the effect of wearing shoes on muscle activity during locomotion in water has not investigated. Furthermore, presently, the effect of wearing vest on muscle activity during DWR and TMR is not known (e.g., Masumoto et al. 2014). Therefore, it has not yet determined what critical features are similar between DWR and TMR. Future study should clarify these points.

Interestingly, it was reported that the absolute (L/min) and relative (ml/kg/min) oxygen consumption ($\dot{V}O_2$) in male subjects were 41 and 23 % greater than that of female subjects during DWR at the same cadence, respectively (Brown et al. 1997). However, the metabolic responses during DWR did not differ between genders, when body fat was controlled by means of measuring $\dot{V}O_2$ relative to lean body mass (i.e., $\dot{V}O_2$ in ml/kgLBM/min) (Brown et al. 1997). These observations suggest that differences in body composition may influence the physiological responses during DWR. Clarification of the contribution of biomechanical parameters and anthropometry (e.g., body fat, body weight, limb length) during DWR will require additional research.

In this study, we did not control the subject's movement patterns (e.g., joint range of motion) during DWR and TMR, because we were interested in their natural behavior (i.e., preferred movement patterns). It was reported that muscle activity during DWR was similar (BF and TA) and lower (RF and GL) than that of TMR when SF was matched between the two conditions (e.g., approximately 80 strides/min; Masumoto et al. 2013b). It was thought that individuals may have reduced drag force encountered on their lower extremity by changing joint range of motion at relatively high SF during DWR, because the drag force was too high to allow full joint range of motion. Future research should clarify the actual influence of joint range of motion (i.e., drag force, a function of velocity, density of fluid, and surface area of the structure moved in a fluid) on muscle activity during running in water.

We fully recognize the limitation of the statistical approach taken where the comparison of muscle activity was largely based upon planned comparisons. Given the high number of comparisons, we restricted our analysis to comparing PSF (per mode) to each of the other conditions as well as PSF during DWR and TMR. An

alternative approach would have been to fit the data with a line of best fit to test for linearity or some non-linear relationship between muscle activity and SF (e.g., quadratic). Nevertheless, there were not dramatic differences in muscle activity across SF conditions within either DWR or TMR. However, there were clear differences when comparing muscle activity between DWR and TMR (except for BF).

Conclusions

From this experiment, we were able to determine that average muscle activity (RF, TA, and GL) was largely unaffected by SF changes during DWR relative to the PSF selected during DWR. Likewise, average muscle activity was largely unaffected by changes in SF during TMR. However, muscle activity was always greater during TMR than DWR for any condition for RF, TA, and GL muscles. Furthermore, the BF muscle activity was comparable during DWR and TMR—and this may be an important feature of DWR.

The observations from this experiment demonstrate that the preferred movement pattern (i.e., PSF) is influenced by environment (i.e., dry land and aquatic environments) such that a lower PSF is selected during DWR vs. TMR even though RPE was the same. Furthermore, muscle activity at the mode-specific PSF was lower during DWR versus TMR. Interestingly, muscle activity was neither maximized nor minimized at PSF for either DWR or TMR. Thus, muscle activity by itself does not explain the selection of PSF during either DWR or TMR.

Acknowledgments This study was supported by a Grant-in-Aid for Young Scientists (B) from the Japan Society for the Promotion of Science (Grant No. 24700758).

Compliance with ethical standards

Funding This study was supported by a Grant-in-Aid for Young Scientists (B) from the Japan Society for the Promotion of Science (Grant No. 24700758).

Conflict of interest The authors declare that they have no conflict of interest.

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